Great Scientific Ideas That Changed the World

Part I

Professor Steven L. Goldman

THE TEACHING COMPANY ®

PUBLISHED BY:

THE TEACHING COMPANY
4151 Lafayette Center Drive, Suite 100
Chantilly, Virginia 20151-1232
1-800-TEACH-12
Fax—703-378-3819
www.teach12.com

ISBN 978-1-59803-305-2

Steven L. Goldman, Ph.D.

Departments of Philosophy and History, Lehigh University

Steven Goldman has degrees in physics (B.Sc., Polytechnic University of New York) and philosophy (M.A., Ph.D., Boston University) and, since 1977, has been the Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University. He has a joint appointment in the departments of philosophy and history because his teaching and research focus on the history, philosophy, and social relations of modern science and technology. Professor Goldman came to Lehigh from the philosophy department at the State College campus of Pennsylvania State University, where he was a co-founder of one of the first U.S. academic programs in science, technology, and society (STS) studies. For 11 years (1977–1988), he served as director of Lehigh's STS program and was a co-founder of the National Association of Science, Technology and Society Studies. Professor Goldman has received the Lindback Distinguished Teaching Award from Lehigh University and a Book-of-the-Year Award for a book he co-authored (another book was a finalist and translated into 10 languages). He has been a national lecturer for Sigma Xi—the scientific research society—and a national program consultant for the National Endowment for the Humanities. He has served as a board member or as editor/advisory editor for a number of professional organizations and journals and was a co-founder of Lehigh University Press and, for many years, co-editor of its Research in Technology Studies series.

Since the early 1960s, Professor Goldman has studied the historical development of the conceptual framework of modern science in relation to its Western cultural context, tracing its emergence from medieval and Renaissance approaches to the study of nature through its transformation in the 20th century. He has published numerous scholarly articles on his social-historical approach to medieval and Renaissance nature philosophy and to modern science from the 17th to the 20th centuries and has lectured on these subjects at conferences and universities across the United States, in Europe, and in Asia. In the late 1970s, the professor began a similar social-historical study of technology and technological innovation since the Industrial Revolution. In the 1980s, he published a series of articles on innovation as a socially driven process and on the role played in that process by the knowledge created by scientists and engineers. These articles led to participation in science and technology policy initiatives of the federal government, which in turn led to extensive research and numerous article and book publications through the 1990s on emerging synergies that were transforming relationships among knowledge, innovation, and global commerce.

Professor Goldman is the author of two previous courses for The Teaching Company, *Science in the Twentieth Century: A Social Intellectual Survey* (2004) and *Science Wars: What Scientists Know and How They Know It* (2006).

Table of Contents
Great Scientific Ideas That Changed the World
Part I

Great Scientific Ideas That Changed the World

Scope:

It is easy to fall into one of two traps in dealing with ideas: either to dismiss them as abstractions and, thus, of less consequence than concrete things, such as swords, plowshares, and factories, or to glorify them *as* abstractions, as creative inventions of the mind, and thus, praiseworthy independent of any practical consequences whatsoever. Ideas are, nevertheless, as concrete as swords and plowshares because they are always tied to a concrete context of values, actions, beliefs, artifacts, and institutions out of which they arise and on which they *may* act. The concreteness of ideas derives from their being produced not only *within* a particular cultural context but *out* of that context, and it is because ideas are produced out of a particular context that ideas are able to influence and even to reshape that context. Treating ideas out of context, then, treating them as if their existence were, in principle, independent of any particular context, deeply distorts the reality of ideas and obscures their power to affect the world.

Ideas and their contexts interact in complex, *mutually* influential ways such that the resultant effect on society of introducing a new idea is unpredictable. The evolution of the Internet from a modest computer networking project funded by the U.S. Department of Defense to a global technology transforming commerce, industry, politics, warfare, communication, education, entertainment, and research illustrates the unpredictability of the idea-social context interaction. The still-unfolding consequences of a small number of innovative ideas introduced to solve technical problems posed by enabling different kinds of computers in different locations to share information in real time continue to surprise, confound, and disturb us!

Unpredictable though it may be, however, for 200 years now, the interaction of science and technology with society has been the primary driver of social and cultural change, first in the West, then globally and at an accelerating rate. During this period, social and personal values and relationships; social, political, and economic institutions; and cultural values and activities have changed and continue to change almost beyond recognition by our great-grandparents. What is it that has enabled such deep transformations of ways of life that have been entrenched for centuries and even millennia?

Certainly, we can identify artifacts—the telephone, the automobile, airplanes, television, the computer—that *appear* to be causes of social change. But identifying artifacts does not reach down to the *causes* of innovation itself, nor does it expose those features of the sociocultural infrastructure that enable innovations to be causes of social change. Artifacts, in spite of their high visibility, are symptoms of causes at work; they are not themselves causes. It is not television or automobiles or the Internet that have changed society. Instead, forces at work within the network of relationships that we call society are causing television and automobiles and the Internet to take the changing forms that they take. One of these forces is ideas, explicitly in the case of new scientific ideas and implicitly in the case of ideas in the past that have been internalized selectively by society, thereby shaping both the sociocultural infrastructure and the lines along which it is vulnerable to change.

The objective of this course is to explore scientific ideas that have played a formative role in determining the infrastructure of modern life through a process of sociocultural selection. But we shall interpret the term *scientific idea* broadly. There is, after all, no sharp distinction between ideas that are classified as scientific and those that are classified as philosophical or mathematical or even between scientific ideas and political, religious, or aesthetic ideas. Alfred North Whitehead, for example, famously linked the emergence of modern science in the Christian West to Judaeo-Christian monotheism: to the belief in a single, law-observing creator of the Universe.

The idea that there are laws of nature at least *seems* to reflect a political idea, while there can be no doubt that mathematical and aesthetic ideas were central to the 17^{th}-century Scientific Revolution. Furthermore, distinguishing science and technology is fuzzy, too, especially since the second half of the 19^{th} century,

when scientific knowledge and technological innovation were systematically coupled in industrial, academic, and government research laboratories.

With this in mind, we will begin our discussion of influential scientific ideas with the invention of writing, which may not seem a scientific idea at all. There is, nevertheless, a profound idea underlying the invention of writing, and a controversial one, as reflected in Socrates's argument *against* writing in Plato's dialogue *Phaedrus*. Writing is also a technology, of course, and thus, serves as an initial example of how technologies embody ideas that we tend to ignore because our attention is almost always drawn to *what* technologies do, to *how* they do it, and to what the consequences are of what they do.

By the time of the earliest written records that have been discovered so far, humans already had embodied, through their invention of a breathtaking range of physical, social, and cultural "technologies," an equally breathtaking range of ideas implicit in those technologies. Lecture One looks back at what humans had accomplished in the way of know-how by the 4th millennium B.C.E., while Lecture Two discusses the invention of writing and the spread of writing systems and texts from about 3500 B.C.E. to the beginning of classical antiquity, circa 500 B.C.E.

Between approximately 500 B.C.E. and 300 B.C.E., Greek philosophers developed highly specific concepts of knowledge, reason, truth, nature, mathematics, knowledge of nature, and the mathematical basis of knowledge of nature in ways that continue to inform the practice of science to the present day. Lectures Three through Five are devoted to these ideas and their legacy. Lecture Six discusses the first appearance in Western history, perhaps in world history, of the idea of techno-science, that is, of technology derived from theoretical knowledge rather than from practical know-how. This was largely a Greek idea that was applied in the context of the rising Roman Empire, and the lecture describes selected Roman-era technologies that had an influence on the rise of modern science and engineering.

Bridging the ancient and early modern eras, Lectures Seven through Eleven explore the idea of the university and its role as a progenitor of modern science; medieval machinery and Europe's first "industrial revolution"; and the Renaissance ideas of progress, of the printed book, and of mathematics as the language of nature. All these ideas are obviously seminal for science as we know it, but they are also, if less obviously, seminal for the rise of modern engineering and the form of modern technological innovation.

Lecture Twelve discusses Copernicus's idea of a moving Earth, the cultural consequences of that idea, and its subsequent evolution as a modern scientific astronomical theory. This serves as a lead-in to Lectures Thirteen through Seventeen, which explore foundational ideas of modern science, among them, the idea of method; new mathematical ideas, such as algebra and the calculus; ideas of conservation and symmetry; and the invention of new instruments that extended the mind rather than the senses and forced a new conception of knowledge.

Lectures Eighteen through Twenty-Eight explore 19th-century scientific ideas that remain profound social, cultural, and intellectual, as well as scientific, influences. These include the idea of time as an active dimension of reality, not merely a passive measure of change; the chemical atom as an expression of a generic idea of fundamental units with fixed properties, out of which nature as we experience it is composed; the ideas of the cell theory of life, the germ theory of disease, and the gene theory of inheritance, all conceptually allied to the atom idea; the ideas of energy, immaterial force fields, and structure and, thus, of relationships as elementary features of reality; the idea of systematically coupling science to technology, of coupling knowing to doing, and of using knowledge to synthesize a new world; the idea of evolution and its extension from biology to scientific thinking generally; and the idea that natural phenomena have a fundamentally probable and statistical character.

Lectures Twenty-Nine through Thirty-Five discuss central 20th-century scientific ideas, including the gene, relativity and quantum theories, the expanding Universe, computer science, information theory,

molecular biology, and the idea of systems, especially self-organizing systems and the allied ideas of ecology and self-maintaining systems.

Appropriately, Lecture Thirty-Six concludes the course by reviewing the ideas that are distinctive of modern science and technology today and anticipating ideas likely to be drivers of change tomorrow, focusing in particular on cognitive neuroscience, biotechnology and nanotechnology, and physicists' search for a theory of everything.

Lecture One

Knowledge, Know-How, and Social Change

Scope:

Science and science-based technologies became the primary drivers of social change by the late 19th century, broadening and deepening the impact of the first phase of the Industrial Revolution. Scientific ideas affect society primarily by way of technological innovations and secondarily through changing how we think of our selves and the world. Of all the scientific ideas that have shaped modern life, none is more influential than the idea of science itself in the form it was given by the 17th-century founders of modern science, a form in which the coordinate idea of techno-science was latent. Central to the idea of science is a conception of knowledge, formulated by the ancient Greek philosophers, as distinct from, and superior to, know-how. Ironically, increasingly sophisticated technological know-how long preceded the idea of science and continued to lead even modern science until the mid-19th century.

Outline

I. Science has changed our lives, but the questions of how it does so and why it is able to do so tell us as much about ourselves as they do about science.

- **A.** Beginning around 1800, science-linked technological innovation—*techno-science* for short—became the primary agent of social change, initially in the West, then globally.
  1. It is through technological innovation that science most directly affects how we live, physically and socially.
  2. With the Industrial Revolution—integrating the factory system of manufacture; mass-production machinery; and water, steam, and (in the late 19th century) electric power—an unprecedented and still-accelerating rate of innovation became *the* driving force of change in modern life.
- **B.** It is the ideas and discoveries of *modern* science that have changed our lives.
  1. With very few exceptions, it is scientific *ideas* that affect us, not discoveries, which invariably turn out to be dependent on ideas for their understanding.
  2. Modern science is that form of the study of nature that emerged in the 17th-century Scientific Revolution.
  3. Modern science is an invention, a uniquely Western achievement, emerging only in the Christian culture of Western Europe.
  4. Modern science is nevertheless deeply indebted to ancient Greek, Graeco-Roman, and Islamic sources; secondarily, to Chinese and Indian influences.
  5. Although some scientific ideas have had a direct impact on how humans think of themselves, the world, and their place in the world, the greatest impact of science has been through techno-science.
  6. Although the idea is Graeco-Roman, techno-science erupted into an agent of social change in the course of the 19th-century Industrial Revolution.
  7. These lectures will demonstrate the assertion of the historian Lynn White that ideas and innovations only “open doors” for a society; they do not force a society to pass through those doors.
  8. How a society responds to ideas and innovations is a function of values prevalent in that society.

II. This course offers a selective survey of major scientific ideas that have shaped our personal, social, and physical existence.

A. It begins with the most influential of all scientific ideas, namely, the idea of science itself.

1. This idea was an invention of ancient Greek philosophers that took on a decisive new form in the 17th century, the form we call modern science.
2. It is from the idea of science, how science is conceptualized, that particular scientific ideas—theories of matter and energy, for example, of germs and genes, of cosmology and information—derive their force.
3. Initially, our methodology will be to "reverse-engineer" the idea of science, exposing its key features and where they came from and asking why the idea of science was able to become a driver of social change via techno-science.
4. The same ideas and innovations have different impacts on different societies; thus, these impacts give us valuable insights into societies and their values.

B. This survey will be broadly chronological but not a systematic history, either of science or of individual scientific ideas.

1. Each lecture will be self-contained, aimed at highlighting a single idea or development in a provocative way.
2. But the lectures will be intensively cross-referenced in the way that the pieces of a mosaic image refer to one another.
3. At the end, we will recover an integrated "picture" of science as a source of life- and society-changing ideas, revealing that science is not "natural" and that its social impact is not inevitable.
4. The first six lectures unpack the idea of science, from the Sumerian invention of writing to the Graeco-Roman invention of the idea of techno-science.
5. The second six explore the transmission of these ideas to modern Europe, from the 12th-century invention of the university to Copernicus's "revolutionary" theory of a moving Earth.
6. Lectures Thirteen through Twenty-Eight address specific ideas and theories of modern science, from Francis Bacon and Rene Descartes on scientific method in the early 17th century to evolution and genetics in the late 19th century. These lectures call attention to a tension between two different conceptions of nature, one "atomistic" and the other process-based, and to the rise of life-transforming techno-science.
7. Lectures Twenty-Nine through Thirty-Six discuss 20th-century theories that continue to shape our lives—quantum and relativity theories, cosmological theories and the ideas underlying computer technologies, information and systems theory, and molecular biology—and those theories likely to do so in the early 21st century.

III. To appreciate that the idea of science inherited from the Greeks was an invention, we need to appreciate the truly astonishing amount of know-how humans accumulated without writing and without the Greek idea of knowledge.

A. From about 9000 B.C.E. to the onset of recorded history around 3000 B.C.E., humans became increasingly adept at increasingly complex technologies.

1. They learned to domesticate plants and animals by way of highly selective breeding to create grains, fruits, and animals with specific characteristics.
2. They invented and mastered increasingly sophisticated textile, ceramics, and metals technologies, including the mining and working of copper, bronze, iron, glass, gold, silver, lead, tin, and gemstones, as well as transportation and construction technologies, from boats and wheeled vehicles to cluster housing, irrigation canals and dams, fortifications, and monumental structures.

3. Concurrently, people were living in increasingly large, typically fortified settlements and engaging in long-distance trade, which implies the creation of appropriate social institutions and social management "technologies."
4. The earliest surviving written documents reflect the existence of long-established legal and moral norms, as well as commercial, social, and religious values and teachings.

B. We can readily infer, from the accumulation of know-how manifested by these prehistoric practices, a highly developed, probably implicit conception of what could be called knowledge.

1. First of all, people could be classified as knowing how to do X or not knowing how to do X, thus as possessing or lacking knowing-how "knowledge."
2. Of those who could be said to know how to do X, it was a matter of routine to distinguish those who were better at doing X from those who did X less well; that is, it was obvious how to rank the possession of knowing-how knowledge and without an absolute scale or standard!
3. It was also obvious that some people did X creatively or innovatively, while others at most did X well in the traditional way.
4. The fact that knowing-how knowledge was invented by our "primitive" ancestors and cumulated over millennia without written records is important to keep in mind.
5. Technologies *are* knowledge; they are, metaphorically speaking, "texts" that practitioners can "read," alter, and disseminate without writing.

Essential Reading:

James E. McLellan III and Harold Dorn, *Science and Technology in World History*.

Elizabeth Wayland Barber, *The Mummies of Urumchi*.

Questions to Consider:

1. Technologies have influenced social development for millennia, but what allowed technology to become a relentless driver of continuous social change in modern Western societies?
2. What can we infer about human beings from their artifacts in the 5,000 years before the first written records?

Lecture One—Transcript

Knowledge, Know-How, and Social Change

Science has changed the world physically and socially. That's indubitable, and I don't think that anyone would give much of an argument against that. Science, especially since 1800, has become a relentless driver of almost continual social change, physically affecting the world, but from our perspective more significantly affecting how we live, where we live, what we do, what we eat, what we wear, the lifespan of humanity. In every way that we feel directly, that we experience directly, science, especially since 1800, is identified with the relentless and even accelerating pace of social change that has been characteristic initially of western societies, and has now become a global phenomenon. I want to emphasize that this is a phenomenon whose onset we can recognize in the early 19th century. We'll set that aside for the moment and I'll come back to it.

One might think, one is tempted to speak, of scientific discoveries as being the source of science's power to be a driver of social change; that scientists have been discovering, continually and relentlessly discovering, new truths about nature, and that the change follows from that. But I want to argue and to emphasize, as I will repeatedly throughout this course, that it is scientific ideas that are responsible for this change, not discoveries; that as a matter of fact discoveries are ideas incarnate. That it is the ideas that are the source of science's power, not discoveries.

Copernicus did not discover that the earth moved around the sun. It was an idea of Copernicus's that the earth moved around the sun rather than that the sun moved around the earth. Einstein did not discover the special or general theories of relativity; Einstein had an idea that led to the special theory of relativity. A different but related idea, as we will discuss in a later lecture, led to the general theory of relativity. It was when these ideas panned out, so to speak, when these ideas were accepted because of their explanatory power, or confirmed by subsequent experimentation, that scientists said that they had discovered new truths about nature; that they had discovered new facts about the universe.

Darwin did not discover the theory of evolution, nor did Alfred Russell Wallace; both of them had a certain idea, and then showed that facts that were known to everyone could be put in a more powerfully ordered and explanatory form if you accepted the idea of evolution by natural selection. Of course we can continue along these lines, but I think you get the idea. Even when you think that you have a case of a discovery, even when a scientist looks at the results of an experiment, or looks through an instrument and discovers, for example, the cell theory of life, which we will take up in a subsequent lecture, what we're really seeing is that an idea has shaped the experiment to begin with; the idea that led to the generalization, based on a few observations, that cells were the fundamental form of all living things.

So I will be recurring throughout this course to scientific ideas and the power of those ideas that will occasionally be referenced to discoveries, but I will try to show you that those discoveries in fact are always associated with ideas that underlie them. It's always, from a persuasive point of view, it's more powerful to talk about discoveries, because they seem totally neutral, than to emphasize that I had an idea that I'd like to convince you of the truth of. It has a certain rhetorical force to argue that as a matter of fact I have nothing to do with this personally. I just happen to be the one that was fortunate enough to discover the following truth about nature.

So what we have in the case of science is that since the early 19th century science has become a driver of change through the power of its ideas. But we need to be more precise still because as a matter of fact science overwhelmingly affects us through technology. Yes, some scientific ideas—the idea that the earth is just a tiny speck in a vast universe—doubtless have some affect on our self-conception and our image of the world. Darwin's theory of evolution is an idea that has so far essentially no practical consequences, although perhaps some are looming in the area of genetic engineering and biotechnology, but as an idea it has had a profound affect on our society, on our self-image, on what it means to be human. So there is a sense in which scientific ideas affect us directly, but in a kind of abstract way.

Practically speaking, science is associated with changing the world, with changing how we live our lives through technology, and in particular through technological innovation. The fact that, beginning in the 19th century, science can be identified as a driver of social change is also a fact about technology in the 19th century, and we will in fact be using throughout this course a term, *techno-science*, which refers to coupling science in a systematic way to technological innovation, transforming the process of innovation in ways that we will be discussing in a later lecture. So that it is science acting in conjunction with technology that has generated the dominant driver of social change globally, physically, and socially over the last approximately 200 years. The emergence of this techno-science, of this coupling of science and technology, is another phenomenon, it's an idea that we're going to need to take a look at.

When I talk about science I will always be referring to modern science. I will be using the term to refer to modern science, which emerged in the 17th century in what is often described as the scientific revolution, although I hope by the time we get to the 17th century you'll see that it's really an evolution out of earlier ideas that were integrated in a creative and distinctive new way. Science in the 19th century is modern science beginning to come to the maturity that gave it the power to effect change, to transform the world, to transform the human condition, existentially, through technology.

This 17th century modern science was uniquely a Western phenomenon. Although there are powerful inputs, especially from ancient Greece and Rome, and from Islam, and secondarily from China and India, modern science only emerged in Western culture. I will refer as appropriate to other cultures, to borrowings from, to influences from, and make some comparisons to China and India and Islam and the ancient world, but as a matter of historical fact, what we mean by science, the evolved product of the 17th century scientific revolution so-called, is a uniquely Western cultural phenomenon. And that's another piece that we need to take into account to understand where did science come from, where did modern science come from, and how does it have the power, what enables it to become, to be, a driver of social change? Neither of these should be taken for granted.

So let's for the moment see where we've gotten to. The word *science* generically means *knowledge* in Latin, but for us it means a very particular way of approaching the study of nature, a very particular approach to the study of nature. What that particular approach is, is the key to science's power, to what it means to be modern science, is a uniquely Western cultural phenomenon. Scientific ideas act on society primarily through technology, but secondarily, they affect our consciousness, they change our sense of who we are, of what the world is, and they also, through technology, give us some idea of what the scope of our possible action on the world is. It gives us a sense of what we are capable of doing. Unfortunately, it doesn't give us any guidance in what we should do, but it certainly gives us a sense of we can now do this, or we can now do that. Once you've got steam power, once you've got electrical power, once you've got the chemical science behind you, you can invent synthetic materials, for example.

This whole process of becoming a driver of change is something that emerged in the 19th century. Even though the idea of science is older and technology is much older, it is in the 19th century that all the pieces, so to speak, came together in a way that caused, for the first time in human history, science and technology together to become the force that has dominated the human condition, I think, over the last two centuries, the single most important factor driving change in the human world and in the physical world since the early 1800s.

In the lectures that follow I will be discussing a selection of scientific ideas, those that seem to me to have most profoundly affected us, either by changing the world in which we live, changing the circumstances of our daily lives, or by significantly affecting our self-understanding. With respect to each of these ideas I want us to explore the questions: Where did these ideas come from? How did they develop? And how have they affected us?

I want to begin with the greatest scientific idea of all, in my opinion, and that is the idea itself of science. The idea of science is not natural. It was not a discovery; it was a deliberate intellectual invention. That it was invented, the form that the idea took, and the fact that the idea has been so influential over the past

400 years are very revealing facts about Western culture that we will repeatedly refer to and attempt to understand.

My methodology in the first third of the course is a kind of reverse engineering of the idea of science. I want to take the idea of science apart, identify its critical features, and about each of these features say: Where did this piece come from? And where did this piece come from that it happened to be available in order for the idea of science to achieve concreteness?

We will begin, therefore, with the invention of writing, which is the incarnation of a very powerful idea, and we can easily recognize that without writing, without texts, science in practice, as we understand science, is inconceivable. So we will trace the evolution of the invention of writing and the idea contained within it from its origins in Sumerian civilization to its adoption by the ancient Greeks in approximately the 9th century B.C.E.

The way that writing and texts flourished in ancient Greece, especially at the hands of a group of Greek philosophers who invented a family of related ideas, the idea of knowledge, which we will see, is also not at all natural, that it was defined by them in a very specific way that became central to modern science. The idea of knowledge. The idea of knowledge of nature. The idea that knowledge of nature should be based on mathematics together with experiment and observation. And even more startling at the time in that context of antiquity, the initial formulation of the idea of techno-science, that technology would be even more powerful if it were based on knowledge than if it were based on know-how.

Lectures Seven through Twelve will discuss the transmission of these seminal ideas, of these foundational ideas that make the idea of science real and possible for modernity to build on. The transmission of these ideas to the founders of modern science in the 17th century by way of the medieval university, the invention of the university—because, again, with common sense we see how important the university was then to the transmission of the ideas of Greek and Roman antiquity to the founders of modern science, but also because the university as a place, as an institution, is central to the practice of science as we understand it.

The university itself is embedded within a social context in which secular and natural values emerge within the prevailing religious tradition. And as we will see as we move from the invention of the university into the Renaissance that we will be talking about how the idea of progress became coupled to technological innovation, and to the idea of science through looking at the idea of progress itself, and the application of mathematics to practical purposes in the Renaissance period, and the impact of printing on Western society; the response of Western society to print technology.

The climactic lecture of this first third of the course will be Copernicus's sort of reinvention of what the universe is. The acceptance of Copernicus's theory in the 17th century brings us across the threshold to the origins of modern science.

Lectures Thirteen to Twenty-Six will explore the great ideas of modern science in the period 1600 to 1900, approximately, and I've organized these into two clusters: one centered on what I will call an atomistic style of thinking—the atomic theory of matter, the theories of the cell, germs, and genes—and a process style of reasoning associated with the ideas of energy, fields, relationships, evolution, and statistical laws of nature and of society.

Lectures Twenty-Seven to Thirty-Six begin with the emergence of a mature techno-science as a driver of social change as it continues to be to this very day. And then we will look at the great ideas of 20th century science—the quantum theory, the relativity theory, the concept of the expanding universe, the computer, the idea of information, molecular biology, and what is sometimes called chaos theory, but really systems theory, and the idea of self-organization of natural phenomena, which is in a certain sense the completion of the idea of evolution first foreshadowed by Darwin and Wallace.

In the final lecture I want to look at several ideas that are likely to be perceived as great in the 21st century. I will be highlighting nanotechnology as an instance of techno-science, neuroscience, and the scientific theory of consciousness, and string theory—the attempt to unify all of the forces in nature into a single theory in physics.

Broadly speaking, the lectures will be chronological. That is to say, I am going to start with the invention of writing, which in a certain sense defines the onset of history—although archaeology has become so sophisticated that what used to be called prehistoric is really part of history as well. We know quite a bit about the preliterate societies and cultures, and we're learning more and more all the time. It's going to be broadly chronological, but it will not be a history of these ideas in any systematic sense of the term *history*. My goal is to identify key ideas and to discuss them in a way that I hope will be thought provoking in terms of raising questions of where they came from, how they came to be formulated, how they came to be adopted, how many of them were opposed? Ideas that we take for granted that are obviously true, but yet were at the time opposed by prominent scientists—not by religious figures, but by the most eminent scientists, often opposed new ideas in science.

I see each lecture as self-contained, but together forming a mosaic image. That is to say, if we look at the invention of writing, we look at the Greek invention of the idea of deductive inference, the whole concept of logic as a science of reasoning, regardless of what you happen to be reasoning about, so each lecture will have a certain self-contained character. But as the pieces fit together, as the lectures unfold, I think they form a mosaic image that there are relationships among these ideas. They fit together in a very distinctive way that I hope will give a metaphorical image at the end of "Ah, that's why science is powerful. That's where these ideas come from. This is the context in which they are embedded that enables them to be drivers of social change."

Now, in particular, I want to focus now not on writing, we're going to take that up first because it came first in the chronological order, but I want to call attention to the idea of knowledge and what it was *not*; which is a little backwards, but let me see if I can clarify what I mean here. One problem that we have in dealing with the past—not the stories that historians tell us, because they already reflect this problem, but in attempting to discuss the past—we necessarily have to talk about it or write about it in a serial way; that is to say, in a linear way. We can only say one thing at a time, and we can only write one string of words at a time. But things in the past happened, many of them happened contemporaneously, and in a complex order of mutual influence.

So it's really difficult to say "let's talk only about writing first, because it came before the Greek definition of knowledge that science subsequently adopted," but we need to recognize that before writing was invented, there was a lot of knowledge. There was a lot of what people other than the Greek philosophers thought, especially Plato and Aristotle (whose idea of knowledge subsequently triumphed, and why that happened is a really powerful question), but they had a very, to common sense, a very bizarre idea of knowledge that you would have thought would not have caught on.

Knowledge in the way that common sense suggests it should be defined, practical knowledge, know-how, had accumulated for millennia before the philosophical idea of knowledge (which was the one that science picked up) was formulated. From somewhere around 10,000 B.C.E., or 9000 B.C.E., until the invention of writing in the 4th millennium in Sumer in the southeastern sector of the Fertile Crescent—today I guess that would be in southeastern Iraq and southern Iran, in that region—to somewhere around 3500 B.C.E., so about 5,500 years ago.

So for at least 4–5,000 years before writing was invented, human beings acquired—*accumulated*—and I want to specifically use that term, they accumulated very sophisticated and very powerful know-how: agricultural technologies, ceramics technologies, textile technologies, metalworking technologies, construction technologies, social organization technologies, government, religion, trade, commerce. We have a really growing but already quite powerful picture from surviving artifacts of how sophisticated know-how was between about 10,000 B.C.E. and the onset of the historical record.

Without writing, know-how accumulated. That means it was disseminated, it was transmitted. It was not each generation having to reinvent the wheel, so to speak. On the contrary, we now know that when we talk casually about, "Well, human beings cultivated grains and domesticated animals," in the case of grains somewhere around 10,000 to 9000 B.C.E. in the Middle East there is record of cultivated grains, and in the Americas 4000 to 5000 B.C.E. of the cultivation of maize. It takes, according to paleobotanists, people who study these things, and contemporary geneticists and biologists, it would take centuries at least, and more likely over 1,000 years, to transform the wild ancestors of maize (what we Americans call corn) and wheat and rice into the varieties that were domesticated.

It wasn't automatically "Oh, well, let's grow rice." Wild rice, wild grain, and wild cereals, the grains fall off naturally, because from a Darwinian point of view, from an evolutionary point of view, it's an advantage for reproduction for the grains to blow off and be distributed, and so they form the next year's crop. But from our point of view, as human farmers, we want the grains to stay on the stalks and to be relatively easy to take off by us, but difficult to get blown off by nature. Transforming wild cereals and wild fruits into the kind of grains and fruits that we want, so to speak, took centuries, at least. That means it was done systematically; that that kind of know-how, which some people might want to call knowledge, that that kind of know-how was handed down from generation to generation.

Very interesting fact about know-how: know-how is embodied in things and in processes. It can be embodied, if you are making copper out of copper ores—you're making a copper object out of copper ores—then the knowledge of doing that is embodied in the process and it's embodied in the thing that you wind up with. So you can see whether somebody knows how to make a bronze pot or not, or a bronze weapon or not, and you can see if they know how to do it well or not, and you can even see that some people do this quite creatively. They invent new processes and new kinds of applications, so that know-how is really quite sophisticated and has many of the same characteristics that knowledge itself has. The kind of knowledge, and now we have to sort of jump ahead, you know what I mean by scientific knowledge, it's theoretical. It's abstract. One of the reasons why you need writing is because scientific knowledge is abstract. It can't be embodied in things and processes. It is captured in texts, which are themselves vessels for ideas, but we'll get on to that in the next lecture.

So when we think about it, we should be awestruck by the accumulated know-how of the prehistoric world, the preliterate world (I think that's more accurate). I referred to a couple of cases of agricultural technology in the way of the cultivation of cereals. The maize, the ancestor of corn, bears no resemblance to the grain that was cultivated in the Andes, actually beginning in Mexico and then was descended down along the Andes to the Incas. But fruits as well. For example, recently archaeologists discovered the remains of figs that were cultivated and that, too, that particular variety of figs—these were found in the Jordan River Valley—were very different, and required centuries, many, many generations, to selectively breed that particular kind of fig from the wild figs that grew in the area.

Textile technology is even older than 10,000 B.C.E. Domestication of animals is not as simple as it sounds either. Wild sheep have hairy coats. The emergence of sheep with wooly coats that you can make sweaters from is something that required centuries of breeding and emerged somewhere around 4000 B.C.E. So hundreds of years before there was writing, people had successfully domesticated goats and sheep and horses and cows, and transformed them in the process. They didn't just say "Okay, build a fence around these animals." They actually transformed those animals in a systematic way. So there is experimentation going on here. There was learning going on here. There was a transmission of learning going on here.

And I've only barely touched on metalworking technology. In 7000 B.C.E., at least, copper was being worked, and within several thousand years bronze was being made, meaning that they had some understanding of mixing tin and copper. Deep mines for copper were already extant in about the 4th millennium B.C.E., again before the invention of writing. Digging a deep mine is not such an easy thing, obviously. Miners understand how complex that process is. So you've got monumental constructions by

4000 to 5000 B.C.E. We're finding the remains of monumental buildings and fortresses and gates where there is trade going on as early at least as 6000 B.C.E., not in the Fertile Crescent, which seems to have emerged a little more slowly than that, but north of the Fertile Crescent, in northern Syria, in northern Iraq, and in eastern Turkey, large-scale settlements with substantial trade over long distance. We find, for example, obsidian blades that came from Turkey in the remains of these cities in northern Syria, so that people were living in ways that suggested that they needed to have a government; that there was organized social life. That's a kind of know-how as well that needs not to be taken for granted; that thousands of people can live in a relatively small area and live well together.

How well did they live? Well, let me close by referring to the observations of Cortez and his party when they came to Aztec Mexico, when they saw Tenochtitlán for the first time, a city with 200,000 inhabitants that they said was more prosperous, more beautiful, more orderly than any city in Spain. It was certainly many times larger than the largest city in Spain at the time. They pointed out and described that the central market in Tenochtitlán was daily visited by about 60,000 people who bought and sold in the great market. This was a city of outstanding accomplishment from a technological point of view. A modern person seeing Tenochtitlán in its prime would be amazed at how beautiful and sophisticated it was without writing and without the Greek idea of knowledge. This notion of know-how being a form of knowledge that has power and sophistication and many of the features we associate with scientific knowledge, and yet being set aside, as we will see in the third lecture when we talk about the idea of knowledge that became part of science, is a very interesting phenomenon, and it lives on in the distinction that we make between science and engineering, between understanding and doing.

Lecture Two
Writing Makes Science Possible

Scope:

Writing is a necessary but not a sufficient condition for modern science, for the kind of knowledge of nature that, coupled to technological innovation, is life-transforming. Modern science is wed to textuality, a legacy directly of the Renaissance embrace of printing and indirectly of the source of the idea of science in Greek philosophy, transmitted to the modern era via the medieval university. From the birth of modern science in the 17th century, it was a given that claims to knowledge of nature must be formulated in writing and disseminated via the written word: books, essays, articles, reports. The invention of writing in the 4th millennium B.C.E. in Sumer is the expression of an idea, coming after millennia of increasingly complex social interaction. It entailed the creation of a system of signs that evolved from idea-pictures to an alphabet and initiated a line of influence that, via Greece and Rome, links Sumerian cuneiform inscriptions on clay tablets to Internet-disseminated scientific journals.

Outline

I. Working backwards from the rise of modern science in the 17th century, writing appears as a necessary though not a sufficient condition for science.

- **A.** The idea of science as a formalized knowledge of nature is only known to us to have developed in literate cultures, and modern science emerged only in the "print-drunk" culture of Christian Western Europe.
  - **1.** The invention of writing thus appears, at least empirically, to be a necessary condition both for the generic idea of science and for the specific idea of modern science.
  - **2.** Writing is not a sufficient condition for either of these ideas, given that the former does not appear in all literate cultures and the latter did not emerge even in text-intensive Islamic, Chinese, or Indian cultures.
- **B.** *Science* is a name for knowledge defined in a particular way.
  - **1.** We saw in the previous lecture that know-how cumulated over millennia without writing.
  - **2.** Writing, therefore, is not a necessary condition for the creation, dissemination, and transmission of know-how, or practical knowledge.
  - **3.** Know-how is concretely embodied in particular objects, processes, and techniques and can be evaluated directly.
  - **4.** The knowledge that is at the root of the ideas of science and of modern science, however, has as its object not concrete experience but an abstract, *unexperienced* "reality."
  - **5.** The carrier of *cumulative and evolving* abstract knowledge effectively *must be* the written word.

II. Writing first appears in the archaeological record in the late 4th millennium B.C.E.

- **A.** The earliest written documents found to date come from the southeastern region of the so-called Fertile Crescent.
  - **1.** This region was ruled by the Sumerians, a non-Semitic people who moved into the region and established a network of cities, among them, Ur, Nippur, Susa, and Uruk.
  - **2.** The Sumerians invented a written form of their language that was inscribed on clay tablets with a stylus.

3. This way of writing is called *cuneiform*, but the type, or system, of writing was *logographic*/*ideographic*.

B. Formal *systems* of writing were long preceded by standardized tokens and inscription symbols.

1. There is evidence, also from the Middle East, for standardized clay objects whose shapes encoded meanings long before writing systems.
2. Pictographic seals were in use in Sumer centuries before writing and, like Sumerian writing, spread throughout the Middle East.
3. Simple inscriptions, probably encoding names and numbers, also were widespread before the invention of writing and for long after.

C. A writing system, like any invention, is the physical expression of an antecedent idea.

1. There is no record of the individual whose original idea the Sumerian writing system was, nor do we know why, all of a sudden, the idea both occurred to someone and "caught on."
2. The Chinese invented writing much later than the Sumerians and probably independently, and writing was invented in the Americas still later, in the 1st millennium B.C.E., but it appeared in Egypt shortly after it appeared in Sumer.
3. It is important to recognize that, like language itself, a system of writing is a *system*, having a holistic character, and thus, is an expression of an idea.
4. The earliest writing systems were ideographic and some, notably Sumerian, but not all, evolved into alphabetic systems.

III. The Sumerian invention of writing was extremely influential, and it was directly connected to the invention of the idea of science in ancient Greece.

A. Hundreds of thousands of clay tablets with cuneiform writing in the Sumerian language have survived, the overwhelming majority of a commercial character—contracts, inventories, and wills—but tens of thousands are political, religious, and literary.

1. The Sumerian writing system was adopted by the Semitic Akkadians, who adapted it to the requirements of their totally different language en route to establishing the first Babylonian Empire.
2. The extensive surviving Akkadian literature includes the highly sophisticated legal codes of Ur Nammu and Hammurabi, as well as religious epics, songs, poems, and mathematical and astronomical texts.
3. Following a pattern that repeats itself right down to the present, the availability of this new language "technology" created a positive feedback loop that multiplied many-fold the behavior it enabled.

B. Over the next 2000 years, the originally Sumerian invention of writing spread eastward and westward from Sumer, evolving from logographic/ideographic writing to syllabic writing systems to purely alphabetic writing.

1. The first alphabetic writing system emerged by the 14th century B.C.E., either in Ugarit (a city-state on Syria's Mediterranean coast) or further south, among the Phoenicians (in modern Lebanon), by people still using variants of Sumerian cuneiform.
2. Variants of the 22-letter Phoenician alphabet (Ugaritic used 30 letters) or of an earlier alphabet of which Phoenician was itself a variant (perhaps Ugaritic) became the ancient Hebrew script, perhaps as early as 1300 B.C.E., and later became the Arabic language script.
3. Meanwhile, the Phoenicians, master merchants of the Mediterranean, taught their alphabet to the then non-literate Greeks around 800 B.C.E. and, a little later, to the Etruscans. Around 500 B.C.E., the Etruscans taught the alphabet to the Latins, better known to us as the Romans.

4. In short, the earliest conceptions (by ancient Greek thinkers) of the idea of science and of scientific and technological ideas found expression more than 2000 years ago and are available to us today thanks to the Sumerians!
5. The Greek response to writing was extraordinary, with books on philosophy, law, poetry, and drama literally pouring out by around 500 B.C.E.
6. The philosophical idea of knowledge that became the cornerstone of modern science was formulated in this context.

C. Writing, like any technology, is first of all an idea.

1. The Sumerians invented a system of writing, and it was extraordinarily influential, but like many technologies, it was not unique.
2. Writing was almost certainly invented independently by the Chinese and again in Central America; the independent origin of Egyptian hieroglyphics, which appear only a few centuries after cuneiform tablets, is less clear.
3. We know nothing about who invented writing or why.
4. What was the necessity that provoked the invention of writing as a response?
5. The Greek response is an excellent illustration of how an innovation "opened a door" for a society that chose to rush through that door.
6. The Greek response to writing also illustrates a recurring feature of certain innovations: They become more valuable the more widespread their adoption.
7. Nevertheless, the spread of writing was not without its critics, ironically including Socrates, who wrote nothing but who founded Western philosophy through the writings of his student Plato.
8. In his dialogue called *Phaedrus*, Plato has Socrates deliver an impassioned argument against writing.

Essential Reading:

Samuel Noah Kramer, *Sumerian Mythology*.

William V. Harris, *Ancient Literacy*.

Questions to consider:

1. Is writing merely recorded speaking, or does writing have a distinctive relationship to thought and, thus, a character of its own, different from the relationship of speech to thought?
2. Given that technological know-how grew progressively more complex for millennia before writing was invented, *could* science, too, have grown as an orally disseminated teaching?

Lecture Two—Transcript
Writing Makes Science Possible

As I said in the last lecture, from the perspective of science as we know it today, science without text, science without writing, without inscription, without capturing the thinking of scientists—and their data, of course, and their reasoning process—in text is simply inconceivable. No writing, no science. This was already true in the 17th century when the scientific revolution took place. When modern science emerged it was already inconceivable that the people who we now recognize as the founders of modern science, it was inconceivable to them that they not write what they were claiming to have gotten knowledge of. So it was inconceivable to Descartes that he could simply tell the people around him his new methodology for gaining knowledge of nature.

Galileo used print technology brilliantly in order to disseminate his defense of the Copernican theory that the earth moves. Just telling that to a group of disciples who sat around him was not even an option already in the 17th century. How did that come to be? Already in the preceding 200 years of the Renaissance period, humanist scholars had made it the norm that all scholarship, all claims to knowledge, not just knowledge of nature, that all claims to knowledge are captured in print. Europe was effectively print drunk as soon as Gutenberg's moveable metal type print technology became available in the middle of the 15th century. Why was Western European society so ready to respond to the new print technology when it was introduced? I believe because of the legacy of the university tradition, which already had captured the Greek notion that learning is captured in books.

Now the Greek philosophers, starting from around 500 B.C.E. at least, wrote books, and those surviving books from the ancient Greek philosophers were the core texts that were studied at the medieval university. When the medieval university was invented, it was invented as a place where people went to study texts to acquire the knowledge of antiquity, to acquire what wisdom human beings had acquired through the study of texts, and that included theological texts as well. It meant studying commentaries on the Bible, for example. So learning, like legal learning, and medical learning, were associated in the university with the study of texts. Actually studying medicine clinically, which was another strand from the ancient Greeks, was to a considerable extent separate from that, as we will talk about later.

So the tacit, the automatic assumption that science entails writing is a legacy that comes from the ancient Greeks, and so the invention of the idea of writing and how it got to ancient Greece, and why the Greeks responded to it in the way that they did, is an important part of the rise of modern science. Note for now, and, again, something that we will be talking about in repeated lectures in the future, the connection between writing and knowledge as opposed to the connection between writing and doing.

In the last lecture I closed with a description of the accumulation of know-how in the preliterate period of human history from about 10,000 B.C.E. down to approximately, let's say, 3500 or 3000 B.C.E., when a writing system became available, and then spread; that know-how is not keyed to writing: knowledge is. I said then that this distinction, that the philosophical idea of knowledge that became a central part of the scientific tradition, that that idea of knowledge is tied from the beginning to writing. I said that this distinction between knowledge and know-how is reflected in the distinction between science and engineering and, by the way, the superior status that our society gives to science vis-à-vis engineering. That understanding is rewarded and appreciated, so to speak, culturally more than just doing, that we think of engineering and technology as merely applied science. That means we're subordinating know-how to knowledge. But even as we will see in the 19th century, modern engineering education, the foundations of techno-science as I described it in the last lecture, is associated with coupling science to engineering and technology—technological innovation—and the key to that turned out to be scientizing engineering. That means introducing science, math, and laboratory courses as the key to engineering education, as opposed to machine shop—to doing. This was a battle in the 19th century that we will be talking about in a subsequent lecture.

So the idea of writing continually comes up, so to speak, as the common denominator here. And that's why I think we need to think about the invention of writing and its transmission to ancient Greece, because that's what became the legacy that applied writing and knowledge in a way that became a tool. More than a tool, a core commitment of science.

Four quick points before we go any further. First of all, writing is a necessary condition for modern science, I believe, but it is not a sufficient condition. The fact that a culture acquires writing, and uses writing intensively, does not guarantee that it is going to generate the idea of knowledge that we find generated by the ancient Greek philosophers, or that modern science is going to arise in that society.

For example, China and Islam, and somewhat later India, all were very print-intensive societies. Especially China and Islam were print-intensive societies. The number of books that were written and printed in China—the Chinese used block printing and then moveable type printing; block printing was used probably 1,000 years before in the West, and moveable type was used hundreds of years before in the West. There were huge numbers of texts, and massive texts, that were printed in China, but the idea of modern science did not arise there. Islamic science and technology, especially from about the 9th century until the 13th century, was far superior to what we might call the science and technology in Western Europe, but the idea of modern science did not arise in Islam. So having writing is a precondition of doing science, but having writing is not a guarantee that science is going to emerge.

Second point: Not having a written language, not being literate, which sometimes has pejorative connotations when we talk about that today, clearly does not mean that a society or a culture is not sophisticated. That's why I spent so much time talking about the extraordinary sophistication of prehistoric, preliterate human beings. How much know-how they had accumulated, what they could do, how they were already transforming the world around them, transforming plants and animals, and through irrigation and construction technologies literally transforming the landscape around them. Within the limits of their knowledge and capabilities, of course—their know-how—they were quite sophisticated. It is a mistake to think that a society that is not literate is therefore not sophisticated and lacks sophisticated know-how.

Third point: What we mean by science is a particular approach to the study of nature, and one of the key foci of this course is to emphasize what makes it particular. But it is not the only approach to the study of nature. For example, in Islam—especially, as I said, in the period from the 9th to the 12th, 13th, 14th centuries—in China, and in India, there was serious and systematic study of nature. But it did not morph into modern science as study in Western Europe morphed into modern science in the 17th century.

Fourth point: The reason why writing is necessary for science, why it is a necessary condition for science, is because what we mean by scientific knowledge is an abstraction. Unlike know-how, which can be embodied in things and processes and evaluated without needing writing, you can look at—I think I used the illustration of somebody making a bronze pot or making a bronze weapon or making a steel blade for a sword—and you can see either it's good or it's not good, the person either knows how to do it or they don't know how to do it, or how well they know how to do it, etc. So the know-how can be literally embodied, can exist in it, and that's what makes it easier to transmit and to disseminate without writing. But what we mean by science, and we see this, we begin to see this in the 17th century, but it was already evident in ancient Greece, refers to a reality that we do not experience, and that we cannot experience. In principle we cannot experience quarks. We do not experience the microwave background radiation that is, for some, a sign that the big bang theory of the origin of the universe is, roughly speaking, correct. We do not experience cells. We do not experience the base sequence in our DNA guiding the cell metabolism and the metabolic processes of our body. Writing is what embodies scientific knowledge.

Okay, with that as a kind of a background, let's take a look at the invention of writing, which as a historical fact could change if new artifacts are discovered, of course, but it seems as though writing was invented by the Sumerians in the mid-4th millennium B.C.E. The Sumerians were a non-Semitic people speaking a non-Semitic language who moved into, possibly from central Asia, moved into the southeastern sector of what we were all trained to call the Fertile Crescent and to consider the birthplace of civilization. Although the writing was preceded by seals and tokens, which have a symbolic character of course, and we would expect that—because for thousands of years before writing appeared, human beings were living in fairly large social complexes with trade and commerce and government and religion, so there had to be some kind of systematic record keeping—but it is with the Sumerians that we get the first writing system that we know about. And we take this for granted.

Writing was an invention. Writing was invented. Writing is a symbol system. It's a system. The whole thing hangs together, you can't just have one letter. Well, actually at the beginning, the Sumerian language system, and as far as we can tell all the earliest language systems, were logographic. That means that the sign stood for some idea. Sometimes this is called ideographic or pictographic. There are differences among these, but we don't need to concern ourselves with them. The first writing system that we know of, in Sumer, was the signs stood for ideas, stood for what we might call a concept or an idea, and it evolved eventually into an alphabetic language. There is no need for an ideographic language to evolve into an alphabetic language; we see that in Chinese, for example.

The Chinese language probably evolved about 1,500 years after the Sumerian language, ostensibly independently, but there was enough contact between, let's say, 3500 B.C.E. and 1500 B.C.E. between the Middle East and Central and Eastern Asia that it is not impossible that the rise of writing in China was not independent. But it is generally considered to, in fact, have been independent. So the earliest Chinese written inscriptions are from the middle of the 2nd millennium B.C.E., although it is suggested that the signs in that language already existed in maybe 2000 B.C.E., but that is somewhat speculative.

Egypt, by contrast, is very close to Sumer, only a couple of hundred miles away, and there was considerable contact between the Egyptians and the Akkadian Babylonians who conquered the Sumerians in the early 3rd millennium B.C.E., the late 2000s B.C.E., The rise of Egyptian hieroglyphics probably was a reflection of the dissemination of the Sumerian writing system.

The Sumerians inscribed their writing system on clay tablets, so that's called cuneiform. It has nothing to do with the language. The language was logographic as a type of language. That means that each symbol stood for an idea, and typically initially had a pictorial character. But that became clumsy when you wanted to write a long book so that fairly quickly, in both hieroglyphics and in Sumerian cuneiform, the symbols became stylized, and no longer had a strictly pictorial character. You had to learn what the relationship was between the sign and the idea it represented or, in time, the sign and the syllable, how you pronounced it, or the sign and, so to speak, the alphabetic letter that let you string words together in the way that an alphabetic language allows.

Note something very interesting about writing. Once you develop a writing system, it's got to be taught. You have to learn it. There's no natural connection. The pictures start out with this natural connection, but that turns out to be very cumbersome, and in fact, even at the pictographic stage we see that in ancient Egypt and in Babylon there were schools for teaching writing. People had to learn it, and of course once it becomes syllabic or alphabetic, then the signs are completely arbitrary, and there's no way that you can learn to read the language without being taught, so there's a kind of school that arises in a society that adopts language.

So cuneiform script, in which the symbols were ideographic or logographic, was introduced by the Sumerians. Regardless of whether the pictures made sense or not in Sumerian, what happened next is quite interesting. The Sumerians were conquered by the Akkadians, who were a Semitic people who sort of migrated east from the land that in the Bible is called Canaan, and they conquered the Sumerians, and established the first Babylonian Empire. They took the Sumerian writing system, which was invented for a non-Semitic language, and they used it in their Semitic language.

Akkadian is a Semitic language. It is a totally different type of language from a totally different family of languages. It's not like the relationship between French and English or even between French and Spanish.

The fact that the Akkadians adopted and adapted the Sumerian script meant that they really did have to take those signs as arbitrary. You really had to learn what those signs stood for because it was a totally different kind of language. That happened sort of seamlessly in the late 2000s B.C.E., and somewhere between 1500 and 2000 B.C.E., that language, which was originally logographic, in which fairly complicated picture-like symbols were used, became alphabetic. And that seems to have happened in the land of Canaan, which in fact is referred to as Ugarit, and there is a text that has been discovered from, roughly speaking, 1200–1500 B.C.E. written in an alphabetic script.

What's particularly important for us is that Ugaritic, an alphabetic language, perhaps the first alphabetic language that the world has known, was adopted by the Phoenicians—the Phoenicians lived in what is nowadays Lebanon—and by the ancient Hebrews, and later by the Arabs. So Phoenician, Hebrew, and Arabic all have very close common roots, and the alphabets in those languages have striking similarities among them, all being Semitic languages. The Phoenicians are of particular interest because they were the master merchants of the Mediterranean for centuries, starting somewhere around maybe 1200–1100 B.C.E. As they traded through the Mediterranean, they disseminated their alphabetic language to non-literate people, I guess because it was good for business. It made it easier to do business with people who could communicate with you in writing, and keep records that you could use and rely on.

And in particular, somewhere around the 9th century, in the 800s B.C.E., they taught the Greeks their alphabet. So alpha, beta, gamma, delta in Greek; alef, bet, gimel, dalet in Hebrew, which is the same as the Phoenician, that's not an accident. Now isn't that a cute coincidence? The letters of the Greek alphabet are similar to the Phoenician and Hebrew Ugaritic Canaanitic alphabetic language. No, it's not a coincidence at all. They were taught that.

It is likely that an earlier phase of Greek society, back around 1200 B.C.E., had a written language, a rather clumsy one, derived from Cretan. You may have read about Linear A and Linear B as two ancient languages. Linear B was deciphered after many years, and seems to have been associated with the Minoan civilization dominated by Crete that was destroyed apparently by earthquakes somewhere around 1400 B.C.E. And the ancient Greeks, the Mycenaean Greeks, the ones that fought the Trojan War, perhaps had some written culture, although there's almost no evidence and certainly nothing like a text. But the Hellenic Greeks, the Greeks that we, so to speak, know of from about 800 B.C.E. on, they were taught writing by the Phoenicians, who also taught it to the Etruscans because they traded with the Etruscans in Italy. The Etruscans taught it to the Latins, whom we know as Romans. So the Phoenicians acted as a conduit for the first alphabetic language, which evolved directly out of the Akkadian assimilation of the Sumerian invention of writing.

Now, the Greeks responded to writing with incredible enthusiasm and creativity. The Greek reception of writing led to almost an immediate explosion of cultural productivity, of poetry, of drama, of philosophy, of mathematics, of medicine. The Greeks started pouring out by 500 B.C.E., obviously not the average citizen, but there was a subset of Greek society for whom the production and reading of books were the norm. We can see this very clearly, for example, in Plato's *Dialogues* written in the middle of the 4th century B.C.E., where it's just taken for granted that an intelligent person, an educated person, reads the books by the philosophers of the preceding hundred or so years. Many of those books failed to survive, but some did, and so we have some idea of what those were.

So since it was in ancient Greece that the idea of knowledge was formulated, became embedded, became the cornerstone of scientific knowledge as we understand it. And since the Greeks responded to writing by making writing books the norm for those who know, there is a kind of a direct line of descent from the invention of writing in Sumer through the morphing of that cuneiform writing into an alphabetic language being taught by the Phoenicians to the Greeks, transmitted through the medieval university to Western Europe as well as other places—Islam, for example.

So it's a kind of interesting way of looking at modern science that a core feature, without which science simply can't be done, has an ancestry that goes back to the invention of writing by the ancient Sumerians.

It has nothing to do with the invention of writing in ancient China, if in fact that was independent, or in the Americas, where in the 1st millennium B.C.E. writing, pictographic writing, and a kind of writing in which the symbols have a phonetic character, apparently, was developed by the Olmec, the Zapotec, and the Mayans; most notably by the Mayans. We only relatively recently deciphered the Mayan inscriptions.

But it's kind of unwieldy to inscribe text on stone as opposed to writing them on papyrus or on parchment and copying and distributing them. We know as a matter of fact that in ancient Greece there was a trade in books already in the 4th century B.C.E.; that people made their living as copyists, for example, copying texts for people. Socrates repeatedly refers to how many drachmas it cost for someone to copy a book if they wanted one, etc.

So we need to recognize, however, some very important things about writing that are often taken for granted. First of all, that it is an invention, and as such, it is the incarnation of an idea. For thousands of years people got along without writing. Why do they all of a sudden need writing? Who did it and why? What was the necessity that was the mother of that invention? We say necessity is the mother of invention. Well, maybe it's true, maybe it's not, but let's suppose we take it for true, what necessity? Was it the social? That the intensifying socialization of life made government and trade, made controlling a population and engaging in life as the population increased and you had all kinds of activities going on, was that the necessity? Well, we don't really know.

There are many different stories in antiquity. People recognizing the power of writing and the glory of writing, sometimes they attributed writing to a gift from the gods. Sometimes to ancient legendary heroes or legendary wise people. In China it was attributed to Ts'ang Chieh, who was a minister of the legendary emperor Huang Di, the "Yellow Emperor." There's no evidence that either of these two characters actually existed, but subsequently in China, looking back to their glorious origins, attributing to their greatest emperor of old and to his wisest minister, the invention of writing.

The Greeks sometimes attributed it to a god, Prometheus. Aeschylus in his plays attributes writing to Prometheus because, he says, well, it was an aid to memory. Euripides, on the other hand, disagrees with that, and thinks that the legendary Greek hero Palanites invented writing as a way of long distance communication so you could send letters to people and tell them news and gossip and what you wanted them to do. Aristotle, writing in the 4th century B.C.E. somewhere around 330–340, writes that writing is in the service of money making; that it is particularly useful for keeping records for the household so that you know exactly how much is coming in and how much is going out, and what you're spending your money on.

There are many tales of the origin of writing, but we don't know who invented it, and we don't know what the motivation for it was. So, one, it's an invention and it involves an idea. It's a system and, as we will talk about, it's a symbol system. That's very important because symbols need to be interpreted and to be understood.

I want to emphasize now something that is of fundamental importance about technology and knowledge, and that is that—I already referred to this—there is no guarantee that because a technology is introduced into a society that it will be exploited, or the form in which it will be exploited. Writing is a technology; writing is an invention. It's a technological innovation. It also has intellectual implications. We wonder what the connection is between writing and thought. Is writing merely a way of capturing speech, or do you get a kind of a positive feedback loop between writing and thought so that when you write things down you start thinking differently because you can then read what you have written, you disseminate what you write, people respond to what you write, that prompts other people to think in different ways?

So that's another interesting thing about writing. It becomes more valuable the more widely it is disseminated. And we'll see this happening sometimes with technologies. The telephone system: every new telephone makes every other telephone more valuable. You don't get a law of diminishing returns. On the contrary, the value of the Internet goes up as more and more people use it, and just as we saw with the Internet, the more people there are, the more new kinds of goods and services that are invented by people to take advantage of the universality of the Internet. The same thing is true of writing; but it's not automatic.

"A new invention," as Lynn White said, "opens doors." We'll come back to that quotation in a later lecture. It does not force any society to enter through that door. And as a matter of fact, as much as you may think, well, writing is a gimme; once you have writing, you automatically accept it. As a matter of fact, that was not the case. Socrates did not write anything; Plato wrote about his teacher Socrates. Socrates, in fact, in the dialogue called the *Phaedrus,* gives a sustained argument against writing, and I want to read part of that, because what Socrates says seems to me very powerful. He attributes the invention of writing to Egypt. He assigns it to Egypt and to the Egyptian god Thoth, who gives it to the king. I'm reading from the text of Plato's *Phaedrus* now:

> Here, O king, is a branch of learning that will make the people of Egypt wiser and improve their memories. My discovery provides a recipe for memory and wisdom. But the king answered and said "O man full of arts, the god-man Thoth, to one it is given to create the things of art and to another to judge what measure of harm and of profit they have for those that shall employ them."

A very prescient and insightful thing for the king to say. The people who make new inventions, who invent new technologies, are not the people who understand what the social impact of those technologies are going to be.

> And so it is that you by reason of your tender regard for the writing that is your offspring have declared the very opposite of its true effect. If men learn this, it will implant forgetfulness in their souls. They will cease to exercise memory because they rely on that which is written, calling things to remembrance no longer from within themselves, but by means of external marks. What you have discovered is a recipe not for memory, but for reminder. And it is no true wisdom that you offer your disciples, but only the semblance of wisdom, for by telling them of many things without teaching them you will make them seem to know much while for the most part they know nothing. And as men filled not with wisdom but with the conceit of wisdom they will be a burden to their fellows.

Socrates goes on and compares a written text to a painting:

> The painter's products stand before us as though they were alive. But if you question them, they maintain a most majestic silence. It is the same with written words. They seem to talk to you as though they were intelligent, but if you ask them anything about what they say from a desire to be instructed they go on telling you just the same thing forever.

The written text is dead. It is almost guaranteed to be misinterpreted, and therefore, it's really not the gift that it looks like. Okay for record keeping, for remembering that so-and-so owes you $50 and it's due next Monday, but a text is not a substitute for direct face-to-face learning and the transmission of knowledge, which Socrates believed was the only way that one person could communicate knowledge to another.

Lecture Three
Inventing Reason and Knowledge

Scope:

As evidenced by the archaeological record, people were reasoning effectively for millennia before the first Greek philosophers, learning how to do a great many complicated, “unnatural” things. Nevertheless, between 500 B.C.E. and 350 B.C.E., Greek philosophers who were subsequently highly influential argued for particular conceptions of reason, knowledge, truth, and reality. Their abstract and theoretical definition of knowledge—as universal, necessary, and certain—contrasted sharply with an empirical, concrete, and practical definition of knowledge. This contrast continues to this day in the distinction we make between science and engineering, between “true” understanding and “mere” know-how. One of the most lasting Greek cultural achievements was the invention of the discipline we call logic by codifying reasoning in a way that supported the philosophical definition of knowledge. The division of reasoning into deductive, inductive, and persuasive forms of argument played a fundamental role in the invention of the idea of science as knowledge of nature.

Outline

I. As an idea, knowledge had to be invented.

- **A.** Plato’s Socrates opposed writing yet appears as a teacher in a large body of writings by Plato, through which Socrates teaches philosophy.
  - **1.** Plato’s dialogues and the still larger body of writings by his student Aristotle are the foundations of Western philosophy.
  - **2.** A central issue for both Plato and Aristotle is the nature of knowledge.
  - **3.** The question “What does the word *knowledge* mean?” does not have an obvious answer.
  - **4.** There is no objective, absolute dictionary in which to look up the meanings of words: People define words!
- **B.** Recall that the accumulation of know-how is quite independent of a formal *idea* or explicit concept of knowledge.
  - **1.** Knowledge could have been defined in terms of know-how, that is, as effective practice.
  - **2.** Indeed, those Greek philosophers called Sophists defined knowledge in this way.
  - **3.** Plato and Aristotle, however, rejected such a characterization in favor of a highly abstract and intellectualized definition.
  - **4.** For them, knowledge was universal, necessary, and certain, hence, timeless.
- **C.** In this abstract definition, knowledge is divorced from experience.
  - **1.** Experience produces know-how, but both are particular, context dependent, merely probable, and subject to change over time.
  - **2.** Philosophical knowledge has as its object a reality behind experience that is accessible only to the mind, which can only arrive at such knowledge by reasoning.
  - **3.** The paradigm of such reasoning for Plato is mathematics, which gives us universal, necessary, and certain knowledge and, thus, validates his definition.
  - **4.** Humans had accumulated powerful forms of know-how for millennia, yet the Platonic-Aristotelian definition of knowledge has dominated Western philosophy.
  - **5.** It was the genius of Greek philosophers to codify—that is, to organize in a systematic way—the activity of mind they called “reasoning” and to define certain products of that activity in

ways that denied to know-how the status of knowledge and to informal/implicit reasoning the status of reason.

6. In the process, they created the disciplines we call logic and mathematics; the idea of a "proof" of a truth claim; and a cluster of correlated, abstract ideas of reason, knowledge, truth, and reality, out of which the idea of science and, much later, modern science itself emerged.

II. Aristotle codified the idea that reasoning meant drawing inferences—inferring the truth of one statement from the truth of others—and he organized reasoning into three distinct modes of inferring whose study makes up the discipline called logic: deduction, induction, and dialectic/rhetoric.

A. *Deductive inference* is the ideal mode of reasoning.

1. Deduction is ideal because, given the truth of the premises from which they are drawn, deductive inferences are necessarily true and, thus, certain, and they can be universal truths.
2. Especially in his books *Prior Analytics* and *Posterior Analytics*, Aristotle organized in a systematic (but highly selective) way the teachings of earlier Greek philosophers.
3. In this, he did for the study of reasoning what Euclid did for geometry, and like Euclid's *Elements*, Aristotle's collection of logic texts, called the *Organon*, was required reading in all Western universities through the 19th century.
4. Aristotle showed that the truth of the conclusion of a deductive argument—he focused on a particular type of argument called *syllogisms*—was strictly a matter of the form of the argument, not its content.
5. This makes the question of how we can know the truth of the premises of a deductive argument—at least one of which must be universal—a crucial one to answer.
6. The problem is that the particularity of sense experience implies that generalizations from experience can never be certain.
7. Aristotle explicitly links knowing the truth of the premises of deductive arguments to knowledge of nature (and, thus, to the possibility of science).
8. Note well the intimate connection here among the ideas of reasoning, truth, knowledge, and reality, especially the concept that *knowledge* means that whose truth is certain and that the object of knowledge and truth is not sense experience but the way things "really" are.

B. *Inductive reasoning* is not just second best for Aristotle; it's a totally different *kind* of inference-drawing from deduction.

1. Inductive inferences are always probable, never certain.
2. The truth of inductive inferences is *not* a matter of the form of inductive arguments: Content matters.
3. Aristotle describes inductive inference as reasoning from particulars to universals—but also from effects to causes—which is why content, derived from experience, matters and why certainty cannot be reached.
4. Nevertheless, Aristotle assigns to induction a role in our knowledge of the truth of the universal statements about reality/nature that serve as premises in deductive arguments.
5. Without such knowledge, we cannot have a science of nature, and the founders of modern science, especially Francis Bacon and Rene Descartes, had to solve the problem Aristotle posed.
6. Keep this in mind for Lecture Thirteen: Experimentation cannot bridge the logical gulf between induction and deduction!

C. *Dialectic* and a related form of arguing called *rhetoric* complete the science of logic.

1. Strictly speaking, dialectic for Aristotle refers to arguments whose premises we *accept* as

true, hypothetically, without *knowing* that they are true.

2. Dialectical reasoning allows us to explore the deductive inferences that can be drawn from a set of premises *if* we accept them as true.
3. The form of dialectical arguments is deductive; thus, although the conclusions of such arguments are necessarily true *logically*, they may not be true "*really*" because the premises may not, in fact, be true.
4. Keep this form of reasoning in mind when we reach the 17^{th} century and the idea of a scientific method that uses inductive-experimental reasoning to validate hypotheses that allow us to have universal and necessary knowledge of nature.
5. Speaking less strictly, dialectic overlaps rhetoric, which is the art of persuasion, using arguments that may appear logical but, in fact, are not.
6. Aristotle's book entitled *Rhetoric* deals in part with the kind of reasoning we use every day to reach action decisions, given that we never possess knowledge that would allow us to deduce what to do in a specific situation.

III. From the perspective of modern science, the relation between induction and deduction is especially important.

A. The experimental method is inductive, but a science of nature that emulated mathematical reasoning would have to be deductive.

1. Francis Bacon seemed to believe that careful experimentation could bridge induction and deduction.
2. He was wrong about this because, logically speaking, induction and deduction cannot be bridged.
3. Generalizations arrived at inductively are, in principle, only probably true, while the premises of deductive arguments must be true necessarily.

B. For Descartes, as for Aristotle, science as knowledge of nature is based on deduction.

1. Where are the premises or principles of nature to come from that will allow us to explain phenomena deductively?
2. This is a recurring issue in science.
3. Aristotle and Descartes decided that we knew the truth of some statements about nature and about reasoning intuitively, but this was a controversial position in modern science.

Essential Reading:

Aristotle, *Prior Analytics*, *Posterior Analytics*, and *Rhetoric*.

Questions to Consider:

1. Are there uniquely correct definitions of the words we use?
2. Why was the philosophical conception of knowledge triumphant given the manifestly superior practical value of defining knowledge as know-how?

Lecture Three—Transcript
Inventing Reason and Knowledge

Let's remember where we're up to. We are in the process of reverse engineering modern science in order to understand the roots of the idea of science, and to understand how it was transmitted to the 17th century so that it was available at that time.

In the last lecture we looked at the invention of writing, the idea of writing, which became incarnated, as I put it, in a writing system, a symbol system that is a written form of language with various consequences, which we discussed briefly. And in this lecture we're going to look at the invention of the idea of knowledge. Now that may sound quite odd. In fact, it certainly does sound odd that you have to invent the idea of knowledge. How can the idea of knowledge be invented? But odd as it may sound, you will see that what we mean by the term *knowledge* in fact had to be invented. That definition is not natural, just as the idea of science is not natural.

At the close of the last lecture I read a passage from Plato's dialogue the *Phaedrus* in which Socrates gave an argument of why writing was not a gift. That as a matter of fact writing was not an effective means of communicating wisdom or knowledge, and in fact it was potentially destructive because it gives the seeming of wisdom. It makes people seem to know things that they don't really understand because you cannot quiz, you cannot interrogate a text. So Socrates himself did not write. One imagines he could have written, but he did not write.

I am sure that it did not escape you how ironic it is that Plato should embed this argument against writing in a written text, and that in fact Plato's writings are overwhelmingly purported to be the teachings of Socrates, who did not write. And there is an irony there. What was Plato trying to do? What was Plato getting at? How did Plato think that he could overcome the arguments of Socrates against writing in the way that he wrote the text that he wrote, in which Socrates appears as an interrogator and not as someone who's accumulating data to be written down in a book hoping to make the ten bestsellers list in Athens in the early 4th century B.C.E.?

As a matter of fact, Plato's writing, he believed, had a quality of dynamism to it that causes us to ask these questions. That the value of the dialogues is largely in the way that we are forced to ask questions, and not to use the dialogues to simply transmit Socrates's ideas, values, and teachings, but to transmit this idea that we need to become engaged with these questions. And, unquestionably, the question that is most prominent and central to Plato's thinking and to Plato's depiction of Socrates is the idea of knowledge.

Here we have a word, knowledge. What does it mean? Where will we go to look up the definition of the word knowledge? In what dictionary, in what absolute dictionary will we go to find the correct definition of the word knowledge? Obviously there is no such dictionary. The definition has to be invented. Somebody has to define knowledge. Now, based on the first lecture and comments that I made in the second lecture, there's no reason why knowledge could not have been defined as know-how. That would have made knowledge practical, concrete, historical in the sense that it changes over time as experience changes over time. But that would mean, since knowledge changes, that knowledge claims at any given time are only probable and are contextual. They are a function of the context in which they emerge.

Any given technique for making copper out of the ore, for making bronze, for cultivating some particular grain, could be in the future improved or changed depending on what we have learned or what we have experienced because of some mutant that all of a sudden arose, and we see the possibility of an ear of corn that's all yellow instead of multi-colored. And you may like the idea of all the kernels of a single color rather than multi-colored. So a know-how–based definition of knowledge would be, again, practical, concrete—I'm calling it historical in the sense that it will change over time as experience changes over time—and there were philosophers in ancient Greece who defended such an idea of knowledge. These were philosophers that Plato mocked as the Sophists.

For the Sophist, knowledge was exactly practical, concrete, contextual, historical, and therefore relative. There was no such thing as absolute knowledge, because human beings don't have absolute experiences. This is clearly a made-up definition of knowledge, which is what we would call today *pragmatic*. It's based on one particular response to human experience.

Plato and Aristotle defended a totally different definition of knowledge. They defended a definition of knowledge which had as its ancestor the ideas of Pythagoras and Parmenides, over 100 years before Plato and Aristotle lived, who had defended what we would call a rationalist view of knowledge. That is to say, they defended a definition of knowledge as universal, necessary, and certain. Know-how is particular, based on particular experiences that you've had; know-how is particular, know-how is probable, and therefore uncertain. So their definition of knowledge was that something can only be called knowledge if it is universal, necessary, and certain. For them, knowledge was timeless. Once you know something you know something, that is timelessly true, because it is universal, necessary, and certain.

So knowledge now is defined in terms—watch this—defined in terms which have dissociated knowledge from experience because our experience is always particular. We experience particular things. We experience this plant and this animal and this lump of ore, but knowledge, according to Plato and Aristotle, is about something that is universal, necessary, and certain. There's nothing in our experience that is universal, necessary, and certain, so the object of knowledge for Plato and Aristotle is a reality behind experience. It's a reality that we do not experience directly. That in fact it is not available to us to experience through our bodies. The object of knowledge is accessible only to the mind.

The paradigm of the form of knowledge in the 4th century B.C.E., the paradigm for Plato and Aristotle, is mathematical knowledge. Especially what we mean by mathematics: that means universal, necessary, and certain knowledge that we have proved using deductive reasoning. This was an invention, just by tradition, of Pythagoras. It was Pythagoras who took the kind of number knowledge that the Egyptians and the Babylonians had accumulated and transformed them into what we mean by mathematics by inventing the concept of a proof. In a mathematical proof, the conclusion. Let's suppose we do something as simple as multiplying two numbers together. If we have multiplied correctly we can be guaranteed of the correctness of the answer. Arithmetic operations are analogous to logical proofs if we have, in fact, followed the rules of arithmetic. They represent a certain set of premises. We define numbers in a certain way. We agree that addition and subtraction and multiplication and division are to be done in a certain way, and if they're done that way, then we're guaranteed that the conclusion is correct.

What is fascinating is that this highly abstract and intellectualized definition of knowledge has been dominant in Western cultural tradition, in the Western intellectual tradition, to the very present. And in fact, it was the definition of knowledge that was built into science, built into modern science as it emerged in the 17th century, and continues to be the case. Mathematical knowledge, notice, is timeless, in addition to being universal. We don't expect triangles to change or to change their properties because we have moved from the 19th century to the 20th century, or because we have moved from the 20th to the 21st, or moved from Europe to Africa, or from Africa to Asia. Mathematical knowledge is universal, it's timeless, it's necessary, it's certain.

It is the paradigm of knowledge for ancient Greece, and it is always referred to, right into the modern period, when there are challenges raised against this definition of knowledge, which flies in the face of experience. So that's a fascinating fact about Western culture, about Western intellectuals, philosophers and scientists alike, that this definition of knowledge has been absorbed.

Now, what the Greeks invented between Pythagoras' time, let's say around 500 B.C.E., and Plato's time, in the middle of the 4th century B.C.E., what the Greeks invented was the science of reasoning. They invented what we call logic today. That is to say, the Greeks invented the idea that you could study reasoning independent of what you were reasoning about. That reasoning was a distinctive activity that the mind engaged in, different from thinking, different from feeling; that there was such a thing as reasoning. Interesting. People doubtless thought they had been reasoning for thousands of years, but the

Greeks decided that this is what reasoning is. You know, it's like somebody saying, "Oh, I didn't realize I'd been speaking prose all my life."

Plato and Aristotle, particularly Aristotle, codified the preceding 200 years of Greek philosophical thinking about thinking, about reasoning, that form of thinking that we call reasoning. And they divided it up into three branches. They decided that there are, in fact, three modes of reasoning. One is deduction, one is induction, and one is called dialectic—it's kind of a grab bag. We'll talk a little bit about that. It's more amorphous than deduction and induction.

The philosophical idea of knowledge, the idea of the definition of knowledge that survived or that flourished within the Western intellectual tradition, was Plato and Aristotle's definition, not the Sophist's definition. And it was keyed to deduction as the only form of reasoning that leads to truth and knowledge. Deduction is a form of reasoning in which if the premises are true—if the premises of an argument are true—the conclusion of the argument must be true. Deduction is a form of reasoning in which if the premises of an argument are true, then the conclusion that you draw must be true; it cannot be false.

Now this is automatically, right from the start, this is a very strange thing to say. What forces me to say that? Why can't I insist that it's false anyway? So there is built into this Greek invention of reasoning as a distinctively structured process in the mind is the idea, the belief in a certain sense, that it is not possible for a normal mind not to draw the inferences from true deductive premises that can be drawn from them.

Now we're all familiar, and the reason why were we taught it—we were taught Euclidian geometry in high school—was not to teach us geometry, but to teach us a form of reasoning which for thousands of years now has been privileged as the most powerful and the only correct form of reasoning if the goal is knowledge. What Euclid did—we'll talk about this more in a subsequent lecture—what Euclid did was to codify 200 years of Greek geometric and mathematical thinking into an organized form in which there are definitions, postulates, and axioms, and then they become the premises of deductive arguments, the so-called theorems of geometry. So that the claim that the sum of the interior angles of the triangle is exactly 180 degrees—must be 180 degrees—is a necessary consequence of the definitions, axioms, and postulates. That is the power of Euclidian geometry that has been recognized for thousands of years.

It's an amazing thing that you can be forced to agree to that even though you might think, "Oh, surely I can make a triangle where there's 179.8 degrees, or 180.2 degrees." No, the concept of the triangle is such that given the definitions, axioms, and postulates, the sum of the interior angles of the Euclidian triangle must be 180 degrees, defined according to the definitions, axioms, and postulates of what we call Euclidian geometry. Euclidian geometry is Greek geometry of the late 4th century B.C.E., as I said, reflecting 200 years of accumulated Greek geometric and mathematical knowledge—because it's not just geometry; *Euclid's Elements*, as the book is actually called.

Now there is a tremendous power associated with pulling things together in this what we now call axiomatic way, in which you take this huge body of knowledge, which had grown up over a couple of hundred years, and show how it can all be deduced from a single set of definitions, axioms, and postulates.

Aristotle did something analogous for logic, for reasoning. Aristotle wrote a series of books, not just one, a series of books, which became, like Euclid, standard texts in all Western schools, right into the 19th century. Aristotle wrote a series of books in which he analyzed deductive reasoning, inductive reasoning, dialectical reasoning; pulling together the previous 200 years approximately (150 years) of Greek philosophical thinking about reasoning along the lines especially that he and his teacher Plato approved of.

We must remember that until the 17th century, and really in logic until the 19th century, Aristotle was the authoritative voice for Western intellectuals. So everyone who went to a post-elementary school, anyone who went to the university, had to study Aristotle. Aristotle on reasoning, on logic, was as authoritative in the early 19th century as he had been in science, in physics, until the 17th century. For Aristotle, knowledge is the key to deduction. Furthermore, this is still the case today in modern science. We consider scientific theories somehow validated—we could say proven—but validated when they make correct predictions. But when we talk about a scientific theory predicting something, what we're really saying is that it is a deductive consequence of a particular theory that X be observed. When we observe X we say, of course, it had to happen because the premises of the theory are true, the theory is correct, as shown by the fact that deductive, logical consequences of the theory are in fact observed.

Consider the general theory of relativity, for example. We say, "Oh, Einstein's theory predicted the bending of light in a strong gravitational field, so bending of light rays as they pass near the limb of the sun." What that means is you can deduce from the theory that light waves are going to behave in that way. You can deduce from the general theory of relativity the existence of black holes and the gravitational lensing effects because the light rays can be bent so much by a really strong gravitational field, for example, a galaxy, that the galaxy can act as a lens and let you see things, bring to a focus items that are far behind that galaxy, and which you could not normally see because you can't see through the galaxy. So these are deductive logical consequences of the theory.

To this day, scientific theories are presented in a deductive, logical way. They are presented in a way that says, "Here is my theory,"—this issue of how we got to that theory, we'll come to that—"Here is my theory. It is a deductive consequence of my theory that X be observed." "I predict," so to speak; but we're not really predicting the world, what we're saying is that it is a logical consequence of the theory that the world be like this. If my theory is true, then the world has got to be like that. And then you do an experiment and you see if, in fact, that is correct. And then if it is, then we say, "Oh, that gives me confidence that this theory is true."

A separate issue is that the history of science makes it very plain that many theories that we now consider to be wrong made correct predictions, so making correct predictions is not in fact a guarantee. It turns out that that form of reasoning does not—"my theory predicts X; I observe X; therefore my theory is true"—does not observe the strict rules of deductive reasoning, so a correct prediction does not guarantee the truth of the theory. But that's the way science is taken.

So deduction is a very powerful form of reasoning, and culturally it's deeply satisfying to us in the West. It satisfies, apparently, some kind of an urge that we have, some kind of a need that we have, for universal, necessary, and certain truth as opposed to living always with pragmatic truth that's relative, that's likely to change as our experiences change. So we see in the history of science that theories do change. Over the last 300 or 400 years that's quite obvious, and yet at any given time we nevertheless believe that now we've got it right. This time we've got it right.

The invention that we're talking about here, the idea that we're talking about here, is the invention of a very particular conception of knowledge, a very particular idea of knowledge in which knowledge is defined in a very specific way which rejects a pragmatic, practical, know-how–based definition of knowledge. Plato and Aristotle made fun of that, as Socrates did. Recognize that there's a very limited kind of knowing that craftspeople have, but it's not real knowledge. And in the case of Aristotle, as we'll see in the next lecture, claiming to know a natural phenomenon—to know why there is a rainbow, to know why anything happens, why a change took place in going from, let's say, a fertilized egg to a tadpole, to a frog, explaining change—then you can only claim to know something if it is formulated within the framework of deductive reasoning.

Let's spend a moment talking about inductive reasoning. Induction is a form of reasoning in which, as Aristotle describes it, for example, we go from the particular to the universal. So based on experience, I saw a swan today, and then I saw a swan yesterday also, and over the last three years my notebooks tell me that I have seen 11,343 swans and they were all white. So I formed the universal generalization, all swans are white. Now it turns out that for thousands of years people did think that that was the case, until in Australia black swans were discovered.

So experience is the basis for inductive reasoning, and because experience is the basis of inductive reasoning, induction can never guarantee the truth of the inferences that you draw from experience. So an inductive argument is one in which even if the premises are true, the conclusion could be false. Putting it differently, the conclusion of an inductive argument is only probably true. The probability is based on the amount of experience and the relevance of the experience to the generalization that you make. You may think, how wrong could you be? If you've seen 11,343 white swans, what's the probability that you've missed black ones? And maybe it's 11,343,343, and the next one that comes up turns out to be a black swan. At the moment, all crows are black, but that doesn't guarantee that we will not discover, somewhere, white crows. For all I know there are white crows, and nobody has let us know that so that we don't have to change logic textbooks.

So inductive reasoning has a probable character. It is induction that leads us to universalized generalizations, but they always have a probable character to them. Now, we're going to come back to induction and the relationship to deduction in connection with science, but first, let me say something about the third form of reasoning—dialectical reasoning.

Dialectical reasoning is, I said, a kind of a grab bag, in the sense that it applies to a form of reasoning in which we, for various reasons, agree to accept certain premises as true even though we don't know that they're true. And in the form of reasoning that Aristotle calls *rhetoric*, we are persuaded to accept them by non-logical arguments. For example, emotional arguments, or threats, or any kind of pragmatic argument that a lawyer makes in order to convince the jury that a client is innocent is rhetoric.

So a more sophisticated form of dialectical reasoning might be hypothetical reasoning in the sciences. Let us assume that the following is true, and let's see what can be deduced from it. In that case, you've got a dialectical argument that shades into deductive reasoning. So, for example, one might say, "Well, let's look to what Einstein actually said in his paper that we think of as the special theory of relativity paper. Let's assume that the speed of light in a vacuum is a constant for all observers regardless of their motion." It doesn't matter what that means at the moment; we'll be talking about it in a later lecture. If we assume that, then certain consequences follow. Certain puzzling phenomena are solved. In another paper he wrote in 1905, he said, let's assume that electromagnetic energy actually comes packaged in discrete little units—quanta—which we now call photons. If we make that assumption, then I can explain problems that have hitherto been unexplained. I can solve those problems.

In science what happens is once a theory like that, where you say let's assume X for the purposes of explaining Y, once the explanation is accepted, we tend to then reproduce the theory. We teach it as if it were true. We teach it as, "It's a principle of nature that the speed of light in a vacuum is a constant for all observers in uniform motion." It started out as a hypothesis. Let's accept this as true and see what follows from it. Does what follows from it match experience? Does it explain? Does it predict? Does it give us control over phenomena? Well, then, that's a sign that it certainly was the right thing to accept, and maybe it was true.

Aristotle analyzes dialectical reasoning from both sides, kind of what you might call a legitimate form of hypothetical reasoning and a more emotion-laden persuasive kind of arguing, which he doesn't have a great deal of respect for, and which he and Plato attribute to the Sophists—that they taught their students how to win arguments by using whatever technique will sway the jury's opinion, regardless of whether their client is guilty or innocent.

Let's go back to the relationship between induction and deduction, because I'm sure that you notice that modern science seems to incorporate induction as well as deduction. We all think of the experimental method as inductive, and when we get to the lecture on the origins of the 17th century scientific revolution, two of the characters we're going to have to talk about are René Descartes, for whom deduction was the only valid form of reasoning, and Francis Bacon, for whom induction was the only valid form of reasoning when you are looking for knowledge of nature. Mathematical knowledge is something else, but if what you want to understand is nature, then you have to use induction.

Now, the experimental method as Francis Bacon formulated it in the 17th century was one in which you used induction to form universal generalizations. But as I said before, they only have a probable character of truth. But through experimental testing—here's my hypothesis; let's test it—if it passes the test, then that validates the generalization. Bacon seemed to believe that you could bridge induction and deduction. You could use a controlled form of induction using experiment to formulate universal laws that could then be the premises of deductive arguments that would give you the truth about nature—universal, necessary, and certain truth about nature. But in fact, he's quite wrong about this.

Logically speaking, you cannot bridge induction and deduction. Inductive arguments are by definition different from deductive arguments. You cannot use the generalizations that come out of inductive reasoning as premises without qualifying them and saying that there is some probability that this is true. But then where are we going to get the premises from? Since, as I said before, according to this philosophical definition of knowledge, the object of knowledge is not experience and can't be derived from experience by inductive reasoning, then where am I going to get my premises from? If I want to have deductive knowledge, if the only form of knowledge that is legitimate is knowledge based on deductive reasoning, for that I need to know true premises. Then I can deduce truths about nature. Where am I going to get the premises from?

Well, Aristotle and Euclid and René Descartes, one of the founding fathers of modern science in the early 17th century, shared the view that, well, there must be some truths that are self-evident or that are available to us by a mental faculty they called *intuition*. Some truths are intuitively obvious, we just see that they are true, or some ideas maybe are innate; some combination of those things. But from Aristotle and Euclid's time until Descartes's time, again, there was an explicit recognition that if what you mean by knowledge is universal, necessary, and certain, if it has to be timeless, then it's got to be keyed to deductive reasoning. And for deductive reasoning to give us knowledge of nature, we need to know some universal truths about nature, some principles of nature, in order to do deduction. How are we going to get that knowledge?

That becomes a problem that we will see recur, and it underlies this whole idea of science. We're reverse engineering and we're discovering roots, but we're also discovering some problems that are going to recur in the history of the evolution of the idea of science from the ancient Greeks to the modern period.

Lecture Four
The Birth of Natural Science

Scope:

For us, *science* simply means a particular approach to the study of natural and social phenomena and a body of knowledge generated by that approach that has evolved over the past 400 years. Initially, however, *science* meant universal, necessary, and certain knowledge generically. Even those Greek philosophers who adopted this definition of knowledge disagreed as to whether such knowledge *of nature* was possible, Plato arguing that it wasn't and Aristotle that it was. Greek philosophical theories of nature long predate Plato and Aristotle, but their ideas influenced Western culture most deeply, right into the 20th century. In addition to his codification of logic, Aristotle's theories in physics and biology and his underlying naturalistic metaphysics and empirical methodology dominated Western nature philosophy through the 16th century. Modern science defined itself in opposition to these theories even as Aristotle's ideas and logic continued to inform modern science.

Outline

I. Plato formulated a rigorous, generic idea of knowledge that was tied to logic and mathematics, but it was Aristotle who formulated the specific idea of knowledge of *nature*, which is what we typically mean by *science*.

- **A.** The relation between mathematics-based knowledge and knowledge of nature is not self-evident.
  1. Mathematics is unquestionably knowledge in the full philosophical sense, but it is not clear what it is knowledge *of*.
  2. Mathematics may give us knowledge of objects that are created by the mind, in the manner of a game, or of objects that exist independently of the mind.
  3. If the latter, these objects may be natural and part of experience or supra-natural and accessible only in the mind.
  4. Knowledge of nature, on the other hand, must be about what is independent of the mind and part of experience.
  5. Mathematics works when applied to experience, so it's not just a game, but it seems impossible to derive mathematical knowledge from experience.
- **B.** It was Aristotle, not Plato, who formulated the idea of knowledge of nature, and he formulated as well the single most influential theory of nature in Western cultural history.
  1. Aristotle was a "scientist" as well as a philosopher.
  2. The 17th-century Scientific Revolution was, in large part, a "revolt" against his theory of nature and his scientific ideas.
- **C.** Aristotle created a comprehensive theory of knowledge of nature.
  1. This theory was grounded in Plato's definition of knowledge as universal, necessary, and certain, and it explained how the human mind could have knowledge of nature given that definition.
  2. The idea of science, as we understand that term, is thus, first of all, indebted to a particular idea of knowledge adopted by Aristotle allied to Aristotle's idea of nature.
  3. Aristotle argued that the logical gulf between induction and deduction could not be bridged by sensory experience, but it could be bridged by the mind.
- **D.** With knowledge of nature established as a possibility, Aristotle embedded his theory of nature in a metaphysics, that is, in a set of absolute, timeless, universal principles that define what is real.

1. One of these principles is that nature is all that there is, that the real *is* the natural.
2. Plato had argued (and perhaps believed) that the real was primarily ideal—his utopian realm of immaterial, universal forms—and that the natural, the realm of form allied to matter, was inferior to, and dependent upon, the ideal.
3. It followed that, for Plato, knowledge of nature was not possible because the natural was particular and continually changing.
4. For Plato, reality was accessible only to the mind and definitely not through the senses-based experiences of the body.
5. Aristotle accepted that form and matter were the ultimate categories of reality, but another of his metaphysical principles was that everything real was a *combination* of form and matter; thus, the real and the natural were one and the same.
6. Subsequently, *this* idea of Aristotle's became a fundamental principle of modern science, namely, that in studying nature we are studying reality: that there is nothing real that is not natural.
7. Another way of putting this principle is that nature is a self-contained system, and we will see that precisely this claim was central to the medieval revival of Aristotle's theory of nature and to modern science.
8. Note, too, how Aristotle's metaphysical principles are analogous to the universal laws of nature proposed by modern science.

II. Knowledge, Plato and Aristotle agree, is universal and timeless, while nature is particular and continually changing; thus, Plato seems right in concluding that science is impossible.

A. Aristotle's theory of knowledge explains how the mind abstracts universals from experience, and his theory of nature explains how we can have knowledge of change.

1. He postulated the existence of a mental faculty, the active intellect, that could recognize in individual objects the intrinsic universal forms of which particular natural objects and phenomena were instances, for example, recognizing in a particular dog such universals as species, genus, order, and class.
2. Knowing "intuitively" the truth of universals, the mind can then achieve knowledge by creating deductive accounts of nature.
3. That is, Aristotle proposed bridging experience-based induction and deductive knowledge by intuitive knowledge of universals that become the premises of deductive arguments.

B. Plato and Aristotle on knowledge of nature illustrate a recurring feature of intellectual history.

1. The history of ideas, like human history generally, is rarely linear and logical.
2. Plato borrowed selectively from his predecessors in formulating his ideas about form, matter, knowledge, and mathematics.
3. Aristotle borrowed selectively from his teacher Plato and from those same predecessors, but his selection was different from Plato's.
4. In particular, Plato adopted certain Pythagorean ideas about mathematics but rejected the idea that mathematical objects existed within the natural.
5. Aristotle rejected the idea that mathematics was central to knowledge of nature, except for optics, music, and astronomy, which he considered special cases.

C. Aristotle's theory of nature is dominated by a theory of change, and his physics, by a theory of motion as one type of change.

1. Aristotle's theory of change begins with his famous "four causes" analysis of change.
2. Change is explained when it is related to four causes, a term that is suggestive of reasons for, or principles or parameters of, change but corresponds only loosely to what *cause* came to

mean in modern science.

3. Note the absence of predictive success and control of experience as criteria of knowledge of nature, criteria considered important in modern science.
4. For Aristotle, as for Plato, knowledge is abstract and theoretical *only*.
5. Aristotle's four causes are material, formal, efficient, and final.
6. Aristotle's theory of nature, including his physics, was thus qualitative because he held that, except for astronomy, optics, and music, mathematics was only incidentally relevant to explaining natural phenomena.

III. Aristotle's physics, though enormously influential, does not begin to exhaust the scientific ideas invented by ancient Greek thinkers that continue to affect our lives today through their incorporation into modern science. Several of these ideas are highlighted below.

A. The idea that everything that is forms a *cosmos*, an ordered whole.

1. An ordered whole implies a structure, a system of relationships.
2. This makes the task of cosmology explaining that structure.

B. The Pythagorean idea that mathematics is the basis of all knowledge of nature.

1. In the 16^{th} and 17^{th} centuries, this idea was attributed to Plato.
2. One of the defining characteristics of modern science is its mathematical character, contrary to Aristotle's view.

C. The idea that reality is composed of timeless, elementary substances with fixed properties.

1. This *substance metaphysics* derives from the writings of Parmenides, cryptic even in antiquity.
2. It was the inspiration for postulating elementary atoms, whose combinations, based on their innate, fixed properties, are the cause of all complex things and all phenomena.

D. The rival idea that there are no elementary substances because reality is ultimately a web of rule-governed processes.

1. The philosopher Heraclitus promoted this *process metaphysics* against Parmenides and the atomists.
2. Since the mid-19^{th} century, this idea has become increasingly prominent in science.

E. The idea that nature is ultimately matter in motion and no more than that.

1. Aristotle's idea that nature *is* reality reduces to materialism if his notion of form is interpreted as a pattern of motion.
2. This is exactly what the founders of modern science did.

Essential Reading:

Aristotle, *Physics*; also *On Generation and Corruption*, *Generation of Animals*, and *On the Soul*.

Lucretius, *On the Nature of the Universe*.

Questions to Consider:

1. How is it that without any instruments and with the most limited experience and experimentation, Greek philosophers formulated so many concepts and ideas that continue to be central to modern science?
2. What is missing from an Aristotelian causal explanation that we expect from science?

Lecture Four—Transcript
The Birth of Natural Science

Now we're ready for the idea of science, which probably almost anybody you stopped and asked what is science or what does science mean would say, "Oh, knowledge of nature." But now I hope we begin to appreciate that when we say that science for us means knowledge of nature, that it means knowledge of nature where knowledge is defined in a very particular way.

As we saw in the last lecture, knowledge is defined to be universal, necessary, and certain; that it is a timeless truth that the goal of science is to discover timeless truths about reality. For the purpose of doing that you have to have the right ideas, including you have to have the right idea of what knowledge is, because if you're working with an idea of knowledge that is keyed to know-how, then you cannot have what we will respect as knowledge of nature, because it will be merely probable, it will be particular, it will be context dependent, and it will change over time.

So the idea of science now begins to emerge as the idea that it is possible to have knowledge of natural phenomena. That is an additional idea to the idea of knowledge. Clearly the Greeks had a case that there was such a thing as mathematical knowledge, because the body of geometric and mathematical knowledge that the Greeks had accumulated between, roughly speaking, 500 and 300 B.C.E. was evidence that you could have a body of universal, necessary, and certain truths that were on the face of it timeless.

That does raise the question of what is the status of these mathematical objects. Where do they exist? Do they exist independently of the mind or do they exist only in the mind? And that raises a further question which the Greeks and then later the medieval philosophers in the West and modern science will have to confront: If mathematical objects exist independently of the human mind, and if they are universal, necessary, and certain, and therefore cannot be learned from experience, how do we know mathematical truth? If, on the other hand, mathematical objects exist only in the human mind, and they are a kind of a complicated intellectual game analogous to chess—every move in chess is a deductive consequence of the rules of chess, but we do not believe that there is any correspondence between the game of chess and the external world. There may be some obsessive chess enthusiasts who do believe that, but we recognize that it's a game.

Is mathematics merely a game where we make up definitions like in Euclid's geometry of a point, a line, a plane, and a solid, and we make up certain definitions about parallelism, and we make certain postulates about parallelism, and then we deduce things from them? It's a kind of a game, but then why does mathematics work? Chess doesn't work. Nobody guides their life on the basis of chess moves, by inferring moves in chess and saying, "Well, now I know who I should marry, what job I should accept, where I should move." So mathematics works. What Eugene Wigner called the "unreasonable effectiveness of mathematics" is certainly puzzling.

So that becomes an issue that we're going to explore a little bit in this lecture and much more in the next lecture, when the mathematical basis for knowledge of nature becomes the subject. But for now, we see how the idea of knowledge that we discussed in the last lecture can become the basis for claiming that knowledge of nature is possible. This claim was specifically defended and developed and transmitted subsequently into Western culture by Aristotle. I think no one would deny that into the Renaissance Aristotle was the dominant philosophical voice in the Western cultural and intellectual tradition; also, by the way, in the Islamic intellectual tradition. Aristotle was the "master of them that know." His medieval commentators simply called him "the philosopher."

I mentioned that Aristotle had codified in his logic books, which became textbooks through the medieval university system, subsequently right into the 19th century. Until symbolic logic was invented, Aristotle's logic works were the standard texts that everybody had to study. It was required for graduation. You could not evade them by taking electives around them.

Aristotle, in addition to being the codifier of Greek theorizing about reasoning, Aristotle was also himself a very accomplished scientist, so to speak, although the term *scientist* was only invented in the 19th century. He would have called himself a philosopher of nature. In pursuit of knowledge of nature, Aristotle wrote on a very wide range of natural subjects. So, for example, on physics, on biology, on psychology, on the weather, on astronomy, Aristotle's works were, so to speak, the baseline for what constituted knowledge of nature and the pursuit of knowledge of nature right into the Renaissance. It was Aristotle the scientist against whom the founders of modern science reacted. That is to say, modern science to a considerable degree constitutes a reaction against Aristotelian science, against Aristotelian knowledge of nature.

Aristotle's claims to knowledge of nature were based on metaphysics and a theory of how the mind can have knowledge. Given what we now understand knowledge to mean, the question has to be raised, how can a human being have knowledge of nature? How can they know the truth of universal premises that cannot be induced, that cannot be inductively inferred reliably from experience? Because those inductive inferences only are probable, and for my deductive arguments I need certainty. I need to know that the premises are true.

Aristotle's metaphysics, insofar as it's relevant to us here, is that nature is all that there is, that the only reality is nature. This is a very important step, and it's an important step away from his teacher Plato, because Plato wrote as if he believed that form and matter were the two ingredients, so to speak, of reality. That everything in nature was composed of form and matter, but that the form could exist separately from the material object, and in fact did in some utopia, in some no-place, some place that was not in physical space. That these forms existed before nature existed, and would continue to exist if nature ceased to exist.

So what gave nature its actuality was that matter, which for Plato was intrinsically amorphous, was shaped, so to speak, from the outside by ideal forms. There's an ideal form of the horse, of the rose, that the creator, so to speak, imposes on recalcitrant amorphous matter, and so we get individual horses and dogs, and so on, which do not have a totally rational character, and are not examples of the universal, because the universal is pure, whereas the matter prevents the form from ever achieving the purity that the form has.

Notice that, for Plato, this means that reality is accessible only to the mind. Our eyes, our ears, our other senses respond to material objects, which are imperfect realizations of ideal forms. It is only the mind that is capable of "perceiving" the ideal forms in their ideality, which was why Plato required mathematical education for people who wanted to study philosophy with him. Not because he thought mathematics was by itself all that important for achieving wisdom, but because if you could not handle the abstraction of mathematical knowledge, if you could not grasp the mathematical objects and their properties and reason about them, then there's no way that you're going to be able to deal with the world of forms, which is beyond those of mathematics.

So there is this legend that above the door of his academy it says, "Let no one who is ignorant of mathematics enter here," but the point is that mathematical reasoning, as we saw in the last lecture, is the key. If you can't handle that kind of formal and abstract reasoning, then you can't do philosophy. Form and matter are separable for Plato just as the soul and the body are separable, as Socrates tells us over and over again. It's because the soul and the body are separable that the soul is capable of grasping these ideal forms.

Aristotle's decisive break with this is: Nonsense; there is only one reality and it is nature. Nature is a closed and self-contained system. All natural phenomena are to be explained within the framework of nature, a principle that will become a founding principal of modern science and articulated in the 12th century. Nature is a closed system. Form and matter are indeed the ultimate constituents of reality, but form and matter cannot exist separately from one another. This is the fundamental principle of Aristotle's metaphysics. We're not going to go into it in any further detail here, but you can grasp this: that for

Aristotle, every thing in nature is a combination of form and matter. But the form and the matter cannot be separated really. Matter could not exist without there being form. Unformed matter does not exist and cannot exist. Forms that are separated from matter cannot exist. This business that forms are too pure and too beautiful to exist within matter—which is something which is maybe a parody a bit of what Plato believed, but it's pretty damn close—form and matter only come together. And in order to understand nature, we need to understand the relationship between form and matter in the particular case of each individual object, and what the relationship between the form and the matter is in those two particular cases.

So this is sort of the metaphysical background of Aristotle's notion of why we can have knowledge of nature. Notice, based on what I've said, according to Plato you cannot have knowledge of nature. We may want to make Plato a very bold and radical intellectual, and he was, but he did not believe that knowledge of nature was possible. Knowledge of nature was not possible because, for Plato, nature was constantly changing because of the material dimension of reality, of actuality, of nature. The matter made it the case that nature was continually changing, and knowledge is changeless, so you cannot have knowledge of the changing. The only knowledge that is possible is knowledge whose object is the ideal form.

Aristotle says, no, you can have knowledge of nature. But how can that be if, in fact, nature is always changing? Aristotle agrees with that, yes, nature is always changing, however, Aristotle says the mind is capable of abstracting universal forms from particular experience. Aristotle attributed—we can't say that he discovered, and we can't say he identified, because we believe he was wrong—but for thousands of years it was accepted that Aristotle postulated that there is a faculty in the mind, which he called the *active intellect*, sometimes called the *agent intellect*, whose specific task—just as there's a faculty of the mind that's called memory, for example—so there is a faculty of the mind that responds to the universal in particulars.

Some people are better at this than others. So you see a dog, one dog. You've never seen a dog before, and a sufficiently acute thinker will recognize that this creature is an exemplar or is an example of a type. And they'll see another creature and say, "That's another dog. No, that's not a dog. That one is, though, and that one is, and that one is." Not only is the universal dog, which is a kind of a low-level universal, perceptible by the active intellect in a particular experience, but even higher level universals such as mammal, such as vertebrate. That when we use such terms we are not inventing categories, according to Aristotle, we are actually perceiving with the mind's eye, which is the active intellect, we are perceiving universals in natural objects.

Now, if we can extract universals from particular experiences, then we have bridged induction and deduction. If we can abstract—now, those universals don't exist as Plato said they did; for Aristotle they do not exist separate from the particular object, they only exist in the particular object—but the mind is capable of abstracting them, forming inferences about natural phenomena based on the universals it has abstracted, forming deductive arguments, which is the only basis of knowledge. So knowledge of nature proceeds in this way.

Aristotle's view on this matter is actually a very good illustration of another phenomenon that is relevant to what we're doing, but not directly in line specifically with the idea of science. That is that intellectual history generally is often presented in a very logical and reasonable way—whereas, as a matter of fact, it's always in a ferment. There are all kinds of missteps that people take. There is backtracking, and various kinds of influences that flow and then stop, and people selectively adopt ideas from predecessors.

So, for example, I said that Plato argued that form and matter could exist separately, or at least this is the mainstream interpretation of Plato, that he had a theory that forms existed separately from matter. Forms were the object of knowledge. We could not have knowledge of anything that was material. Plato had studied and was a master of Pythagorean teaching, and Pythagoras's teaching, as we'll see in the next lecture in some detail, was that mathematical form was within natural objects, that every material object was what it was because there was a specific mathematical form that was dwelling in that object. Like, a dog had a specific mathematical form. A maple tree had a specific mathematical form. An acorn, a frog, everything in nature is what it is because the matter is organized in accordance with a particular mathematical form.

Now, this is very prescient from our point of view. It sounds a lot like modern mathematical physics in a curious way, and we'll be pursuing that connection, too, in the future. But the important thing is that for Pythagoras, who was responsible and his subsequent school was responsible for the development of mathematics as a form of knowledge that we've been describing, the idea of knowledge was embedded in this notion of mathematical reasoning. Pythagoras believed that mathematical forms existed within the natural objects.

Plato absorbed certain things from the Pythagorean tradition, but dismissed the idea that forms of any kind, including mathematical forms, could actually be in material objects. They only had to be sort of, that from the outside they shaped it, but they could not really be in there because the material world was not worthy, could not be a place where the perfect forms existed.

Aristotle, who spent 20 years studying with Plato, Aristotle followed, one could say adopted, the Pythagorean teaching that universals were in material objects. But he rejected the mathematics part because Aristotle believe that mathematics was not an essential component of explanation of natural phenomena. He made exceptions for three types of phenomena where abstract mathematics did describe and explain concrete physical phenomena. These were optics, music, and astronomy.

We will talk more about these in the next lecture as well. But in optics he thoroughly accepted, as the Greeks had, that the angle of incidence is equal to the angle of reflection from a plain mirror, that that was a mathematically precise law. He accepted in music the Pythagorean school's analysis of musical tonalities in terms of precise mathematical relationships. And of course accepted, again, the Pythagorean tradition that the planets moved around the sun in circular orbits with uniform motion, so the motion of the planets had a mathematically precise character.

So in those areas Aristotle agreed that mathematics is directly relevant to physics, to nature; but in all other areas it's only incidental. Yes, you can count, you can weigh. Those may be useful facts, but they don't touch on the explanation of natural phenomena. Mathematics does not touch on the explanation. So the relationship among the Pythagoreans, Plato, and Aristotle is kind of confusing, and it doesn't look as though any one of them is being particularly consistent.

Well, if mathematics is not part of the essence of natural phenomena, what is the basis for Aristotle's science, for his knowledge of nature? Aristotle developed a theory of four causes, in the *Posterior Analytics*, for example. These four causes are better developed in the text called the *Physics*, and in Greek philosophy the word *physics* means nature. Because the word physics means nature, so not what we mean by physics, when Aristotle wrote about physics, he felt quite comfortable including in that book anything that had to do with nature. It was not just what we call physics as opposed to chemistry, biology, geology, etc. So for Aristotle, physics requires for its explanation an account of natural phenomena that fits into a certain pattern, the four causes, as they came to be called; although that's a Latin version of the Greek term that Aristotle used, *aitia*. And in the *Posterior Analytics,* Aristotle says that we can claim to have scientific knowledge—again, it's an anachronistic term, he would have said "knowledge of nature"—we can have philosophical knowledge of nature, as he and Plato defined knowledge, when we can say that X is the cause of why Y is, that it must be the cause of Y—that it is the cause, that it must be the cause, and that it explains why the phenomenon you're trying to explain exists. That is the framework of what constitutes scientific knowledge.

Those are the criteria of scientific knowledge for Aristotle, and he then unfolds, he clicks on the word "cause" and down drops a window, and that window has four causes that need to be included in any account of a natural phenomenon that can be considered explanatory. Notice, there was not the same emphasis that we have in modern science on prediction and control. For Aristotle and for Plato, knowledge is a completely abstract and theoretical thing. The idea that knowledge is validated by using it is completely foreign to this way of thinking. On the contrary, Aristotle says in numerous texts, especially in the *Nicomachean Ethics,* Books 6 and 7, but also in the *Rhetoric,* that the idea for a philosopher is theoretical wisdom, which does not translate into practical wisdom.

Practical wisdom is a separate faculty. It is possible for someone to be theoretically wise and practically foolish. It is possible for someone to be practically wise and theoretically to be an ignoramus. They are two separate things. Theoretical wisdom does not translate into action. As a result he says in the *Rhetoric* quite explicitly, action in the world, behaving in the real world daily, making all the decisions and choices that we do in the course of the day, this behavior is not rational because it cannot be deduced.

Anyway, let's take a look at the four causes, because this is a very famous theory of Aristotle's and it becomes the background for modern science. You can see how in the 17^{th} century this was replaced by a whole new conception of what constitutes a scientific explanation. But for approximately 1,800 years, this was it. First, you must account for the material aspect of a thing. You must talk about the matter of which something is made: the matter of the tadpole, the matter of the acorn, the matter of the dog, the puppy. If we're trying to understand, for example, embryological development, Aristotle did a wonderful series of experiments on chick embryos, studying them every day of their gestation; and if we want to understand how from the fertilized egg we get a chicken, you've got to account for the transformations of the matter of which the embryo is constructed.

The second is you have to identify the form. You have to identify the form that causes the chick embryo to become a chick embryo, and not a sheep embryo. So we today would respond to this in terms of DNA, let's say, and the way that the DNA molecule guides cell metabolic processes.

But for Aristotle there is a form that is resident within every material object, and we must account for that form and how that form operates. That's the third cause, the efficient cause. What is the actual process by which, what are the stages of the process by which the fertilized egg becomes an embryo, and becomes a neonate.

And the fourth cause, the one that actually turned out to be the longest-lived and the most controversial in elimination is the final cause. You have not really explained any natural phenomenon until you can identify that for the sake of which that phenomenon took place. If you want to understand why human beings have incisors, one of the reasons is—the final cause is—so that they can chew meat. So in order for them to be able to chew meat they have incisors. Now you may recognize already that Darwin's theory of evolution is a total rejection of the usability of final causes in a scientific account of nature. The theory of evolution would say that we eat meat because we developed incisors.

So these four causes from Aristotle in the late 4^{th} century B.C.E. until the Renaissance, right into the Renaissance and the dawn of modern science, an analysis of a natural phenomenon in terms of these four causes, clearly qualitative—there's no focus here on mathematics whatsoever, certainly a focus on experimentation—this is what constitutes a scientific explanation. And, as I said before, there is no focus on prediction and control, and it is quite theoretical. It is quite theoretical, and it's aimed at giving what you might call a theory-based explanation.

It doesn't have to be practical in order to be validated, or for someone to say, "So what can you do with it? Now that I know it, what has happened?" Well, from Aristotle's point of view, as he says at the end of the 10^{th} book of the *Nicomachean Ethics*, "Now you are a better person. Now you are using the most excellent part of the human being: namely, that part of the mind that is capable of engaging in deductive reasoning in order to achieve knowledge." In this case, knowledge of nature, which complements philosophical knowledge.

Now, Aristotle, in spite of my saying before that he was the dominant authority and influence for the next 1,800 years on Western philosophy and Western philosophy of nature, the challenge to Aristotle came in the Renaissance when Plato's writings—which were not available in Latin until the Renaissance—when

Plato's writings, and Pythagorean mathematics began to be studied again, as we will see in a subsequent lecture. The challenge came in part from those thinkers in the Renaissance that wanted to mathematize natural phenomena. So, in spite of saying that Aristotle was such a powerful influence, and he was, he was only one of a startling spectrum of Greek thinkers, creative Greek thinkers about nature, who formulated ideas that were transmitted through the Middle Ages, to the Renaissance, to the founders of modern science, and that influenced their thinking.

In the case of Aristotle, unquestionably one of the most powerful influences was simply his defense of the view that nature is all the reality that there was, and that nature was a closed system. But the Greek thinkers before him formulated the idea that the universe was a cosmos. That means a well-ordered whole. It wasn't just a jumble of things thrown together, but the universe had an order to it. And then from a philosophical and what we would call a scientific point of view, the goal is: what is the order? What are the principles of order? What are the laws that make the universe orderly rather than a hodge podge of phenomena? So the concept of the universe as an ordered whole, crying out for explanation.

There are two themes that we're going to see especially pronounced in the 19th and 20th centuries. It turns out, again only through reverse engineering, I think, would we become sensitized to this, that in antiquity a hundred and some years—I mentioned Parmenides, a founding figure who was a very old man when Socrates was a very young man, and Socrates was executed in 399 B.C.E.—Parmenides argued for what I am going to be calling in later lectures a *substance metaphysics* view of reality. That is to say that the ultimate reality is a thing or things. In the case of Parmenides it seems to be a thing; that there is a single, timeless, eternal thing that is the ultimate reality, and that everything that we experience is really secondary to the characteristics of this thing. Any attempt to explain natural phenomena in terms of things and their properties, I'm going to be calling Parmenidean. It's a substance view of reality.

Parmenides was criticized. An alternative was offered by the Greek philosopher Heraclitus who argued that, "No, no, no, no, no. The ultimate reality is change. Change cannot be reduced to timeless things with fixed properties." We're familiar with those things as atoms. "Instead, there are laws of change that are timeless." So this is what I will call a *process metaphysics*.

It is an active sort of intellectual battle in ancient Greece and the 5th and 4th centuries B.C.E. over these two different approaches to knowledge of nature. The Parmenidean approach, based on eternal substances with fixed properties. When Newton in his *Optics*, published just at the dawn of the 18th century, says that in the beginning God created atoms as hard spheres that cannot be destroyed or changed in any way by anybody except God, he is reverting back to this Parmenidean idea that the ultimate reality is timeless and has fixed properties. And the contrasting view of Heraclitus is that we don't have to be afraid of change. We should accept change as fundamental and recognize that it's the laws of change, that's what science should be looking for—not ultimate things, but ultimate patterns, laws of change. We will see how this gets echoed in the 19th and 20th century, right up to string theory, strangely enough.

There was a very strong tradition of materialistic natural philosophy in the century before Plato and Aristotle out of which atomism emerged, and we'll be talking some more about that when we talk about 19th century atomism. But in particular there are two more final points. One is Plato claimed and Aristotle agreed that the true philosopher using his mind is able to carve nature at its joints; that is, to identify real universal principles that exist out there that we don't just make up. And the second point I want to close with is Pythagoras's view that mathematics is the ultimate basis of physics. We're going to be exploring that in the next lecture, and its consequences for modern science.

Lecture Five
Mathematics as the Order of Nature

Scope:

Together with the experimental method and deductive reasoning, the use of mathematics is the hallmark of modern science. Mathematics is the language of scientific explanation because it is, in some sense, the "language" of nature. That mathematical forms are the essence of natural objects and processes was central to the teachings of Pythagoras and his followers. The orderliness of natural phenomena is a mathematical order, as in the difference between music and noise. Beginning with Pythagoras, Greek mathematics, based on geometry primarily, became the paradigm of using deductive reasoning to acquire philosophical knowledge. Archimedes used deduction and mathematics to solve problems in physics. Aristotle dismissed the value of mathematics for natural science, except for music, optics, and astronomy, but Renaissance philosophers, partly under the influence of Plato's writings, restored mathematics to its Pythagorean position.

Outline

I. Looking back from the present, perhaps the single most influential Greek scientific idea was the idea that nature is, in its essence, mathematical.

- **A.** Quantifying nature was one of the core distinctive features of modern science in the 17th century.
  - **1.** This was obviously the case for physics then, and quantification in all of the sciences has become progressively more intense ever since.
  - **2.** Increasingly, the most advanced scientific instruments—for example, particle accelerators—generate numbers that are interpreted as features of nature or converted into "pictures" by computer programs.
- **B.** From the perspective of modern science, the mathematization of nature began with Pythagoras, literally or mythically.
  - **1.** Pythagoras certainly was a real person, who flourished circa 500 B.C.E. and taught that *number* was the basis of the orderliness of experience.
  - **2.** He founded a mystical religious-philosophical movement keyed to this teaching that survived for centuries, with communes and schools across the Greek cultural world.
  - **3.** For Pythagoras, mathematical forms were physically real, not mere abstractions.
  - **4.** There was a great deal of specific number know-how before Pythagoras, as revealed by surviving Babylonian and Egyptian texts, but not mathematics as a distinctive body of knowledge.
- **C.** The idea of a deductive proof is what distinguishes what we mean by mathematics from number know-how.
  - **1.** Pythagoras invented the idea of a general proof of the relationship between the sides and the hypotenuse of a right triangle, in the process, transforming number know-how into mathematics.
  - **2.** The idea of the proof is connected to the codification of deductive reasoning as the defining form of reasoning for mathematics, as it has been ever since the time of Pythagoras.
  - **3.** Deductive reasoning, because it generated universal, necessary, and certain truth in mathematics, became the defining form of truth-generating reasoning for knowledge generally and, thus, for science as knowledge of nature, as well.

II. Pythagoras invented two great scientific ideas: the idea of a logical proof of general truths about quantitative relationships and the idea that quantitative relationships were the essence of the physical world.

A. Pythagoras, supposedly stimulated by an actual experience, concluded that the difference between music and noise, for example, was mathematical proportion.

1. Pythagoras invented the monochord—a single taut string with a movable fret tuned to a given note—to demonstrate this "discovery."

2. He showed that all the notes of the octave could be generated by moving the fret precise quantitative distances.

3. If the initial note sounded by plucking the string was a middle C, for example, then halving the length of the plucked string sounded C an octave higher, while doubling the length sounded C an octave lower (keeping the tension constant throughout).

B. Pythagoras's teaching that mathematical forms were physically real, as illustrated by music, entails a mathematical metaphysics.

1. That is, it entails believing that mathematics, now conceived as rigorously logical truths about numbers and numerical relationships, is the ultimate reality.

2. Mathematical form is the indwelling orderliness of the physical world that we experience.

3. But this poses profound problems when it can be proven that there are mathematically incoherent aspects of the world.

4. Using the proof technique he invented, Pythagoras or his followers proved that certain mathematical forms that were physically real were irrational: could not be expressed as ratios of whole numbers.

5. Later, the need for "imaginary" numbers to solve physically real problems posed a similar disquiet.

6. The implication was that, ultimately, the world was not rational, that the orderliness of nature was superficial!

C. The power and influence of Pythagoras's coupling of mathematical form and physical reality are reflected in the history of music.

1. His insight that whole numerical ratios are what distinguish music from noise became the basis for millennia of passionate disputes over musical tuning systems.

2. As with the diagonal of a square, it turns out that the ratios that generate the notes of the octave "break down" when extended up and down the musical scale.

3. They generate dissonances, which are noise, not music!

4. These controversies, already lively in the ancient world, led to multiple mathematical schemes for tuning instruments.

5. Pythagoras's insight that mathematical form was the essence of music was preserved, but his tuning system was not.

D. These controversies became truly vicious, however, when Western musical harmonies became more complex during the Renaissance.

1. Vincenzo Galilei, Galileo's father, was an active participant in these controversies, which involved sophisticated mathematics, skill in musical performance and composition, and innovative experimentation.

2. The musical stakes were high because the tuning system employed affected instrument design, composition (which combinations of notes would sound harmonious), and of course, performance.

3. The scientific stakes were even higher because of the increasing identification of mathematics with physics during the Renaissance and in early modern science.

E. From the beginning, Pythagoras used the idea that nature was mathematical to solve scientific problems, and this became central to modern science.

1. Descartes identified geometry with space, as did Einstein in his general theory of relativity, though in a very different way.
2. Galileo called mathematics the “language” of nature, stating that this was a Platonic idea though he knew it was Pythagorean.
3. Galileo surely wanted to avoid the association with mysticism and magic that had grown up around Pythagorean teachings.
4. It was, however, misleading to call his view Platonic because Plato denied that knowledge of nature was possible!

F. Pythagoras himself used his mathematical metaphysics to set an agenda for Western astronomy that was accepted for more than 2000 years.

1. He taught that the planets, stars, Moon, and Earth were spheres because that was a “perfect” mathematical shape.
2. That the Earth was a sphere was fundamental to all Western astronomy: Aristotle offered three different proofs, and it was taught in all the universities centuries before Columbus.
3. Pythagoras also concluded, on grounds of mathematical “perfection,” that the form of the orbits of the planets, Moon, Sun, and stars around the Earth was a circular path and that they moved at uniform speeds.
4. Observationally, this seems not to be true, yet for more than 2000 years—up to and including the great Galileo!—Western and Islamic astronomers made it the goal of their theories to explain how the apparent motions were generated by “real” motions that satisfied Pythagoras’s criteria.
5. This was the basis of Ptolemy’s ingenious, highly contorted, epicyclic Earth-centered theory of the heavens that dominated Western astronomy until Copernicus’s moving-Earth theory initiated modern astronomical science.
6. It was not Copernicus, however, but Johannes Kepler who first rejected Pythagoras’s entire agenda, arguing in 1609 that the planets moved in ellipses and, in 1619, that planets moved at non-uniform speeds.

G. Returning to earlier history, in the 3rd century B.C.E., Pythagoras’s idea for a mathematical physics was developed further by Archimedes.

1. Archimedes, killed by a Roman soldier in 212 B.C.E., exemplifies what became the role model for mathematical physics in the modern period.
2. Archimedes was a great mathematician, extending geometry, pioneering trigonometry, and inventing a precursor of the Newton-Leibniz calculus.
3. Concurrently, he applied mathematics to physical and even technological problems—for example, in hydrostatics and the theory and design of machines—while insisting on maintaining mathematico-deductive reasoning.
4. With the reprinting of texts by Archimedes in the 16th century, the Pythagorean-Archimedean idea of mathematical physics was adopted by Galileo and, through him, became central to the invention of modern science.

Essential Reading:

Euclid, *Euclid’s Elements*.

Jacob Klein, *Greek Mathematical Thought and the Origin of Algebra*.

Questions to Consider:

1. If mathematics derives from experience, how can it be universal, necessary, and certain? But if it does not derive from experience, how can we know it?
2. Mathematics "works" in science, as evidenced by the predictive success of theories and their power to control experience, but why does it work?

Lecture Five—Transcript
Mathematics as the Order of Nature

The idea on which this lecture will focus is that mathematics is the language of nature; that an understanding of nature entails using mathematics to describe natural phenomena. Clearly this is central to the rise of modern science in the 17th century, and it is one of the most fundamental features of what we call *hard science* today—the ability to express the theoretical models that a science develops in mathematical language.

We see, for example, that the particle accelerator, a photo of which you see behind me, is a kind of hardware embodiment of mathematical physics; that is to say, what the particle accelerator really generates is numerical data. This is a tremendous machine physically and financially, but in the end what comes out are strings of numbers that are interpreted according to theoretical models, and lead to the announcement that we have discovered a new constituent of matter, a new particle. But what we've really discovered, of course, is a mathematical relationship that we interpret as a sign of the presence of a particular kind of physical particle.

This idea, the idea that mathematics is the essence of nature, that the order of nature is fundamentally mathematical, is an idea that found its expression and application in ancient Greece, and particularly, as I've mentioned in earlier lectures, particularly at the hands of the man called Pythagoras, either directly or through the people that came to cluster around him in the various schools and communities that the Pythagoreans founded, and which lasted for centuries in the ancient world. Pythagoras himself lived in the early 5th century B.C.E.; but, for example, Plato, more than a hundred years later, went to a Pythagorean school, and Pythagorean schools continued to exist right into the Roman period.

Pythagoras's insight—and where he got this from or what motivated him to do it, we don't know; there are various legends about it—Pythagoras's insight was that the order underlying all natural phenomena was a mathematical order. Pythagoras was also responsible in a certain sense for the idea of mathematics itself in the sense in which we understand mathematics. That is, before Pythagoras there was an extensive body of, let's call it number knowledge. There was an extensive body of Babylonian and Egyptian mathematics that the Greeks were familiar with that don't qualify for what we mean by mathematics, even though these people knew a great deal about numbers for practical purposes, and in specific illustrations.

So, for example, there are extant Babylonian and Egyptian texts—Babylonian clay tablets with the cuneiform writing that we talked about, and Egyptian papyri with the evolved form of hieroglyphics which moved to increasingly compact and more literary or language writing system. So there are texts in which they give quite concrete mathematical problems and give concrete solutions to them. They knew very well, for example, that if you have a right angle triangle, and two of the sides are three and four, that the hypotenuse is five. What they did not have was the general idea that we express as the Pythagorean theorem, that for any right angle triangle the sum of the squares of the two sides is equal to the square of the hypotenuse; what we express algebraically as $a^2 + b^2 = c^2$.

The idea of a generalized mathematics based on deductive proof—that was the genius of the Pythagoreans in antiquity, some time in the 5th century B.C.E. That idea transforms number knowledge into what we mean by mathematics. That form of reasoning that we described as deductive reasoning applied to numbers and the relationships among numbers leads to mathematics of a universal and general form.

We find, for example, in various Egyptian papyri, one papyrus is called the Rhind Papyrus, in which there are all kinds of examples of summing series and fractions, and reducing fractions, and the kinds of problems that we all remember painfully from high school algebra. For example, one problem in the Rhind Papyrus is if you have enough money to buy 100 loaves of bread at 10 cents a loaf, how many loaves can you buy at 45 cents a loaf? Pretty simple. However, in what's called the Moscow Papyrus, we find a calculation of the surface area of a hemispherical basket—a much more sophisticated problem. But again, for a concrete case: not a formula for calculating the surface area of *any* hemispheric surface—a specific calculation.

And in a papyrus in a museum in Berlin, there's again a high school algebra kind of problem, again with a specific solution, no attempt at a general solution. If you have a square whose area is equal to the sum of two smaller squares, and the side of one of the smaller squares is one-half plus one-fourth the length of the side of the second square, then what are the dimensions of each of those squares?

This problem lends itself to a relatively straightforward algebraic solution, but they didn't have algebraic solutions. They did have considerable number competency. After all, they did a great deal of surveying for the construction projects that they engaged in (I'm talking about the Egyptians and the Babylonians). The difference was, and it sounds odd to say it, but Pythagoras—let's say Pythagoras and mean by that the Pythagorean school—the Pythagorean school created the very idea of mathematics as a kind of number knowledge in which the goal is generalized proofs of theorems, which make statements about mathematical objects that are universal, necessary, certain, timeless.

So in that sense Pythagoras created the idea of mathematics as we have it, and he also created the idea that it is this kind of mathematical form, mathematics of this sort, which is the essence of nature. The essence of physical reality is mathematical form. And one of the ways that Pythagoras developed this idea was through his discovery, as the history books have it, that the distinction between music and noise is mathematical form; that the distinction between noise and music is mathematical form.

Apparently, somehow Pythagoras was moved to recognize that the difference between two notes separated by what we call an octave is 2:1 in terms of the length of a string that is required to generate that tone. If you have a length of string, he apparently built a monochord with a movable fret, if you have a string that's long enough when plucked to give you, let's say, middle C, if you then halve the length of the string by moving the fret so that it's exactly halfway, the string is half as long, and you pluck now half the string, you will get C an octave higher. If you double the length, you get C an octave lower. And similarly for any other note. But much more than that, if you start with middle C and you move the fret and you pluck the string, you will find that the notes of the octave correspond to precise fractions of the original string length, so that the difference between the notes of the octave are all mathematical proportions. A fifth is 3:2; a fourth is 4:3. And you can in this way, using these fractions, you can generate all the notes of the octave.

And this was a tremendous discovery—it really was—but it also had a tremendous impact on Pythagoras and on the school of Pythagoreans, for whom this was a concrete illustration. This was a verification of the underlying idea that mathematics is the order of the world; that matter would exist in a chaotic and formless state unless it were informed by mathematical patterns.

This leads to a kind of mathematical metaphysics. That mathematics is utterly orderly and completely rational from a Greek deductive reasoning perspective in the way that we discussed in an earlier lecture, but it also generates serious problems. Problems that ultimately became very disturbing to the Pythagorean community and, in fact, reinforced certain mystical and religious aspects of the community, because Pythagoras and his followers formed something like communes throughout the Greek Mediterranean. Over a period of centuries these communes developed their own social structures and their own school system in order to teach the Pythagorean blend of mathematics, mysticism, religion, and philosophy.

The problem, it sounds funny to us, but the problem is if you believe that the underlying order of reality is mathematical, consider the following situation. Imagine that you have a square. For convenience we'll say unit square, but it affects every square that there is. If you have a square and the side of a unit square is one—one inch, one foot, one meter; it doesn't matter; it's one—then the length of the diagonal, using the Pythagorean theorem, the length of the diagonal is the square root of two—$1^2 + 1^2 = 2$. The length of the diagonal of a square with unit side is the square root of two.

That would be okay, except that the Pythagoreans were able to prove that the square root of two is what was, for them, an irrational number, a non-rational number. It could not be expressed as a fraction with whole numbers in the numerator and the denominator. They were able to deductively prove that that was the case, but for them, given their, let's call it simplistic mathematical metaphysics, the mathematical forms that they believed were the essence of reality were based on whole numbers. Those were real numbers, and in fact that name, *real numbers*, attached to integers for millennia.

And other kinds of numbers, like imaginary numbers, were developed in the late Renaissance and early modern period by mathematicians. These numbers were called *imaginary.* But subsequently the name was changed to complex numbers, because imaginary has pejorative overtones. They could not be part of what made nature rational. But you can build a square. You can build a square out of copper, you can build a square out of—and that means that the diagonal of a physically square object is irrational, but then the implication is that there's something, even though it's subtle, there's something ultimately irrational about reality.

Furthermore, the paradigm of the way that mathematics orders chaos, transforming noise into music, also turns out to suffer from a similar problem. The Pythagorean tuning system works wonderfully for generating octaves. So you've got the notes C, D—go through the notes of the octave. If you play around with the monochord and you double the length, you'll get all the octave notes perfect; it works perfectly. But when you start using the fractional notation in order to generate fifths and thirds and fourths, etc., then after you apply them several times it turns out that the chords which sounded harmonious in one octave no longer sound harmonious when you get up two or three octaves higher or two or three octaves lower.

Again, for those of you who are not into music, you may not have thought of this, and it may take a while to understand how serious this was, but for 2,500 years now, the mathematics of tuning systems has been extremely controversial in Western cultural circles—people, obviously, who compose and perform music. There is such a thing as Pythagorean tuning which stays as close as possible to the particular Pythagorean mathematical formulation of harmonies. And then there's something called mean tone tuning, and just tuning, and equal temperament tuning. Bach's *Well-tempered Clavier* is one episode in this continuing saga of trying to find a tuning system in which notes will have the same harmonious relationship as you move from octave to octave.

And I will mention now in anticipation of a later lecture, Galileo's father, Vincenzo Galilei, was an active participant in the late 18th century in what was sometimes a vicious controversy. In fact there was quite often a vicious controversy in cultural circles over how musical instruments should be tuned, and especially as musical instruments became more complex, when we had a wide range of string instruments, and wind instruments, and organs, and later the harpsichord and the piano. How should they be tuned so that when a composer writes out a string of notes they will sound from the instrument as harmonious as they were conceived in the mind of the composer?

In fact, this led to a distinction, which was very important for Kepler, between what you might call theoretical music—music that was never meant to be performed—and instrumental music, which needed to be performed, but which always had some kind of imperfections. If you tune to get perfect fifths, then you're going to have slightly sour thirds and sixths. If you tuned to get perfect thirds and sixths, then you're going to have slightly off octaves and fifths. You can't have it all ways.

In fact, the system that we use today essentially is one of equal tempered tuning. I won't go into the details of that, but what's interesting is that Galileo's father was an early champion of equal tempered tuning back in the late 16th century. He wrote a book in 1580, it came out in 1582, called *A Dialogue*—remember Galileo himself published a famous book that starts off with the word dialogue, dialogue concerning the two great world systems, the one that got him prosecuted by the Inquisition—his father wrote a book called *Dialogue Between Ancient Music and Modern Music* in which he argued against the Pythagorean system, and against his one-time mentor and friend, Gioseffo Zarlino, that we needed to shift to an equal tempered system. And in that book, and in a later book in 1589, Vincenzo Galilei actually used experimentation in mathematics to prove that the Pythagorean school and tuning system, which was based on this beautiful insight of mathematical proportions, was a myth; that as a matter of fact, unless two strings are absolutely identical in terms of material composition and tension, you cannot reproduce, you cannot get the same notes by simply making sure that the lengths are the same. So he did a very substantial series of experiments—very interesting that his father did this, and Galileo did similar kinds of experiments—and he used experiment to show that the Pythagorean tuning system was based on an idealization that cannot be realized.

So to step back for a moment, what we're dealing with here is the idea of mathematical physics, the idea that ultimately nature is mathematical. This idea in the 17th century took the form, for example, of Descartes's identification of geometry with physical space, which is somewhat echoed in Einstein's general theory of relativity, in which geometry and space become identical. And our Galileo's claim that the language of nature is mathematical, and its characters are circles, squares, triangles, etc.

This was a Pythagorean idea, which Galileo called platonic because, as I suggested earlier, by the Renaissance period, Pythagorean teachings, which had been revived in the late Middle Ages in Renaissance, became associated with mysticism, with what's called the Hermetic tradition and later with Kabbalah, as that became translated from Hebrew and Aramaic into Latin in the 16th and 17th centuries. Then mysticism picked up a lot of Pythagorean motifs that somehow the secrets of nature were contained in numbers, and this was associated with various mystical teachings. This had all kinds of problems from the point of view of the church and heresy, so Galileo and others called the mathematical interpretation of physics, of nature, physics in the broadest sense of nature, called it a Platonic interpretation rather than a Pythagorean interpretation.

Now we have already discussed the fact that this is sort of misleading, because Plato in fact believed that knowledge of nature was not possible because he did not believe that mathematical forms could in fact exist within nature—that they existed in a kind of a non-physical spatial place, some non-place physically speaking, and were independent of and superior to nature. They were relevant to nature, but they were not in fact the underlying stuff of nature. There was no mathematical metaphysics underlying science for Plato. There was for Pythagoras.

But nevertheless, the revival of Pythagorean ideas continued right into the 20th century. Pythagoreanism is alive in string theory today, for example, and Roger Penrose is one of the most eminent mathematical physicists of the generation. He's pretty open about being a Platonist, but it's really being a Pythagorean. Pythagoras and his school were extremely active in the development of Greek mathematics and science over the next several hundred years.

For example, it was Pythagoras—because of his mathematical metaphysics, it was because of this conviction that the underlying reality of nature was mathematics—who argued that it must be the case that all heavenly bodies, including the earth, are spheres, because a sphere is the most beautiful solid. It has the most perfect symmetry, and it has the perfection (notice, this is an aesthetic judgment) which, because mathematical is identified with physical reality, it is that solid that contains the greatest volume for the smallest surface area. This is a form of perfection which Pythagoras just assumed must be part of the physical world, so the earth was a sphere.

In fact, whatever you may have been taught in high school, no educated person in Columbus's generation believed that the earth was flat, and in ancient Greece it was a standard teaching. Aristotle tosses off three different proofs that the earth is a sphere; but he had to prove it, because he didn't accept the Pythagorean idea that mathematics was the essence of physical reality. So he needed to give physical proofs for the sphericity of the earth. For example, looking at the shadow cast by the earth onto the moon's surface during a lunar eclipse, so you can see that the surface of the earth is a section of a circle, which he said shows that the earth is spherical.

He also gave a simple argument, that when you see a ship sail away from a port, then what happens? When a ship gets further and further away from you, it doesn't get smaller and smaller and smaller. First, the hull disappears, then the lower sails disappear, and then the highest sail tops disappear. This shows that the surface of the earth is curved, and that the ship, as it's sailing away from you, is dropping down, so to speak, below the horizon.

He also gives a somewhat more sophisticated proof having to do with the change in the position of the stars as you move from, let's say, the equator towards the North Pole; although of course, he never went to the equator, and he never went to the North Pole. But Greeks did compile statistics about the positions of the stars in the sky as a function of latitude as you move, let's say, from Lower Egypt to Central Europe.

So the Pythagoreans argued that the shape of each planetary body and all of the stars—although all they were really concerned about was the earth and the sun and the moon and the planets—they were all spheres. And they moved in circular patterns, because a circle is the most beautiful line to follow for the same reason; namely, a circle is that shape where you've enclosed the largest area for any given line length. You cannot encompass as much area, if you're given a line to work with and you want to enclose the greatest possible area, making a square or a triangle or a rectangle won't do it. A circle will do it.

So that's the perfection of the circle. And it seemed from a mathematical point of view that the planets should move at a uniform speed. I mean, why should they slow down? Why should they speed up? So Pythagorean astronomy was based on the idea that the planets move at uniform speeds in circular paths. The sphericity is relatively irrelevant for us.

Now you say, "So what? What's the big deal?" The big deal is that for the next 2,000 years, right up to and including Galileo, this became the central problem for astronomers. I once called this the Chicken Little syndrome in the history of science. Why would you believe such a thing when in fact the Greeks themselves knew, Pythagoras himself knew, that these assumptions do not match the way the planets actually move across the night sky? The outer planets, for example, at various times stop, go backwards, and go forwards again, which we understand because the earth overtakes them as the earth orbits the sun, but they believed the earth was stationary.

And so this is a really curious, and for us, powerful, reinforcement of the idea that mathematical physics is an idea first; it's not a discovery. Because here we have an idea that flatly contradicts empirical experience, and nevertheless, the mathematical problem that Pythagoras posed for astronomers was accepted as legitimate for the next 2,000 years. And the task was: how can you come up with a theory in which the planets actually move around the earth at uniform speeds in circular paths even though it doesn't look that way? So you've got to match the observational data to the underlying mathematical model of what is really happening.

We see the planets moving at irregular speeds, but really they're moving at regular speeds, as you can see on my mathematical model, which has to be able to predict what we actually observe. And it's just incredible that people didn't step back and say, "Wait a minute. Why don't we just start with the data and make a model that matches the data without making these assumptions?" Even Galileo could not break the hold of circular orbits at uniform speeds.

Copernicus's theory, which lets the earth move, retains circular orbits and uniform speeds. It's still Pythagorean, and as a result, after the first chapter of his great book of 1543, the next nine chapters are incredibly complicated because, in fact, circular orbits and uniform speeds don't match what we observe. So he has to invent a system in which the planetary bodies, including the earth, move in much more complicated patterns that observationally generate the data that we see. And therefore his theory, when you actually use it astronomically, is not that much simpler, and no more accurate, than the theory of Ptolemy in the 2nd century, who's theory was, so to speak, the perfect expression. The ultimate, the climactic expression of the Pythagorean problem in astronomy was solved by Ptolemy using a mathematical model, extremely complicated, with epicycles on epicycles, but in which the planets moved at uniform speeds in circular paths, and was able to predict with an accuracy that was reasonable, before the telescope was invented, where you could expect Mars to be tonight, tomorrow, the night after; where you could expect Jupiter and Saturn and Mercury and Venus to be in the night sky. It worked better for the outer planets.

And that Ptolemy's theory, which was central to the curriculum of the Islamic and Medieval Christian universities, was the standard, was the gold standard of mathematical physics until Copernicus challenged it, but using Pythagorean assumptions, which were really only overthrown by Kepler, who said, you know, that they don't move in circular orbits—they move in elliptical orbits, and they don't move at uniform speeds—planets change their speed as they go through their orbits, moving more slowly when they're further away from the sun, more rapidly when they're near the sun. And Galileo found this ridiculous. How ugly. It was Newton who showed that Kepler's version of Copernicus's idea was in fact correct because it follows directly from the universal theory of gravity. We'll be talking about that in a later lecture. Our focus here is on the rise of the idea of mathematical physics.

I've focused on the Pythagoreans and the Pythagorean schools where, of course, they were not homogeneous in their ideas. Aristarchus of Samos in antiquity, sort of a late Pythagorean, suggested that maybe the earth moves around the sun, and maybe it's not the center, and astronomy would be a lot more simple if we recognized that the sun was the center and not the earth. Copernicus himself says he got the idea for his theory by reading about Aristarchus of Samos's suggestion within the text of perhaps the greatest mathematical physicist of the ancient world, Archimedes, who lived in the 2nd century B.C.E. and who developed a mathematics-based methodology for solving problems in physics. He was the founder of hydrostatics, he wrote on the theory of machines, he invented the concept of center of gravity, and calculated the center of gravity of pretty complicated mathematical objects which could then be built. For example, calculating the center of gravity of a ship, that had implications for designing the hull of the ship once you understood that the center of gravity was important to the way that the ship responded when it turned, for example.

So Archimedes solved a wide range of problems in mathematics. He's generally considered to be one of the greatest mathematicians of all times, anticipating the integral calculus with a kind of a quick and dirty geometric solution to the problem of calculating the area contained by a curve, which is what integral calculus is all about, and was subsequently sort of invented by Newton and Leibniz in the late 17th century.

Archimedes was truly a mathematical physicist, and his writings, when they were translated into Latin and published in the Renaissance period, had a tremendous influence by their own admission on Galileo and on Newton. Both of them referred to Archimedes as, in a certain sense, the exemplar of what a scientist should be doing: using deductive reasoning and mathematical reasoning of the deductive sort, and mathematics, in order to not just describe but to expose the mathematical patterns that are the essence of physical reality.

So this idea, which is so central to modern science, we find developed to a considerable extent as an idea within ancient Greek culture.

Lecture Six
The Birth of Techno-Science

Scope:

There is a qualitative difference between the impact of technology on society from the Sumerian invention of writing to the 19th century and its impact since then. The difference largely reflects 19th-century innovations that exploited scientific knowledge and institutions created to stimulate this "techno-science" and channel its products into society. Techno-science became a powerful driver of change in the 19th century, but the idea that the best practice/know-how is based on theory/knowledge first appears in the Graeco-Roman period. Archimedes not only pioneered mathematical physics, but he also developed a mathematics-based theory of machines and mechanical devices. The early-20th-century discovery of a complex machine dating from this period revealed that Greeks built machines to express theories. Vitruvius, in his influential book *On Architecture*, promoted the idea that effective engineering must be grounded in science, and Ptolemy used sophisticated mathematics to generate accurate maps of the heavens and the Earth.

Outline

I. In the Roman Empire, practical know-how/craftsmanship began a transition to knowledge-based engineering—techno-science—that would be resumed in the Renaissance and erupt in the 19th century into the leading agent of social change.

- **A.** The first steps toward late-19th-century techno-science were taken in the late years of the Roman Republic and the first centuries of the empire, roughly 200 B.C.E. to 300 C.E.
    - **1.** Rome conquered Greece in the mid-2nd century B.C.E. and assimilated the continuing practice of Greek philosophy, science, mathematics, and technology into Roman cultural and social life.
    - **2.** By that time, the idea of science as mathematics-based, abstract/deductive knowledge of nature had crystallized out of Greek philosophical thought.
    - **3.** In addition, the first steps toward techno-science had been taken by Greek inventors and mathematicians.
- **B.** A pivotal figure in the dissemination of the idea of techno-science was the 1st-century-B.C.E. Roman "architect" Vitruvius.
    - **1.** The term *architect* then was closer to what we mean today by *engineer*.
    - **2.** An architect was, in effect, a civil-cum-mechanical engineer who was expected to design the devices or constructions whose realization he then oversaw.
    - **3.** Vitruvius was influential in his own time but far more influential in the Renaissance and early modern period.
- **C.** Vitruvius wrote an "engineering" handbook that was rediscovered in the very late 15th century and repeatedly reprinted over the next 200 years, influencing the rise of modern engineering.
    - **1.** His book *On Architecture* is effectively a handbook for engineers.
    - **2.** Its chapters cover siting cities; laying out streets; and designing and constructing roads, houses, water systems, and public buildings.
    - **3.** The public buildings include theaters, and Vitruvius refers to techniques of "naturalistic" painting for scenic backdrops.
    - **4.** The ninth chapter of the book is about time-keeping and the tenth is primarily about the range of machines available to architects to do the civil or military work they need to do.

5. Both of these sections and his distinction of "engines" from machines illustrate perfectly Vitruvius's claim in the opening paragraph of *On Architecture* that the architect must be "equipped with knowledge" of a kind that is the "child of practice and theory."

D. Vitruvius's claim that that the architect/engineer "must be equipped with knowledge" and with knowledge of many fields is a true intellectual innovation.

1. For Plato and Aristotle, knowledge is fundamentally different from, and superior to, know-how.
2. For Vitruvius to simply state as if it were self-evident that the best know-how is linked to knowledge is startling in context.
3. Knowledge yields understanding and is the "pure" pursuit of truth, while know-how is the "impure" pursuit of effective action in some particular context.
4. This distinction between theory and practice surfaced as a major source of tension in the 19th century, for example, in attempts in the United States to couple science to technology.
5. Vitruvius was not the first to *apply* abstract knowledge to concrete know-how, but he may have been the first to formulate the idea that know-how *should be* based on knowledge as a matter of principle.
6. This marks the birth of the idea of techno-science.

E. Vitruvius's claim that the union of theory and practice is fertile is an important one.

1. Theory seeks to explain by deductive "demonstration," exemplified by geometry, the favored form of mathematics for the Greeks, as it was even for Galileo and Newton in the 17th century.
2. Practice, by contrast, devises what works and uses it whether or not the practitioner can explain why it works.
3. Vitruvius acknowledged Greek predecessors from the 3rd century B.C.E. on who applied knowledge to create new kinds of machines.
4. The claim that the effective design and use of machines and engines depends on knowledge from which design and use can be deduced is, however, an innovation in its own right.
5. In the process of making his claim, Vitruvius also created a "space" for a new figure, which we recognize as an engineer, who stands between the scientist and the craftsman and possesses a distinctive expertise of his own.
6. As we will see, this engineer comes into his own in the 19th century and plays a key role in uniting ideas and innovations.

II. Vitruvius explains that he has learned what he knows from reading in the works of his great predecessors.

A. He names dozens of authors of books that he has studied on the subjects that he writes about in his book.

1. Among these are Ctesibius of Alexandria, Archimedes, and Philo (Philon) of Byzantium, all from the 3rd century B.C.E.
2. Ctesibius invented a family of machines based on force-pumped water and air, as well as a complex water clock and improved military catapults. Although his book disappeared, his machines were influential for centuries.
3. We already know Archimedes as a great mathematician and founder of mathematical physics, but he also was noted for contributions to applied physics, especially his theoretical account of the five basic machine types, and for civil and military applications of machines.
4. In antiquity, Archimedes was said to have built an orrery, but this was discounted as far too complex a machine for him to have built until the discovery and analysis of the so-called

Antikythera machine.

5. **5.** Dredged up early in the 20th century off the coast of the Greek island of Antikythera, this device, almost certainly from the 2nd century B.C.E., is easily the most sophisticated machine that would be made in Europe for at least 1500 years.
6. **6.** X-ray analysis reveals that the Antikythera machine is an extraordinary combination of precisely machined, interconnected gears that probably made complex calendrical and/or astronomical calculations, then displayed them on its "face" (now decayed).
7. **7.** This artifact, whatever its precise purpose, is clear evidence of a machine designed and constructed to embody ideas and theoretical knowledge.
8. **8.** It is a machine that required theoretical knowledge for its conception and design, together with carefully coordinated specialized know-how for its construction.

B. Vitruvius also stands as one figure in a long, innovative Roman tradition of sophisticated architecture/engineering.

1. **1.** On the one hand, there are the machine designers, such as Hero (Heron) of Alexandria. Hero echoes Vitruvius's union of theory and practice, science and engineering, and describes dozens of possible machines using steam, water, and air power.
2. **2.** On the other hand, there is the astonishingly sophisticated technological infrastructure of imperial Rome.
3. **3.** The water supply system and the network of public baths in the city of Rome, serving a million people, still inspire awe, especially the Baths of Caracalla and those of Diocletian.
4. **4.** The ruins of Pompeii attest to the existence of a central water supply system metered at each home.
5. **5.** The Romans both could and did build water-powered grain mills but on a limited scale.
6. **6.** For Vitruvius, Archimedes exemplifies the linkage between theory and practice, knowledge and know-how that distinguishes the architect/engineer from lesser craftsmen.
7. **7.** More generally, we need to appreciate the existence of a rich and technologically innovative intellectual tradition in Greek and Graeco-Roman mechanics, both before and after Vitruvius, a tradition that was imported wholesale into Islamic culture from the 8th century on.

Essential Reading:

Vitruvius, *The Ten Books on Architecture*.

A. G. Drachmann, *The Mechanical Technology of Greek and Roman Antiquity*.

Questions to Consider:

1. **1.** Given the weakness of theory in relation to practice in antiquity, why would anyone claim that, ideally, practice must be based on theory?
2. **2.** Why didn't the Greeks and Romans build calculators and water- and steam-powered machines that they seem to have known how to build?

Lecture Six—Transcript
The Birth of Techno-Science

We have seen how the idea of science evolved in the world of ancient Greece through the work of philosophers and the thinking of philosophers from, roughly speaking, 500 B.C.E. down to approximately 300 B.C.E. in the form of, first, a very particular definition of knowledge that was coupled with a very particular conception of reasoning. And especially the idea of deductive reasoning as being the only way to fulfill the conditions of knowledge—namely, that knowledge had to be universal, necessary and certain. And the third piece of the puzzle that we needed was that mathematics is directly relevant in some sense. That mathematics in some sense is the essence of the order underlying nature, and that therefore the scientist, the student, someone who wants to explain natural phenomena, is going to have to use mathematics.

There was, if you recollect, another piece to understanding science as a driver of social change, how science changes the world, and that was the idea of techno-science. That is to say, coupling knowledge to know-how. Know-how developing, as we discussed, independently of science, of course, for millennia before writing, and then more or less independently of science certainly through and down into the Greek period that we've been discussing. But the idea of techno-science in the 19th century, I had suggested, is the means by which science emerged as a dominant driver of physical and social change in the world in which we live.

That idea, of coupling knowledge in the philosophical sense, of coupling the idea of science as we have just been discussing it, to know-how, first emerged in the Graeco-Roman world, and although at the time it had limited impact in terms of changing the world, that idea was well developed. It was not just a hint that I'm trying to exaggerate, but that idea, that knowledge could be coupled to know-how—mathematical, deductive, scientific knowledge of nature, could be coupled to know-how—and that that would give us more power than we have ever had over natural phenomena. That idea was well developed in antiquity, and a pivotal figure in this regard is the Roman Vitruvius. We would call him an engineer; at that time he was considered an architect, because the title "architect" in the Roman period translated very well into what we mean by an engineer, and in part because what the architect was really expected to do was to develop ingenious devices, engines that would be able to accomplish things that people ordinarily could not accomplish by, for example, moving weights or by channeling water. We will see examples of this.

So Vitruvius was an engineer from our sense, but the title that he had was architect, and he wrote a book called *Ten Books on Architecture*, which was important in its own time, but it became even more influential in the Renaissance, when that manuscript was discovered and published, and in the course of the late 15th and 16th centuries went through dozens of editions. It became a kind of a standard text for the training of Renaissance engineers, and modern engineering finds its roots in the Renaissance, as we'll see in a later lecture.

So Vitruvius is a pivotal figure in his own time, and a very influential figure in terms of the development of modern engineering and its eventual coupling in the 19th century to science, creating in the process this powerful driver of change. But, again, the idea of techno-science emerges in antiquity, and we see it very clearly in Vitruvius. This book of his called *Ten Books on Architecture* (we would call it 10 chapters in one book on architecture), this book on architecture is really a civil engineering handbook. In the course of these 10 chapters Vitruvius describes how an architect/engineer should go about siting a new city, where you decide to put it—if you've been sent out by the emperor to build a new city somewhere, because Rome has just conquered some section of what subsequently came to be called France—and where you should put the city, how you should build the streets and the roads of the highways leading into the city, the streets within the city, how houses should be situated, how you build the houses, how you build and site public buildings, where you put the theater and how you design the theater, including considerations of acoustics and scene painting. So, for example, he has reference to using central vanishing point perspective, a mathematical technique that we of course identify with the Renaissance, but the Romans were familiar with it and had a name for it, which reveals its Greek roots; *skenographia* was essentially scene painting. The idea was that the audience should see a backdrop that looked realistic, naturalistic, and he has reference to this. Some of the chapters are devoted to military applications of engineering, but particularly interesting is that at the very beginning of the book, the opening paragraph of the book, Vitruvius writes as follows, "The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgment that all work done by the other arts is put to test." It's by the judgment of the architect/engineer that all work done by the other arts—and arts here means crafts—is put to test.

> This knowledge, the knowledge that the architect/engineer must possess, is the child of practice and theory. Practice is the continuous and regular exercise of employment where manual work is done with any necessary material according to the design of a drawing. Theory, on the other hand, is the ability to demonstrate and explain the productions of dexterity on the principles of proportion.

This paragraph all by itself is the basis of a short paper, without having to go beyond it to explicate how startling these claims are. To claim that the knowledge that an engineer must have is the child of practice and theory is quite a startling claim, because we have never heard before that you can get a fertile hybrid out of joining practice and theory. Know-how is one thing. Theory is another.

From the point of view of the Greek philosophers, especially the Platonic Aristotelian tradition in which knowledge was defined as we've been talking about it, subsequently incorporated into science, practice is of no concern to the theoretician. The theoretician wants to understand nature, wants to understand the truth about reality. It is not part of the, so to speak, mental and spiritual makeup of the theoretician to be concerned with practice. Practice is what mechanics do. That's the arts—the mechanics. They have craft skills, and they build things, and they do things, and of course we need them in order to make life comfortable, but they don't understand anything like we who understand. You may be a master of thermodynamics, but you don't know how to fix your car's engine when it malfunctions.

This distinction between theory and practice is deeply rooted in Greek philosophy. In fact, in the 19th century, right here in America, there were major controversies over the attempt to link physics as it was developing in the 19th century to technology. As I'll mention in a later lecture, one of the leading American physicists of the 19th century, one of the few that had a European reputation, Joseph Henry, in fact invented the electric telegraph, built an electric telegraph between his laboratory in Princeton and his home a mile away so he could tell his wife when he was going to be home for lunch. Then he did nothing with it. When Samuel Morse wanted to hire him as a consultant, because without Henry's knowledge Morse could not have made the electric telegraph a success, Henry refused on the grounds that that's not what you do with science. Given today, with biotech start-up companies and so on, this is a strange attitude. But in the 19th century there was a major controversy in American intellectual circles and especially scientific circles of whether there was any place for practice in the world of theory, whether that's not a prostitution of theory.

And here is Vitruvius saying—he didn't invent this, he is saying this in the 1st century B.C.E.—that the kind of knowledge that an engineer must possess is the child of practice and theory, so that practice and theory can give birth to a child. This is a fertile union, as opposed to hybrids in nature, which are typically sterile. Here he's saying that practice and theory are not two different things, but are analogous to (mixed metaphors) to two sides of the same coin. Practice, he says, is the continuous and regular exercise of employment where manual work is done, guided by the design of a drawing. Interesting for being just a casual reference to the fact that in those days people worked off drawings. We take it for granted. In fact, none of these drawings have survived.

Theory, on the other hand, is the ability to demonstrate. Now, what is a demonstration? I mentioned this in an earlier lecture, and in fact in the last lecture Archimedes's methodology was famous for showing that a demonstration in science means just what it means in mathematics. You have to be able to show that the phenomena you are trying to explain can be deduced from the principles that you have established. So from your theory you have to be able to deduce the phenomenon that the theory tries to explain. That's what a demonstration is.

Just as in mathematics you demonstrate the truth of a theorem, like the angle inscribed in a semicircle must be a right angle. You demonstrate this by showing that it is a deductive logical consequence of the definitions, axioms, postulates, and other theorems of Euclidian geometry that are relevant to demonstrating that point. The word "demonstrate" here means deductive proof. Theory is the ability to deductively prove and explain the productions of dexterity on the principles of proportion. The principles of proportion are mathematics.

The Greeks, as we will be talking about in a later lecture, had a very passionate commitment to geometry and rules of proportion in mathematics, and an almost total distrust of or disinterest in what subsequently came to be called algebra. So the Greek mathematics is geometry, trigonometry, and proportion. Trigonometry is in a sense the mathematics of proportion, and Euclid's *Elements* contain books or chapters on proportion.

So when Vitruvius is saying that the role of theory is to demonstrate why machines work and how they work based on principles of proportion, he's saying you have to give a mathematical, logical proof. That's the role of theory. And an engineer must know how to couple knowledge, mathematical, scientific knowledge, to practice. In fact in the course of this book Vitruvius describes many wonderful kinds of machines, and in the very last chapter, he refers to a distinction between machines and engines. He says it's important for an engineer to recognize—it's even more important for his customers to recognize—the distinction between *machines*, which although built, he says, according to scientific principles, he uses that phrase, and he uses the Greek word because this is the Greeks who made this up. Remember, the Romans had conquered the Greeks in the 2nd century B.C.E., about 150 years before Vitruvius wrote this. The Romans conquered Greece, but they assimilated Greek learning and strongly supported Greek scientists, mathematicians, and philosophers, and considered that to be an important asset under the umbrella of Rome, subsequently the Empire after the murder of Julius Caesar. So he sees this as a Greek contribution—that scientific principles are used to design machines, but basically machines are relatively crude devices that take a lot of people to use, and they're made out of wood, and they're used to hoist weights or to build relatively crude constructions. But *engines* are built based on intelligence. Engines are devices that a single person can operate because they have been designed in such a way, using theory, that they reflect knowledge, and so they are much more powerful than machines. They are different from machines because they embody more theory, and they work more effectively, and they allow us to do things that machines do not allow us to do.

Now, Vitruvius is making another distinction in that paragraph that I read that will become extremely important in the 19th century. He is carving out a space for the architect/engineer that is different from the cultural and social space occupied by artisans—the people who do the arts, mechanics—and on the other hand, scientists—the people who develop the theory. The engineer, he says, has to have knowledge that is the child of practice and theory. The engineer's drawings guide the artisans, the craftsmen, the machinist. The scientist develops theories that the engineer links to practice.

Now, in the 19th century, as a matter of fact until the 19th century, the overwhelming majority of the people that we call engineers did not have much training in science. They were really gifted mechanics and gifted inventors with a natural bent. We'll see a lot of that when we get to the 19th century, how true this is. It was in the 19th century that engineering as we understand it became professionalized exactly as a community that stands between the theoreticians on one side, with one foot in the camp of theory, and one foot in the camp of practice, and transmits so to speak, let's call it scientific knowledge; transmits that to the craftsman in a way that allows ideas to become technological innovations. That allows knowledge to become technologies that affect how we live.

So Vitruvius is already saying here that the engineer is not a scientist (that term is anachronistic, I've said that several times, but it's just too convenient not to use), not a natural philosopher of the Greek theoretical sort; that's Archimedes. But that turns out not to be so great because Archimedes, however reluctantly, in fact did apply his theoretical knowledge to the design and construction of machines, although he seemed not to be really excited about doing that. He liked to just do the theory. And on the other side, the engineer was not a craftsman. The engineer guided the craftsman. Socially speaking, this is a very interesting distinction that comes out of Vitruvius.

Now I said that Vitruvius was a pivotal figure in his own time, and by that I meant that one can look back from Vitruvius and forward from Vitruvius and see how, roughly speaking, a couple of hundred years each side, 150 years each side of Vitruvius, let's say, there was a substantial body of techno-science knowledge that was generated. That is to say, Vitruvius did not invent the idea that theory could be linked to practice in ways that led to new kinds of engines that had never existed before and that did wonderful things. It looks as though, while there were some machine design books that were written in the 3rd century B.C.E., it was really in the 2nd century B.C.E., about 150 years before Vitruvius, that there were a number of books that were written by people who used mathematical knowledge to design new kinds of machines. Vitruvius refers to a number of these.

There was a Greek named Ctesibius of Alexandria, who was the son of a barber, and who designed a number of really quite fascinating machines that were based on using compressed air and water. He designed a force pump with a cylinder and piston and a valve that would allow you to compress air, compress water, and to use the force-driven air and water in order to drive various kinds of machines. So according to Vitruvius, he built "singing black birds." He built little model birds that when air was forced through their mouth openings, they trilled, and various other kinds of toys which are called *automata*. They are sort of self-moving machines, and the word *automatic* comes from that. Automata, historically, refers to machines that move, typically driven by either compressed air or water.

And Ctesibius invented a whole spate of machines, some of them quite practical, using the force pump. For example, Vitruvius refers to a Ctesibius force pump that was used in Rome for fire engines. That's the way they had fire engines that used Ctesibius's pump, improved versions of Ctesibius's pump, in order to pump water out for fires. Hero of Alexandria, about a hundred years after Vitruvius, describes a Ctesibius pump that was used for watering gardens, the way you would use a hose today. Almost certainly the pump was operated by a slave. It always helped to have slaves around to make these machines work as effortlessly as possible for the person who owned them.

Ctesibius also invented a wide range of machines, including a much-improved catapult that used bronze springs in order to store more energy and release it very quickly, which if you're using a catapult in anger you want to do. So Ctesibius's own book has disappeared, but numerous subsequent writers in the ancient world referred to Ctesibius's machines, so we have no doubt. And we can actually reconstruct some of these and actually figure out how these machines worked and whether they worked well from the descriptions that were subsequently given.

There was another machine design author using this kind of mathematical knowledge named Philon of Byzantium (sometimes called Philo), but probably the most important predecessor of Vitruvius was Archimedes, and I already mentioned him in the last lecture as the historic exemplar of mathematical physicists. I won't go over that, and I hope you're convinced that he was an extremely powerful influence, especially since he was the mentor, conceptually, of Galileo and Isaac Newton.

But Archimedes also made machines, and he also developed a scientific theory of how what are called the "simple machines of antiquity" worked. A scientific theory of how the lever works, a scientific theory of how pulleys and windlasses and screws and wedges work. The screw doesn't mean what we mean by a screw, but the Archimedian screw is a device for lifting water. If you can imagine a water wheel that is wrapped around an axle that has a gigantic screw thread in it, then you can move water. As the water in a river turns the water wheel, the axle rotates, and because of the thread pattern on the axle, water gets carried. It is like a kind of a water mill.

So Archimedes had a theory, which was widely used, to build machines. Now he also had a reputation for building by legends, because most of his books were lost, but enough survived so that when they were republished in the Renaissance he had this tremendous influence on others, including Galileo and Newton. But Archimedes was reputed by legend to have built wonderful machines that emulated the way the planets moved. We call that an orrery, a machine in which, for example, if we take the popular view then that the earth was the center, how the sun and the moon and Mars and Mercury and Venus and Jupiter and Saturn, how they moved around the earth at the right rates, relatively speaking. That's called an orrery. Nobody believed that he could really do this.

However, in the early 20th century, an ancient shipwreck was explored off the island of Antikythera off the Greek coast, and a device was found, completely rusted and a mess visually, called the Antikythera Machine, which is just because it was found near the island of Antikythera. It took about 60 years before historians of technology decided to study this lump of rust, and using modern technology today, with X-rays and so on, discovered that this machine was an incredibly complicated collection of gears very carefully machined such that it unquestionably had to be built in accordance with theory, and almost certainly was built to be the driver of an orrery, to reproduce planetary motions.

This is very interesting for a number of reasons. First of all, wow, it's interesting that they could make a machine that required that kind of precision in terms of machining and that they had that knowledge of gear trains, which we normally would have associated only with the late Middle Ages. But it also means that they were making machines that embodied ideas. The machine is specifically designed to show you the power of an idea; namely, an astronomical theory. Once the Antikythera Machine was found, then all of a sudden the legends about Archimedes building orreries for people, and having a globe on which the positions of the stars in the night sky were shown, they now are taken much more seriously, that these are not merely ridiculous legends praising a great figure, but that in fact there was this level of competence.

Looking forward from Vitruvius, one of the great writers who left books on machine design in which he, again, explicitly stated that coupling scientific knowledge (as we call it) to practice was Hero of Alexandria—one of whose books that has survived is called *The Pneumatics of Hero of Alexandria*—and he says in his opening paragraph:

> The investigation of the properties of atmospheric air having been deemed worthy of close attention by the ancient philosophers and mechanists, the former deducing them theoretically, the latter from the action of sensible bodies, [that means from practice, straight practice, the mechanics—they know how to do things but they don't understand them—but the ancient philosophers deduced natural phenomena (he gives them too much credit)] we also have thought proper to arrange and order what has been handed down by former writers and to add thereto our own discoveries, a task from which advantage will result to those who shall hereafter devote themselves to the study of mathematics.

And Hero then goes on to describe dozens of different kinds of machines, including steam power–based machines in which the force of escaping steam is used to make things happen, and so Hero's book is a very good insight into the kinds of machines that could be designed and that could be built in the Roman world. Another book of this sort, which nevertheless is not very original, but refers to the designs of earlier technoscientists, is a book written about 200 years after Hero by the mathematician Pappus.

I want to spend a little time talking about the technological infrastructure of ancient Rome. Just as in an earlier lecture I tried to suggest how much awe should be inspired in us by understanding the know-how accomplishments of human beings from about 10,000 B.C.E. down to the Greek period, so the technological infrastructure of ancient Rome was very deep. It really is almost as awesome as all of that cultivation of cereals and domestication of animals and the metalworking technologies. We would, if we were fortunate enough to be born into the ruling class, have found it quite comfortable to live in ancient Rome, a city of one million people during the Empire that was notoriously clean. It had at the peak of the Empirial period 900 public baths distributed around the city. The water supply into Rome, it is estimated, amounted to approximately two hundred million gallons a day—approximately 200 gallons per person—in order to flush that city out. There were public toilets all over the city, all sewage was underground and flushed into the Tiber River—tough on the river, but it made the city nice and clean, it smelled and looked clean. It supported all of these other baths as well as residential water which, for those people who could afford indoor water supply, was metered.

So, for example, Pompeii, destroyed on an August day in the year 75, we can see in the ruins of Pompeii that the big homes in Pompeii had metered residential water from a central water supply. And we know a great deal about the water supply of Rome because Frontinus, who lived about 75 years after Vitruvius, was an educated Roman of high social status who was given the task by the emperor of renovating the water supply feeding the city because the population was growing very rapidly. And Frontinus wrote a book, which has survived. He, himself, was not an engineer, but he had to learn enough mathematics in order to understand calculations about the cost of pipe; whether you want lead pipe, or terra cotta pipe; nozzles; flow rate through different nozzles. Because the government taxed the water, it was important to know how much water was flowing.

In the 3rd century, the emperor Marcus Aurelius Antoninus, who was nicknamed Caracalla, built an enormous bath complex, the ruins of which still survive in ancient Rome. The Baths of Caracalla covered 33 acres. The bathhouse itself was 750 feet long and 380 feet wide—that's two and a half football fields long and a football field wide—and contained a series of baths, starting with hot, and going to lukewarm, going to cold, going to an outdoor pool that could accommodate 1,600 bathers at a given time. Plus the grounds had a theater. They had a library divided into two parts: books in the Greek language, books in the Latin language. There were reading rooms for the public containing works of literature, and one hopes philosophy and mathematics as well.

A hundred years later the emperor Dioclesian built a public bath that was twice the size of the Baths of Caracalla, and that could accommodate over 3,000 bathers at a given time. So think of the technology infrastructure necessary to support the kinds of construction that the Romans did, and nevertheless, they did not deliberately, as we know from documents, they deliberately did not want technology to have the power to change the social status. And so they could build water mills, they built one large water mill complex near Aurel in southern France with 16 waterwheels, but did not pursue that kind of technology at the level that would change the social system.

Lecture Seven
Universities Relaunch the Idea of Knowledge

Scope:

Schooling is not unique to a text-based culture, but it is necessary, because writing must be taught and, as Socrates observed, because texts must be explained, clarified, and interpreted. The university was invented in the 12th century as the "ultimate" school: not merely a higher-level school but a community of scholars pursuing knowledge for its own sake. The text-based intellectual culture of Greece and Rome and, subsequently, of Islam made the medieval university inevitable once the desire to possess that culture arose. It made the Greek idea of science, in both the generic and specific senses, central to western European cultural life. From the 12th through the 16th centuries, universities created a population of educated people exposed to Classical, Islamic, and contemporary mathematical, philosophical, medical, and scientific texts. Universities thereby made available to the founders of modern science intellectual "tools" they used to create modern science.

Outline

I. The university in the Christian West was an innovation with profound intellectual and social consequences.

- **A.** The collapse of the Roman Empire in the 5th century marked the onset of an intellectual "Dark Age" in western Europe.
    - **1.** The period from roughly 400–1000 was a time of significant physical, social, and political change in western Europe, but virtually nothing innovative was done in philosophy, science, mathematics, or technology.
    - **2.** This began to change in the 11th century, and by the 12th century, there was a sudden explosion of cultural, social, commercial, and intellectual dynamism.
    - **3.** This amounted to a cultural "renascence" that differed from the better known Renaissance in not seeking to revive the culture of antiquity.
- **B.** There had been schools of one kind and another in Europe, some of them advanced, at least since the 5th century B.C.E.
    - **1.** In fact, Babylonian cuneiform tablets and Egyptian papyri from the 2nd millennium B.C.E. are clearly textbooks for teaching arithmetic, geometry, and medicine.
    - **2.** Hippocrates's medical school on the island of Kos and a rival school in Cnidus date to the 5th century B.C.E.
    - **3.** Hippocrates transformed the healing "art" by using texts to transmit ideas along with information, leading to the organization of this information into knowledge by way of medical theories.
    - **4.** The followers of Pythagoras maintained a network of schools from the 4th century B.C.E., and Plato and Aristotle founded formal schools of philosophy in Athens that remained open until the 6th century.
    - **5.** From the 9th century, there were Islamic colleges of advanced learning that were known to Europeans, especially those that taught medicine, and analogues in China and India.
- **C.** The Catholic Church maintained a hierarchical school system throughout the so-called Dark Age.
    - **1.** There was a need for priests, of course, but also for civil servants, clerks, and administrators for the Church and the secular government, as well as for doctors and lawyers.
    - **2.** Local monastic schools fed regional cathedral schools, and beginning in the 10th century,

there were medical and law schools in Italy and France.

3. In the 12th century, there was an enormous increase in the student populations at the cathedral schools of Paris and Bologna especially, leading to the creation of the first universities there.
4. The university idea spread rapidly, especially in western and southern Europe, but with dozens of universities created by 1400, from Oxford and Cambridge in England to Krakow in Poland.

II. The medieval university was a new kind of social-intellectual institution.

A. The four recognized faculties/degrees were law, medicine, theology, and philosophy, with philosophy encompassing all secular learning other than medicine and law.

1. This would remain the case until the 19th century, when philosophy fragmented into modern disciplines ranging from the humanities to the physical sciences and mathematics.
2. The invention of the university, like the invention of writing, emerges as a major scientific idea from the reverse engineering of modern science.
3. The pursuit of secular knowledge in the philosophy and medical faculties became an essential condition for the emergence of modern science in the 17th century and for the maturation of modern science into a driver of social change in the 19th and 20th centuries.

B. The key to appreciating the university as a social-intellectual innovation is the value attributed to secular knowledge for its own sake.

1. The Church immediately recognized the potential threat of the universities to religious teachings and values but tolerated them nonetheless.
2. The size of the university population by 1400 constituted a new social and commercial phenomenon.
3. The collateral growth of secular governments claiming independence from the Church was closely tied to the university movement.
4. Socially, the degree-granting structure echoed the familiar craft guild structure.

C. The secular dimension of the university was not at all a rebellion against religion or the religious establishment.

1. The primary assertion was the legitimacy of the pursuit of secular knowledge for its own sake (not for the sake of salvation) and the autonomy of that pursuit.
2. Both of these claims were considered to be consistent with the faith-based character of medieval European society.
3. The explicit tension between these claims and the claims of faith is manifested in the struggle between the philosopher Peter Abelard and Bernard of Clairvaux, one of the leading churchmen of the 12th century.

D. Abelard effectively resurrected the naturalist philosophy of Aristotle, whose writings were newly available in Latin in the 12th century.

1. This philosophy incorporated Aristotle’s idea of knowledge as a body of universal, necessary, and certain truths generated by deductive reasoning.
2. Aristotle’s intellectualism and naturalism were reflected in Abelard’s claim that the human mind could arrive at such knowledge on its own and that humans could achieve the good on their own.
3. Bernard of Clairvaux rejected the possibility of deducing religious truths independent of faith and charged Abelard with heresy for teaching that humans could be saved by their own efforts.
4. Bernard destroyed Abelard, but even he did not crush the newborn universities when he could have done so.

III. The university thus emerges as a secular social phenomenon in the 12th century, an institution sheltering the study of secular knowledge within a faith-based community and loyal to its religious teachings and values.

A. The university must be understood as a *response* to a social demand for such an institution, not as *creating* that demand.

1. Once created, however, and as an institution dedicated to the text-based study of knowledge, which texts were to be studied?

2. Overwhelmingly, the texts came from ancient Greek and Roman writers on mathematics, philosophy, astronomy, medicine, and law.

3. Beginning in the 12th century, contemporary thinkers, such as Abelard, were generating important new texts.

4. Concurrently, and quite independently, the assertion of the legitimacy and power of Aristotelian reasoning within a faith-based community was made in Islam and Judaism.

5. Averroës, the greatest Islamic philosopher of the period, and Maimonides, the greatest Jewish philosopher, both championed an Abelard-like intellectualism while proclaiming their religious orthodoxy.

6. Nevertheless, like Abelard, each was severely criticized by defenders of the absoluteness of religious truth, and Averroës came close to execution as a heretic, yet both became important influences on late-medieval Christian philosophy!

B. The university assimilated the Platonic-Aristotelian definition of knowledge for all the subject areas studied under the rubric of "philosophy," including nature.

1. Only such a definition could put knowledge on a par with revelation as a source of truth.

2. Inevitably, therefore, philosophy encountered the problem of knowing the truth of universal statements that could serve as the premises of deductive arguments.

3. A range of mutually exclusive solutions to this problem was proposed, but the problem endures within science even today.

4. The philosophical study of nature in the university generated a set of ideas that was subsequently incorporated into modern science, which ties the idea of the university more closely to the idea of science.

5. These ideas included: that nature was a closed system, that explanations of natural phenomena could not invoke supra-natural causes, that experience and experiment are the basis of nature study, and that mathematics is the key to knowledge of nature.

6. Nevertheless, while some of the founders of modern science were academics, most were not, nor was the university a center of modern scientific research until the 19th century.

7. Galileo and Newton, for example, were university professors, but Francis Bacon, Rene Descartes, Robert Boyle, Robert Hooke, Christian Huygens, and Gottfried Leibniz were not.

Essential Reading:

Charles Homer Haskins, *The Rise of Universities*.

Edward Grant, *Physical Science in the Middle Ages*.

Questions to Consider:

1. Why didn't the Catholic Church suppress the manifestly secular new universities?

2. Why didn't modern science emerge in the 14^{th} century?

Lecture Seven—Transcript
Universities Relaunch the Idea of Knowledge

Our subject in this lecture is the idea of the university, which is conceptually and chronologically a big jump from the last lecture when we were talking about the technology infrastructure of ancient Rome and the rise of the idea of techno-science in the Graeco-Roman period. Roman dominance, but most of the contributors to it, Vitruvius notwithstanding, were in fact Greek citizens of the Roman Imperium.

From approximately the 5th century, let's say with the collapse of the Roman Empire beginning in the 5th century, and until the 12th century, it used to be the case, it may be politically incorrect today, but it used to be the case to call this the Dark Ages. And this is the kind of comment that you get from intellectuals who are really saying, "Nothing of particular cultural or intellectual import happened during this approximately 700 years." But as a matter of fact, a great deal was happening in Western Europe at that time, physically and politically, in terms of dealing with population changes and invasions and conquests. But it is true that not a good deal happened during this period of time that is relevant to the idea of science or the transmission of Graeco-Roman technoscientific knowledge, scientific knowledge, mathematical knowledge to the modern Western world.

It was in that sense a dark period, which suddenly became illuminated in, roughly speaking, the 12th century. Well, it started in the late 11th century, but it was the 12th century when there was an explosion of cultural, social, political, and economic dynamism in Western Europe, which has led some historians to call this the 12th century Renascence. We could have called it the 12th century Renaissance as well, but then that might have been confusing when you referred to it, because the term renaissance is most familiarly applied to Europe and especially Italy in the period roughly from the 15th century into the 17th century. So we don't want to use the term renaissance twice in that context, so people called this the 12th century Renascence. In both cases it means a rebirth.

Now we'll see later that the Renaissance, properly speaking, was a deliberate attempt to recapture the cultural excellence and the intellectual excellence of ancient Greece and Rome. The 12th century Renascence was not such a deliberate effort. In fact, what it means is that there was a rebirth of dynamism in Western Europe after centuries of relative passivity. Relative, of course, because the closer you look the more you see that things were happening that were relevant to our story; but, relatively speaking, passivity, and then all of a sudden an explosion.

Now, in this lecture I'm going to be talking about one product of that explosion, and that was the invention of the university, the idea of the university, which had never existed in Western culture before as it came to be institutionalized, as it came to be formalized. There were schools, of course, and some of these schools were advanced in the sense that they taught what we would consider college- and even graduate-level materials. Even in ancient Babylon and in Egypt we know that there were schools for the priesthood; that there were medical schools, that there were schools for teaching mathematics. I've referred to a number of surviving papyri, for example, that were clearly intended to be textbooks.

In ancient Greece, starting at least from the time of Hippocrates in the 5th century B.C.E., on the island of Cos, there was a medical school that was a text-based medical school, in addition to clinical practice. The teachings at Cos, at Hippocrates's medical school, were text based. There was a rival medical school in the city of Cnidus, which was primarily clinically based, and this led to debates which continued for centuries and in fact are still echoed today, about whether medical education (later I'll refer to engineering education) should be outcome based or theory based.

Of course, the people who prefer theory say that, "Oh, they're not two separate things," that theory and outcomes need to be connected together. But a strong argument has always been made that people who have practical experience should not be discriminated against because they don't have book learning, and cannot give you a theory to explain why what they did works. This is particularly relevant in medicine. The history of medicine, until the 20th century and the rise of what we call scientific medicine, was one in which physicians' reputations were based overwhelmingly on outcomes, on what happened to their patients, without much concern about whether there was much of a foundation, a theoretical model that they were using in treating their patients.

So Plato founded a school. I've referred already to the Pythagorean schools, which went on for centuries after the 5th century B.C.E. Plato founded a school called the Academy in Athens. Then his former student, Aristotle, who had been passed over for the leadership of the Academy after Plato died, in a huff went off and set up his own school, which came to be called the Lyceum.

The Academy and the Lyceum, both in Athens, existed for almost 1,000 years, continuously training generation after generation of students until finally, in the 6th century, the schools were closed down by the Roman Emperor Justinian. Because by that time Rome and culture had become so Christianized that he felt it was intolerable to have schools teaching pagan philosophy. And so the schools that Plato and Aristotle had founded were closed approximately a little over 900 years after they were founded. And those were what we would consider certainly college-level schools.

So the idea of schools, and of schools that trained people at a high level, certainly preceded the invention of the university. And in Islam, especially, starting somewhere around the 9th century, certainly by the 9th century, there were increasingly sophisticated colleges that not only taught the Qur'an and its interpretation, but also taught what we would consider philosophy, and natural philosophy, and law, and literature—especially poetry and music, which were very prominently and creatively pursued in the Islamic world.

There is an analogue of all of this happening in China as well, and by this time, by the 7th–8th century, India has developed extraordinary competence, especially in the branch of mathematics that we came to call algebra, and had schools for mathematical training that were in existence in what in the West is called the Dark Ages.

The church, the Catholic Church, also had a school system. At a minimum they needed to educate people to become priests, and also in order to provide the basic civil service needs of the government. So there were local monastic schools, which taught reading and writing to anyone who wanted to send their children there to learn that, and the fees were very modest. And there were larger cathedral schools, obviously regional schools, that went up to the next level of education, and these were typically where you learned enough skills in reading and writing and mathematics, or arithmetic I should say, so that you could provide certain functions in the society, which were very limited in the period in question. I'm talking here, roughly speaking, from 500 to about 1000.

There were law schools and medical schools in Salerno and Montpellier—Montpellier in France, and Salerno in Italy—that were certainly in existence by the 10th century, and especially in the area of medicine were using knowledge that was transferred from the Islamic world where medicine was pursued very aggressively. They were primarily using the texts of the Greek Galen, who in the 2nd century in the Roman Empire period, developed a medical theory that was as dominant in medicine until the 16th century as Ptolemy's theory in astronomy was dominant until Copernicus, Kepler, Galileo, and Newton in the 16th and 17th centuries.

But what happened in the 12th century was that the inflow of students into several cathedral schools and into several of the leading professional schools, for some reason, some of which I'll talk about in the next lecture, increased to the extent that the university was invented as a way of accommodating the demand for, let's call it, higher education.

And in particular in two places, Bologna and Paris, depending on whether you come from one or the other city, you'd think your city had the first university. They've been arguing about this for about 800 and some years now. But at roughly the same time in the second half of the 12th century, both Paris and Bologna developed universities, and the university idea caught on extremely quickly, and spread, so that by 1400 there were dozens of universities all over Western Europe, extending from Oxford and

Cambridge, in England, to Kraków in Poland. We're talking Central Europe now, all the way to Central Europe; but the concentration was overwhelmingly in Western and Southern Europe. The leading early universities, in addition to Paris and Bologna, included Salamanca in Spain and Padua in Italy, Cologne in Germany, and this is a very interesting social phenomenon. The fact that the universities spread so quickly is a sign of the pressure from the social context to create these universities, to make these universities, once the idea of the university had been formulated and institutionalized.

The medieval university—which at a certain level has not changed all that much right down to the present—the medieval university was divided into four faculties, four clusters of professors who lectured in four different areas. There was the faculty of philosophy, the faculty of medicine, the faculty of law, and the faculty of theology. Now, law, medicine, and theology are self-explanatory and they served specialized needs.

The philosophy faculty was a grab bag, and in fact until the 19th century when the philosophy faculty fragmented into what we recognize as the modern departments of physics, chemistry, biology, and then of course the liberal arts departments and the social science departments, it was the case that in the medieval university, and until the 19th century, if you were not studying law, medicine, or theology, you were studying what was broadly considered philosophy. It means that's secular wisdom; that's secular learning. And the university is part of this 12th century Renascence.

This cultural dynamism was driven, I am going to argue, overwhelmingly by secular values within a religious context without denying the spiritual dominance of the church at the time. There was an upsurge of social pressure to make life better, and one expression of this that is particularly important to understanding modern science and modern science's ability to change the world, is the university.

In the next lecture we're going to be talking about technology and industry; but now, the university, because using this methodology of reverse engineering the ability of modern science to be a driver of change in the world, we see in the 19th century that the university became a center for scientific research which it had not been for centuries before the 19th century. In the 20th century this became increasingly the case. So that today we take it for granted that the university, especially in the United States and Western Europe, that the university is a primary center for the generation of new knowledge.

How did the university come to be there in the 19th century to be able to play that role? That's because the idea of the university was invented in the 12th century, and the university as an institution was created at that time, and its mission was to advance secular knowledge. The church recognized the potential threat that this represented and the inconsistency with putting such a high value on secular knowledge compared to salvation, for example, spiritual knowledge and salvation. The church regularly attempted to control, to monitor and to control what was going on in the medieval university, but interestingly did not attempt to shut them down. And it may be that they were just socially, politically, and economically too important in the centers.

Each one of these universities, on average, had thousands of students. So that taken together, dozens of universities meant that there were certainly, by the 13th century, there were probably at least 100,000 students at the various universities all over Europe. They represented a very substantial revenue stream for the towns in which they were concentrated, and they also represented a very important pool of resources, of labor resources, because what was happening at the same time is, of course, the beginnings of the modern nation-states of Europe—the beginnings of England, and France, and Italy, and Germany, and of the countries that became Belgium, and Holland, etc.

And to the extent that the civil governments became increasingly large, and challenged the notion that Europe is basically organized under the umbrella of the Catholic Church, the Pope's political claims were increasingly challenged in the courts in the Middle Ages. So those governments needed more civil servants, and the universities turned out doctors, lawyers, and civil servants of all kinds, in addition to educating large numbers of people who had a gift for and who enjoyed studying philosophy, and within philosophy, natural philosophy—what we understand by science.

So the philosophy faculty was a fundamentally secular faculty. Everybody was religious. All of the professors were priests. You could not become a professor if you were not ordained. The church was quite sensitive to this, and the society recognized that this was an issue.

The degree structure in the university considerably emulates the structure of certification for a guild. So, for example, a bachelor's degree means that you have a certain amount of knowledge analogous to an apprentice, somebody who has served an apprenticeship. A master's degree, in spite of the word "master," means that you are really analogous to a journeyman. You are certified to have much more knowledge than a bachelor, but you're not ready yet to profess. You can't be trusted to teach new material, to teach interpretations. A doctor of philosophy, the doctorate degree, means you are like a master in a guild.

So the guild structure was you served an apprenticeship. At a certain point your master decided that you were competent in the basic skills, so then you became a journeyman. That's like being a master's candidate at the university. A journeyman went around to different masters and picked up more advanced skills, did a project, analogous to a master's thesis, which was not original but showed that they were good enough to set up on their own. Then when they produced a piece of original work, when they made something that was impressive in that particular guild—for example, in the goldsmith's guild if you made a piece of gold jewelry that impressed the other masters, then they would give you the equivalent of your doctorate. Then you could become a master, and you could set up your own shop.

Analogously, once you had the doctorate, then you could be trusted to lecture, and it was as much a character reference as an intellectual reference. Because once you're sitting in front of hundreds of young students and interpreting, let's say, a literary text, Plato, Aristotle—well, not Plato; his texts were not known in the Middle Ages—Aristotle, or interpreting a biblical text, interpreting the Song of Songs, you could do a lot of damage to the minds and souls of the students. So the professorships were held by people who were ordained.

I'm not suggesting here that the secular character of the university was a reaction against religion. It was an assertion of the autonomy of secular and intellectual values, together with religious values. And this was very problematic initially for the church.

So I think that a thing that I want to explore here for a moment is the autonomy of the intellectual vis-à-vis the spiritual. This is a tension between reason and faith in the context of a faith-based society. It's not a war between science and religion in the sense that one rejects the values of the other. Within the framework of a faith-based society in the 12th, 13th, and 14th centuries there was an explicit tension among those religious intellectuals—all of whom considered themselves to be loyal sons of the Catholic Church—between those religious individuals who also asserted the power of reason, that intellectual endeavors were legitimate.

Now, an expression of this tension is to be found in the relationship between the philosopher Peter Abelard and the great churchman Bernard of Clairvaux. Bernard, relatively unknown today outside of Catholic circles, was one of the most powerful figures of the 12th century, in part because he inherited the leadership—well, not inherited, he became the head of the Cistercian monastic movement. The Cistercians, who were founded in the late 11th century, wound up in the course of the Middle Ages building 742 monasteries all over Europe. All of them built to a central plan—adapted to the local environment of course—but built to a central plan and almost all of them using water power very intensively, so that they were little industrial sites, and they did very well financially, most of them.

So he was very powerful because he was the head of a very successful and far-flung monastic order, but he was also in his own right a prominent intellectual and was very politically influential in papal circles. Bernard attacked Peter Abelard, who was the most prominent philosophical intellectual in Paris on the eve of the creation of the university in Paris, attracting at least hundreds, and if we believe him, thousands of students to his lectures on philosophy and theology. And Bernard reacted against the claim that you could use reason, as Abelard claimed you could, even to explain the mysteries of the Catholic Church. So in order to defend the integrity of the faith, Bernard attacked this claim that reason was the power that human beings had to arrive at truth—not revelation, not the Word of God, but the deductive consequences of the kinds of premises that you get from reading philosophy.

Abelard was steeped in the Aristotelian tradition. The texts of Aristotle were becoming available to the medieval thinkers of the 12th century, and eventually became the standard text of the university 50 years after Abelard. The texts of Plato for historical reasons were not available for another 300 years, almost 400 years, so that while they knew about Plato, and had some commentaries on Plato, there were almost no Platonic texts—only a fragment of one text called the *Timaeus*, which deals with the creation of the world according to Pythagorean principles—mathematical, physical principles. None of the other Platonic texts were available until the Renaissance.

So Abelard was defending an intellectual position that through philosophy, through deductive reasoning, we can discover all the truths that are necessary to discover, including the truths of religion. And Bernard hounded Abelard, bringing him to trial as a heretic over and over again for teaching such things, for example, as ultimately everybody goes to heaven, nobody is condemned eternally to hell; for teaching that human beings by their own effort are capable of being good and, so to speak, getting out from under the thumb of original sin. And these were clearly doctrines that the Catholic Church needed to oppose. Bernard opposed Peter and made his life quite a hell. Abelard also made his own life hell through his own efforts. You may know the story of Abelard and Héloïse, but I don't want to digress onto that.

The university emerges in the second half of the 12th century. It didn't create the demand; it was responding to a demand, and the demand was for an institution that would transmit secular learning, where people could study texts and study ideas. And where did the material come from? It was overwhelmingly the textual material that came from Greece and Rome that had been generated back from the days of Euclid, and Aristotle, and Ptolemy's theories. The standard subjects were logic, astronomy, mathematical theory of music, Euclid's elements of geometry, and Roman law.

Roman law typically meant the Roman law corpus, so-called *Corpus Juris Civilis*, of Justinian's time—the same Justinian that closed down the pagan academies of Aristotle and Plato in Athens. That collection of Roman law, together with commentaries on that, became the standard text not just for the law schools, but they were also studied in the philosophy faculty. But overwhelmingly the curriculum was based on the study of texts from the Greek period and from the Graeco-Roman period, because not much had been written in the intervening period, from about 400 until 1100.

There were now in the 12th century, it actually started a little earlier than that, but in the 12th century there were now Christian thinkers who were doing philosophy, and writing new books, which came to be subject matter incorporated into the curriculum. And increasingly it wasn't just a matter of mastering Greek learning, it was also a matter of mastering the learning of the latest thinkers, like Peter Abelard, for example, and lots of others.

It is interesting to note that in roughly speaking the same time period—the 12th and 13th centuries—that the university was created in Western Europe, that there was this aggressive assertion of the power of reason in a faith-based community, the power of truth arrived at by reason and not only by revelation, that this same phenomenon was also taking place in Islam and in Judaism. Roughly speaking a generation after Abelard, you have Averroes and Maimonides. Averroes in the Islamic world creating a rationalized philosophically based version of Islam, and Maimonides doing the same thing in Judaism. Both of those figures were intensely controversial in their respective cultures, were condemned in their respective cultures by pietists (so-called right-wingers as we would say today), who recognized that this attempt to put reason on a par with faith was fundamentally destructive of faith. That's one thing.

Second, it is important to recognize that the medieval university's teaching of philosophy had to be based on the Platonic–Aristotelian notion that knowledge was deductive, that it was universal, necessary, and certain, and that we had to base knowing on deduction, because only universal, necessary, and certain knowledge had a right to stand up to truth by revelation. If all you're offering me is probabilities, how can I put that on a par with what God has revealed, with God's revealed word? If you're going to say that reason is capable of giving us knowledge that is on a par with revelation—which even Thomas Aquinas, for long the, so to speak, official philosopher of the Catholic Church, comes very close to saying, or says—then it's got to be knowledge. It can't be probability. It's got to be certainty.

And so the universities' philosophical curriculum embodied this idea of knowledge and incorporated it, not just in the teaching of philosophy, but in the teaching of natural philosophy as well. And we find the roots of 17th century scientific revolution are already starting to grow and spread in the context of the medieval university, with its secular orientation.

There are two points that I want to raise here. One, to remind you of the problem of universals, which I talked about in an earlier lecture, which immediately became relevant. If we're going to claim that human reason can achieve universal, necessary, and certain knowledge, then we've got to be able to know the truth of universals. How can the human mind know the truth of universals? What is the logical status of universal statements, of a statement of the form, "All crows are black; all humans are mortal"? What is the status? How can we possibly know the truth of a universal statement given that experience is always particular and limited?

And the responses to this, this was such an incredibly controversial and lively thing that people could have had talk shows, if there were talk shows at the time, they would have been populated by people attacking each other because they took different positions on universals; but everyone agreed that the key to knowledge was universals. You had to be able to establish the truth of universals. And these debates, which took place from roughly speaking 1100–1350, heavily influenced the methodology that was developed in the 17th century that we will talk about as the methodology underlying the rise of modern science.

The second point that I want to make is to call attention to the extent to which ideas that were subsequently crucial to modern science became articulated and developed in the context of the medieval university. Let me point out that historically it is not the case that the founders of modern science were university professors. It's not like today, where you sort of expect a serious scientist to have a university appointment, and not to be working for an industrial corporation—although some do, and especially those that used to have industrial research laboratories that supported pure research like Bell Labs, but that's pretty much gone by the wayside. Galileo and Newton both had university professorships, but Descartes didn't, and Christian Huygens didn't, and Spinoza didn't, and Leibniz didn't, just to mention four great figures in the 17th century that played a major role in the creation of modern science.

The point that I want to make about the study of natural philosophy in the Middle Ages is that what was made a principle of the philosophical study of nature, science, at the time was the Aristotelian notion that nature is a closed system, that natural phenomena can only be explained in terms of other natural phenomena. It is inappropriate, it is not permitted, to refer to supernatural phenomena in order to explain natural phenomena. The idea is that through experience and experiment—they didn't observe this very often, but they at least claimed that it is only experience and experiment—you can justify claims to knowledge of nature; and the idea that you've got to use mathematics in order to reveal the underlying structure and order of natural phenomena, which we recognize as an echo of Pythagoreanism.

These ideas will become explicitly coupled to the rise of modern science in the late Renaissance and the 17th century. Meanwhile, we need to turn to a collateral expression of the creation of the university, which we will do in the next lecture.

Lecture Eight
The Medieval Revolution in Know-How

Scope:

The invention of the university was symptomatic of a new dynamism that characterized western Europe in the period 1100–1350: Gothic cathedrals, expanded trade extending to India and China, urbanization, and technological innovations of enduring influence. Innovations dramatically raised agricultural productivity; improved ship design; and via new nautical charts and the use of the compass, stimulated expanded trade. Water- and wind-powered mills became ubiquitous, followed by a wide range of water- and wind-powered machinery. The need for complex gear trains and the means of transferring power led to the invention of the weight-driven clock, the cam, the clutch, mechanical automata, and the dissemination of mechanical skills in the population. Expanded trade led to new financial techniques and institutions, among them, banks and corporations. In effect, western Europe experienced an industrial revolution as well as a cultural renascence, revealing the role played by society in determining the influence on it of innovations.

Outline

I. The 12th-century renascence was unquestionably a time of intellectual rebirth, but philosophical ideas were only symptomatic of a much deeper cause with wide consequences.

- **A.** It can be argued that Europe experienced its first "industrial revolution" in the 12th century, not the 19th century.
  1. The invention of the university was one symptom of a rebirth of social and cultural dynamism in the Christian West.
  2. Another symptom was a sudden, dramatic increase in the use of machines and in technological innovation generally.
  3. One can legitimately call this an industrial revolution, but it is not an expression of the Graeco-Roman idea of techno-science.
  4. This industrial revolution, like the first phase of the more famous 19th-century one, was closer to the tinkering/inventiveness of know-how in prehistory.
- **B.** The use of water- and of wind-powered mills is a dramatic illustration of this medieval phenomenon.
  1. Roman "engineers" were quite familiar with water-powered mills for grinding grain, but only a few such mills were built before the empire was overrun.
  2. By contrast, when William the Conqueror ordered a survey of English assets shortly after his victory at Hastings in 1066, his surveyors counted thousands of water mills in use.
  3. This degree of exploitation was matched elsewhere in western Europe and, shortly thereafter, in northern Europe and intensified in the period 1100 to 1400.
  4. Although initially used for grinding grain, mills were soon adapted to powering machines for making paper out of rags, for operating the bellows of iron forges, for cutting wood and stone, and for hammering, fulling, and tanning.
  5. Building and operating these mills required significant capital investment for the period and led to the formation of the first shareholder-owned corporations, some of which still exist after more than 700 years.
  6. Starting probably in the 12th century and certainly in the 13th, windmills began to be exploited intensively, both for grinding grain and for pumping water.
  7. The British were noted for developing windmill technology, but the Dutch became its masters for pumping water on a large scale to drain swamps and low-lying land.

C. One value underlying this embrace of industrial technology is secularism.

1. We saw this as a value underlying the university movement in the assertion of the autonomy of reason vis-à-vis faith and the attribution of value to the pursuit of secular philosophy and knowledge of nature.

2. Here, secularism finds expression in the value attributed to working hard, to wealth, and to labor-saving devices.

D. The volume of machine utilization had broad and deep implications for medieval society.

1. The construction of so many mills implies an extremely broad base of mechanical skill.

2. The centuries-long stream of innovations in mill designs and in the construction, efficiency, and application of mills is expressive of the depth of the medieval engagement with technology, implying continual experimentation in the search for a technological "edge."

3. All these applications required mastering gear-train design and construction, as well as power takeoff, transmission, and control mechanisms, for example, the clutch and the cam, lantern and crown gears, and gearing for speed and power.

4. Furthermore, a mill construction industry of this magnitude creates a massive demand for hardware on a scale that forces innovation in metal cutting and fabrication and a demand for standardization.

II. By far, the most famous popular invention of the period in question was the weight-driven mechanical clock.

A. Mechanical clocks, in the form of water clocks, were common in the Graeco-Roman and Islamic periods.

1. These clocks evolved into an application of science to technology as Archimedes had developed a mathematical theory for the physics underlying their design.

2. The weight-driven mechanical clock, which for centuries was no more accurate than well-made water clocks, triggered a totally different social response in late-medieval Europe from the water clock.

3. Technologically, this new clock is indebted to the body of gear-train knowledge that grew up around watermill and windmill machinery.

4. The key innovation is the verge-and-foliot escapement that checks the falling weight and uses its downward motion to drive the time display (for centuries, just an hour hand) and often complex automata.

5. The higher the clock mechanism was mounted, the longer the fall; thus, these clocks became public time displays located in monumental structures, such as campanile.

6. With the clock came the standardization and commercialization of time, but this surely reflects existing social values, not the causal consequences of the clock as an artifact.

B. As a matter of fact, the clock has been perceived by many historians as the "defining technology" of the late Middle Ages.

1. The clock, it is claimed, secularized time and, in the process, secularized the temporal organization of social life, while previously, social life was organized around the religious "hours" of the Catholic Church.

2. The point at issue is technological determinism, that is, whether a new technology causes a society to adapt to it, if necessary at the expense of prevailing values, or whether prevailing values determine the way a society responds to a new technology.

C. Neither the clock nor watermills and windmills, however, were isolated instances of Western society opening technological innovation "doors," then rushing through them.

1. Innovations in agricultural technology and a suddenly favorable climate raised farm productivity even as the population increased dramatically.

2. These innovations included a “heavy,” iron-tipped ploughshare capable of working the denser soils of central and northern Europe, replacing the “light” plow inherited from the Romans.
3. The introduction of the breast harness allowed the use of horses as draft animals, replacing the much slower oxen.
4. The more widespread adoption of fertilization and a three-field crop rotation system, “scientific” farming for the time, also increased yields.
5. The higher agricultural productivity seems related to the rapid growth in urban populations, reinforcing commerce and the university movement.

D. Concurrently, organized long-distance trade increased dramatically, aided by marine technology innovations.

1. A centrally mounted stern-post rudder, with a complementary steering system, that allowed ships to sail in deeper waters far from shore was in use by the 13th century, and soon after, so-called lateen sails replaced square rigging, dramatically improving maneuverability.
2. The magnetic compass was in use by the 12th century, and more sophisticated seaport charts increased the reliability of navigation.
3. Contact with Moslem merchants in North Africa and the Middle East increased the scope of trade and stimulated the adoption of managerial technologies that reinforced expansion of trade, for example, Hindu numerals, double-entry bookkeeping, and letters of credit.
4. One clash of values that arose in this context was the religious prohibition against usury and the growing need for capital by merchants and entrepreneurs.
5. Ultimately, the social pressure for economic growth forced a redefinition of usury to allow making money from money!

E. These developments illustrate what Lynn White meant by saying that innovations only opened doors for a society.

1. This view of White’s, which puts responsibility for responding to an innovation on society and its values, contrasts with technological determinism.
2. On this latter view, new technologies impose themselves on society in ways that derive from characteristics of the technologies.
3. The Portuguese used new nautical technologies to sail to Asia and seize the spice trade.
4. This inaugurated a centuries-long period of European colonization and exploitation that literally transformed the world.
5. Western and southern European societies rushed through the doors opened by the available and newly created technologies of the 12th and 13th centuries, creating a social environment favorable to secular knowledge, industry, and commerce.

Essential Reading:

Jean Gimpel, *The Medieval Machine*.

Lynn White, *Medieval Technology and Social Change*.

Questions to Consider:

1. Why, after centuries retrospectively called the Dark Ages, did European culture suddenly become dynamic in the 12th century, and why only western Europe?
2. How did the Crusades reflect and affect this dynamism?

Lecture Eight—Transcript
The Medieval Revolution in Know-How

Let's pretend that this lecture was given concurrently with the preceding lecture, so that you could hear both of them at the same time. This gets back to a problem that is generic to speech and to writing, for that matter, which is that they're both linear, and reality is not linear. It's multi-faceted, and lots of things happen in parallel.

The 12th century Renascence was much more broadly based in Western European culture than the university movement. The university was merely one symptom of that Renascence, and it's the one that I chose to talk about first because it is the one that reverse engineering 19th techno-science calls to mind. But the base of the 12th century Renascence really was the first industrial revolution that took place in Europe, and it's quite an astonishing phenomenon reflecting this explosion of cultural dynamism that I referred to in the preceding lecture, and it happened in parallel with the university. In fact, the university must be understood as symptomatic of this development in Western and Southern European culture that took place at that time, roughly speaking from 1100–1350, when we have the first outbreak of the black plague—a very devastating period in European history, which may account for the time it took to move beyond the achievements of 14th century Western Europe.

In any event, what I want to talk about in this lecture is European technology, the industrial revolution of the 12th and 13th centuries, this aspect of the cultural Renascence that not only regains the kind of expertise that the Romans possessed—I referred to the Baths of Caracalla as only one instance of the quite astonishing technological capabilities of the Romans, but I also referred, very briefly, to the fact that the Romans knew how to build water mills, water-powered mills for grinding grain. That there were a small number of such mills in the vicinity of Rome.

There was a very large complex that I referred to near Aurel in France that contained a total of 16 water-powered grain-grinding mills in one single complex, and apparently could grind enough grain to keep a population of 80,000 people fed. So the Romans could build water mills, but they deliberately did not spread that technology.

By contrast, what we find in medieval Western Europe is an incredible number of machines being built, water- and wind-powered machines being built and broadly applied across many industries. This is just one facet of this industrial revolution that is a parallel expression of the 12th century Renascence through the university movement. It nicely complements the theory–practice distinction.

Let me point out that there is no room to talk here about techno-science. The idea that theory should guide practice is not an attribute of this industrial revolution, which is more like the technological innovations of the millenia from 10,000 B.C.E., roughly speaking, down to the Graeco-Roman period.

But let's just look at water mills. When William the Conqueror—he wasn't called that before he left Normandy, it was not a very nice name that he had while he was still in Normandy, but he was William the Conqueror after 1066—after William conquered England, he ordered a survey of the resources of England so that he could distribute the country among the 10,000 knights that accompanied him to England. That was the reason why they went on this adventure and risked both—and risked life. (That's all that mattered; if you lost a limb, you lost your life, pretty much, in those days.)

This survey was compiled in what is called the Domesday Book, and you can count the population of England at the time. The area covered by this survey had about 1.4 million inhabitants in it, so it was pretty empty, and it had over 5,000 water mills. There were, in fact, over 5,600 water mills in England alone at the end of the 11th century. And the number of water-powered mills grew dramatically all over Western Europe, leading to many lawsuits, for example, from towns where the speed of the river had been so reduced by mills upstream that they couldn't build water mills. There is a body of law that grew up that we would recognize today as I guess environmental law of a particular sort.

The water mills were used initially to grind grain, I mentioned that, but in the 12th century they started being applied much more broadly than that. The water mills were applied to fulling cloth, which requires pounding the cloth in order to give it the qualities that you need before you make fabrics and apparel, and to felting wool. The waterwheel was used to drive trip-hammers that pounded the wool in order to make felt. They used the water mills to power sawmills. So you had water-powered sawmills sawing lumber as opposed to having people doing the sawing of the lumber.

Water mills were applied to the bellows of forges; the first iron forges that we know about had water-powered bellows in order to maintain the temperature of the fire in order to melt the iron ore and get the iron. We're talking here the 12th and 13th centuries. In the 12th century you get the first paper-making mills. To make rag paper, it's got to be pounded. You've got to pound those rags in order to get them to the point where you can make paper out of them. The first paper mills in Europe were in Spain. That was in the 13th century.

At the turn of the 14th century, the first French water-powered mill was built, at the Moulin Richard de Bas. This company is still in business, still making paper—fine paper used primarily by artists—but that company has been in continuous existence since, roughly speaking, 1320. And it's not the only one. Water-powered mills became so important to the economy that, for example, also this one comes from France, near Toulouse, there was a complex of water mills that became incorporated in which the shares of the mills—there were a total of 96 shares spread out over the mills that made up the complex—those shares were publicly traded. Over the centuries that corporation continued to exist until the mid-20th century, by which time its water mills were being used to generate electricity, and they were nationalized by the French government as part of the creation of *Électricité de France*. And there was a Swedish company that was incorporated in the 13th century, Stora, that also continues to exist to this day.

So what we're talking about is an economic, technological revolution in which machinery becomes increasingly familiar. We normally think of the Middle Ages as a very crude time, but the period from 1100–1300, crude in many other respects, was one in which machinery became ubiquitous in Western and Southern Europe—water mills and their many applications, pounding olives in order to make olive oil—and recognized everywhere as "Look at how much labor we are saving." The productivity of Western and Southern European societies rose dramatically, and this is another expression of the underlying secularism.

Where am I going with this secularism? As we will see in a subsequent lecture, I'm going towards the idea of progress and the role that it played in making science the kind of enterprise that society would accept as a driver of change. The desire for change, keyed to the idea of progress, was what was behind the embrace of science and techno-science. In what we see in the 12th, 13th, and 14th centuries is that within a faith-based culture there was a growing sense that we wanted to live better.

There was also growing wealth. There was a positive assertion of work: that work was a good thing to do, because you could make money from work; because you could make life more comfortable for yourself through work. Work was not a punishment, which it does seem to have been perceived to have been from the Graeco-Roman period. The really nice people, the people who mattered in society, didn't work. In fact, we still have into the modern period this idea that a gentleman is someone who does not work for a living unless he's a professional—a doctor, a lawyer, a civil servant working for the government, a priest, a minister—then that's okay. But to actually have a job, to need a job in order to pay your bills, then you're not a gentleman. If you work for a living you are not a gentleman, by definition. Now, we don't use the word gentleman this way today, but into the 20th century that's the way it was used in Europe, in all European countries. There was something negative about work. But in the 12th, 13th, and 14th centuries, people became excited about work because they were doing new things in new ways and they were benefiting from that work.

The windmill was clearly invented first in Central Asia. There are windmills—horizontal windmills—in Iran in the 8th, 9th, and 10th centuries. But what the Europeans invented was the vertical windmill, a simple post windmill. A horizontal windmill works okay if the wind's always blowing in the same direction, but in Western Europe the wind changes direction too much, too often to use a horizontal windmill effectively, so they invented a windmill that was mounted on a post so that it would turn into the wind; and that allowed wind-powered machinery, wind-powered mills powering machinery, to become popular. Eventually, of course, it created Holland. The Dutch used windmill-powered pumps in order to drain the, approximately, I think about a third or a quarter of Holland that today that would have been underwater except for this pumping. They became international experts in pumping, in irrigation, in clearing swamps, etc., based on the application of wind power.

Now, it's a wonderful story to talk about this machine and that machine, but what's really interesting is, what's happening here is we have a society in which there is a very broad base of mechanical expertise in the design and construction of gear-driven machines. It looks as though the Romans knew about cams (camshafts), but it was only in the 12th, 13th, and 14th centuries that you had wholesale, you had machines that exploited the cam principle. Because when you build a windmill you need to be able to take that power off and transmit it, so you need to know how to make things like crown gears and lantern gears. You have to have a clutch so that you can disengage the water mill, which keeps turning, because that river is still flowing, but you may not want it to turn whatever machine that you have on at that time. So you need a clutch to engage and disengage, you need ways of transmitting power so that it goes at right angles if the windmill is turning on one axis but you want the power to go on another axis. Also, you need to change reciprocating motion—back and forth motion—into rotary motion. Or in the case of the windmill, rotary motion into reciprocating motion. The ability to do all of these kinds of things became very broadly based in Western Europe.

One can legitimately say that not only was there an industrial revolution in the sense that machines became increasingly prominent in the economy and the social life of the time, but there was also an industry generating the knowledge, and the expertise, and the resources necessary to support those other industries. Just as, for example, it's wonderful to make computer chips, but in order to make computer chips you need to have machines that can make computer chips. Those machines, stepping machines for example, that are responsible for printing the circuit designs onto these minute bits of silicon, those machines you almost never hear about. Without those machines the companies like Intel and so on that manufacture chips that you do hear about wouldn't be able to do it. So there is an infrastructure at work here in a society that uses machines this intensively.

Now, the most famous gear-driven machine of the High Middle Ages unquestionably is the mechanical clock—the weight-driven mechanical clock. Now, we didn't invent the clock. I think that I mentioned in the last lecture Ctesibius, the Greek engineer I will call him, who was cited by Vitruvius as being one of those who used scientific knowledge in order to design machines. Ctesibius was famous for having built a very accurate clepsydra, or water clock, a so-called compound clepsydra that measures the outflow of water. Because the Greeks understood that water flows through a nozzle at a fixed rate if you keep the head of water constant, so you can measure, and you can let the volume of water that flows through a tiny little orifice drive the hands of a clock. As long as you keep the level of the water constant in the tank, then the water will flow out at a constant rate, and you can have a clock that measures hours and minutes.

The way to the mechanical clock was therefore not a revolution in timekeeping, per se; in fact, it was less accurate initially, and for quite a while, than a good clepsydra. But the way to the mechanical clock became a public instrument. The way it was designed, the time was kept by a weight that fell under the force of gravity, and there was a special gear mechanism, which was called a verge-and-foliot escapement, which caused the falling weight to stop every, let's say, second. So then every jerk of the escapement was one second, and then that drove the hands of the clock.

Now, in fact it was so crude that there were no minute hands for centuries on these kinds of clocks; only hour hands. But by the same token you can see that you're going to have to wind the clock up all the time unless you mount the clock very high up. For example, you mount it in a gothic cathedral tower, or in a tower specially built that you put a clock face in. So the clock became a public timekeeper in the West, and it piggybacked on the kind of knowledge of gear-train design that was ubiquitous in the society.

The amount of technological innovation involved here was analogous, I believe—at a lower level of technical sophistication, but it was analogous—to the rate of innovation that we have experienced post-World War II in the West. There was a tremendous enthusiasm for this among many people, and other people who didn't like this much change. But the clock has been singled out by historians as what Jay David Bolter once called the defining technology of that age (I'll be using that metaphor again when we talk about the computer) but the clock as the defining technology of early modernism, as if somehow the clock drove European society in secular directions. It spatialized timekeeping, some famous historian has said, and in opposition to the spiritual timekeeping of the Church, the seven religious hours of the day in the Catholic ritual. Here we have instead a spatialized timekeeping which is completely secular.

The clock didn't force European society to become secular. It was the underlying secularism of the society which made the clock an attractive innovation, as opposed to an innovation that could be ignored. So this is one aspect of the industrial revolution of the 12th century.

Concurrently, a great deal else was happening in the society. For example, agricultural technology was completely revolutionized by a number of innovations that included developing an effective breast harness for a horse, so that you could use a horse rather than an ox. A horse is approximately twice as fast as an ox in doing farm work, and while it eats more—it costs more to feed a horse than to feed an ox—you more than get it back in the speed with which it can work. But in Roman times, horses wore neck collars; with a neck collar, if the horse has to pull a heavy weight, then it chokes. The breast collar allows the horse to exert its strength with its body, not with its neck. And not only the breast collar, but also an effective harnessing mechanism, so that horses could be used in tandem. So you could have a wagon pulling heavy loads, for example.

That was a very important innovation, which reshaped a good deal of farming; together with the systematic use of a three-field rotation system as opposed to the Roman system which the Middle Ages had inherited of taking your farm and planting one half of your field, and you let the other half lie fallow. The three-field rotation involved a winter crop, a spring crop, and a fallow crop, and you alternated these fields in a particular cycle. It dramatically increased the productivity even of the existing farms, together with the first systematic use of manure as a fertilizer in order to build up the soil. For example, keeping your animals on the fallow field during the year that it was fallow so that that field became enriched when it would not have a crop sown on it, and then through the rotation cycle this kept the field fertile.

Agricultural technologies were enhanced by the heavy plow. The plow inherited from the Romans was okay in Italy where the soil is relatively light and thin, but utterly useless in northern France, Germany, the so-called Low Countries that became Belgium and Holland, and in much of England. A new kind of plow was invented with heavy wheels, with an iron-tipped plow, and a so-called moldboard and coulter that turned the earth aside as you pulled the plow. Hooking such a plow up to horses opened whole new areas of Europe to farming, and they were very productive because they hadn't been farmed before. The soil was very rich and the crops were very substantial.

So yields doubled and tripled and quadrupled in the course of the 12th, 13th, and 14th centuries, which, by the way, meant that fewer people were needed to work on the farm, which is why, probably, urbanization increased in the 12th century, and why there were so many people around who said, "Well, I might as well go the university; might as well go to school; might as well learn something." Or, "It's much better to be living in Paris and London, Oxford and Cambridge, Bologna and Padua, than to be living on an isolated farm. And they don't need me here anyway, and my oldest brother's going to inherit the farm, so what the heck am I doing wasting my time here? I might as well become a doctor or a lawyer, or even a philosopher."

Concurrently, a dramatic change in nautical technology took place, new innovations in nautical technology. The centrally-mounted sternpost rudder was introduced, which meant that ships for the first time could be controlled in heavy seas, so you didn't have to only coast along the shore. You could go from Europe to North Africa directly instead of going around the periphery of the Mediterranean, because the centrally-mounted sternpost rudder, which was enabled by the gearing that allowed a single steersman holding a big wheel to control a heavy rudder mounted centrally on the ship as opposed to only in the rear, that that kind of gearing reduces the effort necessary to control the rudder.

The centrally-mounted sternpost rudder was used together with the lateen sail, which seems to have been borrowed from Islamic merchant ships. As opposed to the square rig sail, the lateen sail is much more maneuverable and allows much better tacking in the wind than the square rig sail does. So the combination of the lateen sail, the centrally-mounted sternpost rudder, the compass (which was brought into Europe in this time period, ultimately from China through intermediaries), and new kinds of maps—borrowed, I believe it is correct to say, from Islamic sailors and merchants—new kinds of maps, together led to a tremendous increase in marine trade in Europe.

And that increase in trade, which made Europe increasingly prosperous in this period, that increase in trade was also supported by changes in banking and commerce. So, for example, Leonardo of Pisa in 1202 published a book which introduced double-entry bookkeeping into the European business world from Moslem traders in North Africa, from whom he seems to have gotten it. As a matter of fact, while the history books say that this was the beginning of double-entry bookkeeping, it took centuries before businessmen routinely used double-entry bookkeeping, and there were good reasons for being cautious about it.

The nice thing about double-entry bookkeeping is that you can look at the record and see exactly if you're making money or losing money; but the danger is that anyone else who sees your books can tell also. And so at a time when businesses were privately owned, not everybody wanted to have a set of books that were so transparent that anyone could see how well they were doing. But that is a sign that businesses were becoming unmanageable, because so much business was being done that you couldn't keep it in your head. Merchants had so many investments going on, and so many different ships going to this place and that place, buying here, selling there, that they needed a more sophisticated way of keeping records.

That is all by itself a sign of heightened activity. But even more powerful in terms of this underlying social pressure that I've been trying to suggest, this secularism that was driving a lot of these changes—or let's put it differently, it was driving the adoption of these changes—was the rise of banking. Even though there were something like banks in the antique world of Greece and Rome, what we recognize as modern banking really begins in the 12th, 13th, and 14th centuries. Banking was initially controlled by a small number of families in mostly Italian towns, Florence and Genoa, and Luca, which got overwhelmed eventually, but Venice was another important center. The Bardi and Peruzzi families stand out as having become very, very prominent and powerful bankers.

The problem here was the Church opposed lending money at interest because that's usury, and it's forbidden by the Bible. And so there was a tension here between a tremendous increase in the scale of business, the opportunity to make lots of money, and then this religious principle that you're not allowed to charge interest on money. You're not allowed to make money on money. Well, how can we invest in businesses if we don't get a return on the money that we're investing? We make profit; what are we supposed to do with the profit? Just spend it all on food and clothes and houses? We want to use part of that profit to build new businesses.

So now I'm making money on money, and the Church says that that's a terrible crime, and I'm going to go to Hell and burn forever because I've lent money at interest. What gave? Well, the Church had, in a series of Church councils—that's the highest level of promulgation of definitive Church teachings that took place in the 12th, 13th, and 14th centuries—the Church repeatedly condemned usury. There is no excuse for usury; there is no basis for usury. However, behind the scenes they changed the definition of usury. That, well, if you're lending your money in something that's risky, then it's okay to expect a return, because why should anyone risk their money for the sake of what is a risk? So what happened behind the scenes was that while we retained the religious teaching that usury is wrong, and it is wrong, we will not compromise on that, we redefine usury so that we support the growth of commerce.

So trade, nautical technologies, new ship designs, for example, eventually became the kinds of ships that the Portuguese in the 15th century used to sail to Asia and begin the transformation of the world under the thrust of European imperialism. What the Portuguese did in the 15th century was to pull together developments in the 12th, 13th, and 14th centuries in sail design, ship control design, ship design, the use of the compass, the use of new, more sophisticated kinds of maps, and to then go out into the open oceans, eventually sail around Africa to India, and then begin all of those voyages of commerce and colonization and exploitation that characterized the next 500 years of world history.

It is in the context of this industrial revolution that the historian of medieval culture, Lynn White, used the expression which I referred to in the second lecture; namely that new technologies only open doors. They do not force a society to enter through that door. This was in opposition to the view that is called technological determinism—that once a technology is introduced into a society, the technology dictates how that society must adapt to the implementation of that technology.

Many people, especially in the 1960s and 1970s in the anti-establishment fervor of the time, acted as if once an invention has been released, once an innovation has been channeled into society, it's all over. A society has to adapt to it. Whereas, what White was saying, and I think that this requires considerable thought and needs to be paid attention to: When we see an innovation embraced by a society, then that's a sign that society recognizes that a door has been opened and it wants to go through that door.

The 12th century Renascence, powered deep down by putting a value on the secular, is, I believe, what lies behind the enthusiastic embrace by Western and Southern European societies in the 12th, 13th, and 14th centuries, of these doors, of these new technological innovations. So you don't embrace a door; you walk through the door. They embraced the innovation by not just walking, but by racing through those doors, by making the clock a means by which social life could be structured differently than it had been before, and in ways that just happened, not coincidentally, to reinforce the requirements of the growing business environment.

They raced through the door of the nautical technologies in order to exploit the benefits of trade that this opened up. They raced through the doors opened up by gear train, wind- and water-power technologies, exploiting gear train designs in order to industrialize, in order to sustain a growing population at a higher level of prosperity. If you put this together with the university movement and the kinds of issues that I referred to in the last lecture, especially the study of nature in ways that clearly reflect the beginnings of the mentality that in the 17th century became modern science, it raises this question of why didn't modern science arise in the 14th century? It seems as though absolutely all of the ingredients that we are going to see in the 16th and 17th centuries are right there in the 13th and 14th centuries. And there is no satisfying answer to that question.

Historians have said, "Well, it was the black plague. It was the plague, which in 1347 first broke out in Europe, and over the next 50 or 75 years devastated the population." Maybe that played a role in it, but I don't think that that in fact is the answer. It's just another illustration that in the end, human history is not logical.

Lecture Nine
Progress Enters into History

Scope:

The aggressive embrace of the idea of progress by Western societies was a symptom, not only of the openness of those societies to be transformed, but of their *active pursuit* of social transformation. Explicitly, the idea of progress was a product of the early Renaissance, introduced by poets, artists, and scholars of the Humanist movement, who invented the related idea of a rebirth of cultural excellence. Implicitly, however, the 12th-century industrial revolution and cultural renascence are evidence that the active pursuit of social transformation by western European societies was already in place. Furthermore, the social transformation being pursued was secular, in spite of the contemporary power of the Catholic Church. Gothic cathedral construction notwithstanding, people were pursuing wealth, comfort, pleasure, personal freedom, and civil power. The idea of progress is, thus, a secular idea that paved the way for secular modern science to become an agent of social reform based on scientific reason.

Outline

I. The idea of progress is not a scientific idea, but it is an concept that became identified with the idea of science and with modernity at a certain point in European history.

- **A.** If history is logical, the logic certainly is elusive, as reflected in the fact that modern science did not emerge in the 14th century.
  - **1.** There have been theories of history, notably that of G. W. F. Hegel, in which events unfold deterministically according to universal laws.
  - **2.** Aristotle had argued that history was not logical in the deductive sense because it was particular and, thus, could not be a science.
  - **3.** All the ingredients for the rise of modern science seemed to be at hand in the 14th century, including the value placed on secular knowledge, but the cultural dynamism of the preceding centuries waned.
  - **4.** Attributing this waning to the black plague sounds plausible, but this explanation is not convincing, in part because the idea of progress first emerges in the 14th century!
- **B.** The idea of progress first gained currency in Europe within the Humanist movement of the early Renaissance.
  - **1.** The 14th-century Italian poet Petrarch embedded the possibility of progress into the Humanist movement that he instigated, mentored, and inspired.
  - **2.** Petrarch proclaimed the prospect of a “renaissance” of the cultural excellence achieved by the Classical-era Greeks and Romans.
  - **3.** Petrarch periodized European cultural history into a glorious Classical Age, a Dark Age, and the dawn of a rebirth of the Classical Age.
  - **4.** The rebirth was signaled by the emergence of new Italian poetry, especially Dante’s *Divine Comedy* and Petrarch’s own work.
- **C.** Petrarch was concerned primarily with language and literature, not with politics, social institutions, philosophical knowledge, or technology.
  - **1.** Petrarch’s life extended over the first outbreak of plague in 1347–1348; thus, physical well-being was not central to his idea of progress.
  - **2.** Nor did he see the university as we do or think that windmills and clocks heralded a new age.
  - **3.** Petrarch was extremely sensitive to language, and he abhorred the debasement of spoken and written Latin over the previous 1000 years.

4. But now, he thought, the times were changing, and people were emerging who were committed to pursuing literary excellence.

D. Petrarch argued that the path to excellence began with imitation of the greatest literature ever written, namely, that of the Classical Age.

1. Such imitation required recovery of great literary texts and their close study so that their style could be emulated.
2. Emulation, however, was only a means to the end of rising above the literary achievements of the past, and here, the idea of progress makes its debut.
3. Progress is possible if we assimilate the best of the past and build on it creatively: The goal is to be better than the past.

II. The Humanist movement has often been dismissed as a pretentious nostalgia trip that impeded modernity, but this is a serious error.

A. Emulation, recall, began with the recovery and close study of the "best" literary works, those of Classical antiquity.

1. By 1300, hundreds of texts had been translated into Latin, but overwhelmingly, these translations were of very poor quality.
2. Typically, translations that fed into the university "market" were of Arabic books, which were themselves translations of translations most of the time.
3. The ideal, of course, would be to have the original Greek or Latin text to study closely, but the originals were all gone.

B. The Humanists, inspired by Petrarch, began a centuries-long search for ancient manuscripts.

1. The targets were monastic libraries, private libraries, Moslem scholars and merchants, and Byzantium.
2. They succeeded in finding thousands of manuscripts that were copies of Greek- and Roman-era originals, including many in natural philosophy, medicine, mathematics, and technology.
3. Although the Humanists were often not interested in the content of technical works for their own use, they were committed to publishing accurate original editions of them.

C. The generic problem was that the copies the Humanists found were invariably corrupt.

1. The Humanists responded by developing techniques for recovering accurate original texts from corrupted copies.
2. One family of techniques involved manuscript collation if there were multiple copies of the same manuscript, as was often the case.
3. A second technique was manuscript emendation, which was much more challenging than collation.
4. Emendation required understanding both the content of a text and the original language so well that corrupted words could be recognized and replaced and lacunae filled in.
5. This project revealed the historicity of language—that words and scripts changed their meanings over time—and the need for specialist dictionaries.

D. The search for manuscripts began in the late 14th century, intensified in the 15th, and extended through the 16th century.

1. Fortuitously, the Humanist project of recovering accurate texts of great works of literature, philosophy, mathematics, and "science" overlapped the introduction of printing.
2. Printing dramatically improved the ability of the Humanists to publish and distribute recovered texts; it also held the promise of underwriting the costs of scholarship or enabling a life as an independent scholar.
3. Most important, it made more effective the Humanist organization of a network of interacting, sometimes collaborating scholars, reviewing and critiquing one another's work, constructively and destructively, in progress or after publication.

E. In the process of pursuing their own interests, the Humanists made the idea of progress an issue for Renaissance Europe, and they provided valuable intellectual "tools" for modern science.
   1. They published, for the first time, accurate printed editions of scores of texts by Classical mathematicians, "scientists," philosophers, and technologists, correcting countless errors and making previously unknown texts available.
   2. Vitruvius's *On Architecture*; Ptolemy's *Geography*; the complete works of Plato; several treatises by Archimedes, including *The Sand Reckoner*; Apollonius of Perga's *The Conic Sections*; and works by Hero of Alexandria were profound influences on modern science.
   3. The Humanist challenge of using critical methodological "tools" to recover an original text from corrupted copies is strikingly similar to the challenge of modern science: using the "scientific method" to discover the reality behind "corrupt" sense experience.
   4. The Humanist creation of informal networks of scholars and formal associations, sharing ideas and work in progress and exposing their finished work to peer criticism and approval, was reflected in the way modern science was practiced, including the formation of scientific societies.

III. The idea of progress is so central to modern life that we take it for granted as a fact or a self-evident truth.
   A. The case for progress changed dramatically in the 15th and 16th centuries.
      1. Petrarch's idea of progress was, as we have seen, narrowly conceived, but it put the idea in people's minds.
      2. In the course of the 15th century, the idea of progress was explicitly coupled to new knowledge, especially mathematical and "scientific" knowledge, and to new technologies.
      3. The dynamism of the 12th and 13th centuries again animated European societies, and this time, the new technologies were based on knowledge, primarily mathematical knowledge.
   B. The case for progress was much broader and much stronger by the end of the 16th century, but progress was still a controversial claim to make.
      1. A common theme in the Renaissance was the "battle" of the ancients and the moderns, a battle fought in words mostly but often in various forms of spectacle/entertainment.
      2. On the side of the moderns were the compass, the new printing technology, paper, maps, and voyages of global discovery.
      3. The idea that people were better—wiser—in the 16th century than in the distant past was rejected by many who held that the case for progress was superficial.
      4. By the 17th century, the "battle" had been won by progress, which became associated with reason and, thus, with science.
      5. The proclamation of the Age of Reason in the 18th century was based on a belief that science could be an agent of reform in human affairs.
      6. The maturation in the 19th century of the idea of techno-science certainly *changed* the human condition, but has technological progress *improved* that condition?

Essential Reading:

Robert Nisbet, *A History of the Idea of Progress*.

Donald R. Kelley, *Renaissance Humanism*.

Questions to Consider:

1. What accounts for the emergence and embrace of a secular idea of progress in societies dominated for centuries by spiritual ideas and values?
2. Have science and technology delivered on the promise of the idea of progress that the products of reason would improve the human condition?

Lecture Nine—Transcript
Progress Enters into History

I said at the end of the last lecture that human history is not logical—obviously, sort of a personal commentary on the events that I was describing from a certain perspective. For example, those of you who are familiar with the philosopher Hegel might say, "Oh, no. According to one view of history at least, Hegel's deterministic view, history does unfold like a logical argument, in the nature of a deductive syllogism."

But from a common sense perspective, most of us feel that the twists and turns of history are not logical. Indeed, given the focus of this course on the idea of science and in particular on the specific definition of knowledge that became incorporated into the idea of science, it was Aristotle's view that history could not have a science. There could be no science of history because the individual events that make up history are particular, and therefore, do not lend themselves to universalization. And so if you can't have universals then you can't have universal laws of history and so history cannot have a science. There can be knowledge of history. You can have histories, of course, and they can be valuable in guiding behavior, but there can be no true science of history.

I'm not saying that Aristotle was right, of course, and certainly not that Hegel was right; but to say that history is not logical was provoked by the reflection that it seems as though modern science really ought to have emerged in the 14th century, some time early in the 14th century, out of the tremendous excitement and innovative intellectual and social, technological, commercial, and political ferment of the 12th, 13th, and early 14th centuries.

There, in the early 14th century, when you think that now these views about nature study, about mathematics, about experiment, about the autonomy of the intellect, etc., should now converge, and we would see modern science emerge. If that had happened, we would have said, "No wonder modern science emerged. Look, we can see its antecedents very clearly." It would have seemed quite logical to us if modern science had emerged in the early 14th century.

Instead, what happened was that there was a waning of the social dynamism that I referred to as the reason why we call the 12th century "the 12th century Renascence." This broad-based dynamism, the flow of innovations, and the enthusiasm with which these innovations were embraced, and implemented in society, drove change in society, then waned in the 14th century. Why?

Well, I mentioned at the end of the last lecture that the outbreak of the plague surely played some role in this. But in spite of the glibness with which we referred to the plague and its devastation in the 14th century, especially, and then episodically after that, it's not exactly clear how devastating the plague was. The plague broke out in 1347, 1348 in Europe. According to attempts by scholars to reconstruct its damage, somewhere plausibly between 10 percent and 30 percent of the population was killed by the plague. These are, of course, devastating numbers.

Keep in mind that the 'flu epidemic of 1918 is supposed to have killed somewhere on the order of 400,000–500,000 Americans, a staggering number in absolute terms, but representing perhaps one-half of one percent of the population of the United States at that time—the population being about a hundred million. So if, in fact, the plague killed even 10 percent of the population of Europe, then that would be 20 times the percentage of the population that was killed, and if it were 30 percent, then we'd see it was quite devastating.

But at the same time the Hundred Years' War between England and France, which broke out in the 1320s and lasted until somewhere in the 1430s, was being prosecuted with vigor, and in fact there are almost no literary references of the day to the plague. So how much we can say that it was the plague that forced a kind of break in the unfolding of the idea of science within European culture. It is not at all clear.

And what's really ironic, and what makes us really, I think, feel that history isn't logical, is that it was in the 14th century that we can see the first explicit expressions of the idea of progress, which is what this lecture is going to be concerned with. We're going to be talking about the idea of progress. The idea of progress is not a specifically scientific idea, and yet it quickly became coupled to science, that science became the standard bearer of the idea of progress. And it was the idea of progress that underlay society's embrace of science and technology as drivers of social change, as we will see in the course of this lecture.

What seems to us illogical is that, here is the 14th century, in which the dynamism of the preceding 250 years clearly wanes, and at that time the idea of progress is formulated. Furthermore, the idea of progress is introduced explicitly into European culture not in response to the innovations and the knowledge and the institutionalization of new forms of knowledge and trade and commerce, etc., characteristic of the preceding 250 years, but in a community of scholars who above all cherish poetry and literature and purity of language.

That seems quite ironic and illogical, so to speak. If the idea of progress had been introduced because someone wanted to stand up and say, "Look, things have slowed down, but look at what we have done over the past 250 years. We are better off than we had been. We are making progress," then that too would have seemed logical. But in fact the idea is initially coupled with a movement called Humanism. It was only in the 16th and 17th centuries that the idea was transposed, you could say it was co-opted, by those who argued that progress is being driven in Western society by science and technology, by new scientific knowledge, and by technological innovations.

The author of the idea of progress—I mean he gave voice to this idea—was Petrarch. Petrarch was an Italian poet of the 14th century in the generation after Dante, whom he admired greatly, and Petrarch was himself not particularly interested in science and certainly not in technology. He was a sensitive aesthetic soul who wrote poetry and admired Dante. But where Dante's *Comedy*—which Petrarch's friend Boccaccio called the *Divine Comedy*, because he thought that the poem that we know as the *Divine Comedy* was divine; you could not improve upon it—while Dante wrote that in Italian, Petrarch reverted to Latin.

And Petrarch unquestionably loved, at some very deep personal level, loved beautiful language. This is perhaps part of the poetic sensibility, but Petrarch went way beyond that. He was a broadly based intellectual, and it was Petrarch who introduced this sort of rough periodization of human history into the Classical Period of Greece and Rome, when cultural and especially linguistic excellence had been achieved. That is to say, the beauty and the power and the grace of Greek and Latin literature, Greek and Latin poetry, Greek and Latin drama, and history writing, and philosophy writing, the beauty of the language, as well as, of course, the power of the ideas, this is what Petrarch admired tremendously.

In the middle (medieval), the middle and dark period there was a total collapse—you might think he was concerned about health and wealth—no, total collapse of linguistic purity. Latin had been vulgarized, and nobody spoke good Latin anymore, and Greek was forgotten. So now Petrarch said he sees in Dante and in the generation of Italian poets that is beginning to emerge after Dante, Petrarch sees the beginning of a rebirth, which has come to be called the Renaissance—the rebirth.

A rebirth of what? A rebirth of linguistic excellence; a rebirth of cultural excellence. We see people beginning to recognize that beautiful language, that beautiful poetry expressed in beautiful language, that beautiful literature is once again a value; and he promoted this value. So on one side this movement that he stimulated, that he founded, called the Humanist movement, which for the next 250 years approximately, maybe 300 years, exerted enormous influence in Western culture, was a literary movement at its heart.

It was concerned with recapturing the beauty and the linguistic purity and the power of classical Greek and Latin, which makes it seem as though these people were irrelevant to the rise of science. And, in fact, in the first half of the 20th century, most historians of science dismissed the humanists as people who prevented the earlier emergence of the idea of science, or who actively obstructed a focus on what we would recognize as the scientific study of nature. I think this is completely incorrect and is being increasingly recognized as incorrect, and for reasons that you'll see very shortly, I think.

Petrarch himself, although the humanists have been accused of being some sort of amateur aesthetes who merely wanted to go around reconstructing classical Greek and Latin, and then writing and speaking in ways as if they were still living in ancient Athens and in ancient Rome, Petrarch himself clearly indicated that the goal is to recover the linguistic beauty and purity of classical Greek and Latin. Not in order to repeatedly emulate the poetry of Homer, or the dramas of Aeschylus, or the poetry of Livy and Ovid. There is a goal, he says, and he compares the humanist to the bee, he says the bee draws the pollen from the flower, but it transforms it into honey. The goal of the humanist is to return to the kind of cultural excellence characteristic of Greece and Rome in order to move beyond that, in order to improve on it.

And this becomes sort of the first articulation of the idea of progress, the first expression that it is part of our mission on earth, so to speak, to improve upon what we have been given, and that it is possible to do so. But from Petrarch's point of view, the precondition of doing that, the precondition of improvement, is first becoming a master of the past, of the best of the past. Once you have become a master of the best of the past, then you could improve upon the past.

Now, this is in the 14th century, and Petrarch's followers—and there were many of them over the next few hundred years, thousands of Europeans became participants, as I said, over approximately 300 years—became participants in the Humanist movement. Why were they called humanists, and what was characteristic of the movement? It is not that easy to give a simple answer to it. At one level, people were attracted to the movement. They were often young intellectuals who objected to the university curriculum, which was heavily loaded with studying Aristotle's logic, Ptolemy's astronomy, Euclid's *Elements*, and very dry technical exercises in grammar, and rhetoric, and dialectic. They were forced to study music at a mathematical level and master the existing arithmetic texts, what we would call arithmetic, geometry, logic, and astronomy. What they wanted to study was literature. And in fact that was a small component of the curriculum, the one that came under the heading of grammar.

So there were those people who were humanists in opposition to what they perceived to be the science and technical philosophy dominated curriculum of the medieval university. There were others who were, like Petrarch, primarily interested in recovering pure Latin and learning Greek so that they could get back to at least the level that ancient Greece and Rome were at. To that end those people for hundreds of years sought out manuscripts by scouring the monasteries of Europe, where often in monastic libraries here and there, there was a text; there was a manuscript of an Aristotelian text, of a text of Euclid, of a text of Ptolemy. Of course, they weren't looking for those texts specifically. Very often they were not particularly interested in science and mathematics. They were interested in the literary texts. They were interested in the poetry texts. They were interested in the drama texts. They were interested in the history texts.

But along the way they were in love with everything Greek and Latin, and so along the way they did recover texts by Euclid, and manuscripts of Ptolemy. Almost all of these texts had been dramatically corrupted in the course of being translated from their original language, copied over for centuries, translated into Syriac and into Arabic, translated from Arabic into Hebrew, and then into Latin in the 12th and 13th centuries, and the texts were often copied by monks. As part of their work ritual they were required to do certain work, and copying manuscripts was part of that. The monks were often barely literate themselves, so that enormous numbers of errors crept into the copied manuscripts, which the humanists became increasingly sensitive to. And so they started collecting as often as possible original manuscripts, and they also attempted to learn Greek and Latin of the classical sort, based on their manuscript study, so that they could recognize errors in the manuscript.

So they studied Greek and Latin and, inevitably, they also had to study Hebrew and Arabic, and those became new courses of study in the medieval university, especially Hebrew added to Greek in addition to

Latin. So that in the 16th century you start getting the first professorships of Hebrew and Greek, and the expectation that an educated person is going to know at least Greek and Latin, and a scholar has to work with Hebrew, ideally with Arabic, as well as with various vernacular languages by the time you get to the 16th and 17th centuries. There was a strong linguistic focus, a strong historical focus, and in the course of collecting these thousands of manuscripts, what the humanists did was to develop a set of critical tools, objective critical tools, for restoring the original manuscript from corrupt copies.

Effectively every copy is corrupt. There is no such thing as a clean version of Ptolemy's *Almagest*, the core text in astronomy, or Euclid's *Elements of Geometry*, or Aristotle's *Writings on Logic*. There is no correct text that you can recognize and say, "Oh, this is the correct text. Throw out all the others." What you have is maybe dozens of partial or complete manuscripts, all of which have errors in them. What do you do? How can you recover an unavailable correct text, and how will you know when you have gotten there?

This is a nontrivial problem in scholarship. And the humanists, over a period of centuries, developed very sophisticated critical tools, beginning with manuscript collation. You start with collecting as many manuscripts as you can of a particular text and you start comparing those texts. And you can often recognize and repair lots of mistakes just by collation. Very often you can't do that, and you have to emend the text; because it may be that while you have 11 copies of a particular text, all 11 come from an original source, and they are repeating the same mistake in that source. If you recognize the error, then you need to be able to emend the text. But you have to be very careful with emendation. You have to make sure that what you have recognized is an error, and that what you are going to insert is the correction, because you don't have the correct word or the correct phrase available to you.

What the humanist scholars were doing was, I believe, doing something that was profoundly influential on the rise of the scientific method in the 17th century. They were developing critical tools that allowed you to make overt—to make available to you as a reader—a correct version of the original text that is covert, that's hidden, that's not available; we don't have it. And yet they're bringing it to life. They are teasing that text to life using these critical methodological tools, and that's very similar, it seems to me, well let's say it's analogous, to making visible to us the hidden processes of nature, which are not available to us to see. Even after the scientist tells you that matter is made out of quarks, you cannot now go back and look at the English muffin that you're having for breakfast and say, "Oh, yes, I can see them now. There are the little devils, whirling around inside the protons and neutrons."

Just as science makes visible to the mind a reality that is otherwise invisible to the mind, so the humanist scholars were making visible to us, giving us a text we could read with some measure of confidence, that this is the text that Plato wrote, that Aristotle wrote, that Euclid wrote, that Ptolemy wrote.

The humanists also did something else that was very influential for modern science, and that was that they constituted a community of scholars distributed all over Europe who regularly communicated with each other, who shared their work, especially starting in the late 15th century and throughout the 16th century. Sharing their printed work, and getting critical comments back from others, and founding societies where scholars got together to discuss their shared work, and ultimately journals in which this work was published. All of which became sort of precedents that became central to science in the 17th century where societies of scientists were communicating with one another, notifying one another about their ideas and discoveries and claims to knowledge, and getting critical responses—"Yes, we repeated your experiments and indeed your work. We can confirm this. No, we didn't get these results."—that idea that science is a collective practice by a community of scholars with shared standards, those were in fact formulated by the humanists.

Now, by the time we get into the 16th century, especially as we will see in the next lecture, by the time we get into the 16th century, the humanists worked within the very core of a new dynamism, a resumed dynamism in Western and Southern European, and generally in European, society that we recognize as the Renaissance. And even in the 15th and 16th centuries, already in the 15th century, the idea of progress, which starts out as a literary and aesthetic idea, becomes associated with science and technology, with technology, with techno-science. Now while in the 12th, 13th, and 14th centuries the innovations that were transforming European society were not techno-science, they were technological innovations that emerged out of craft tradition, not by the deliberate application of mathematics to natural phenomena.

The water mills and the windmills and the centrally-mounted sternpost rudder that I referred to, the breast harness for the horse, the heavy plow: these were not derived from scientific theories. In fact, scientific theories didn't have much to offer until we get to the 19th century, and they were not derived from the application of mathematics specifically. So I would not attach the term techno-science to the 12th century Renascence and its immediate consequences. But in the Renaissance we are going to see techno-science emerging; that is to say, that Graeco-Roman idea of knowledge driving technological innovation is going to re-emerge with vigor in the 16th century especially, but beginning in the 15th century. And the idea of progress is going to become attached to science, technology, and techno-science, and ever after, right from then on.

The idea of progress has been carried by and has driven the embrace of science and science-based innovations as a sign of progress. There was in the 15th and 16th centuries—to give you an idea that I'm just not making this whole thing about progress up—there were very many literary works and popular entertainments that were called the battles of the ancients against the moderns. And these battles were, of course, mock battles in which there was merely a debate between intellectuals, one of whom was defending the view that we are no better than they were; in fact, we would be lucky to come close to the hems of their garments. It was only in the old days that people knew how to write. It was only in the old days that people knew how to think clearly; that those were the golden old days. And on the other side, no, don't be ridiculous. They didn't know how to do the things that we can do. Of course, this has to be, now we're talking, the 15th and 16th centuries. They didn't have printing with movable metal type. They didn't have gunpowder. They didn't have the compass. They didn't have paper. They didn't know about the world as we do. We have circumnavigated the globe. They didn't know about the Americas. They had never actually been to China. They didn't understand.

And by the end of the 16th century, there was so much novelty, so to speak, in European culture that the battles were over. It was no longer a battle, because the idea of progress had won. Everyone recognized by the time you get into the 17th century, by the time you get into the generations between Galileo and Newton, the battle was a memory. Isn't it cute that people used to argue about this type of thing?

And so when we see in the 18th century what in Europe was called the Enlightenment, that this is a direct expression of the idea of progress having been co-opted by science as the living embodiment of reason. That the root to progress is through the application of reason to human affairs, science is the living embodiment of reason, and so science becomes, in the 18th century, identified as an agent of social reform.

And science and technology together in the course of the 18th century, even before they had the power to transform society in the ways that they did in the 19th and 20th centuries, science and technology, especially in Germany, France, England, and in Italy, are explicitly identified as the means by which the human condition can be indefinitely improved.

This had been promised by Francis Bacon and René Descartes in the early 17th century when they were two of the founders of modern science, but in fact the promise took quite a while to fulfill. In the 18th century, the idea that reason is the means by which human beings can achieve secular salvation becomes not just a prominent theme in Western intellectual life, it becomes a powerful force in Western society. It underlies the American Revolution. It underlies the French Revolution. It underlies the desire to make a science out of everything.

It was in the 18th century that we had the beginnings of a sustained, serious effort to make a science out of society. The beginnings of the science that in the 19th century was given the name sociology. A science out of the mind, of how the mind works, especially among the French intellectuals; a science out of economics; a science out of political life—the application of mathematics to political policies, and political decision-making; those are all expressions of the Enlightenment. They all are to be found in the 18th century.

Adam Smith's *The Wealth of Nations*, for example, was published in 1776, a year of some consequence for us, and the founders of America were strong believers in this idea, especially someone like Thomas Jefferson, that what we're doing here is based on reason. "We hold these truths to be self-evident"—the Declaration of Independence specifically refers to the idea that there are self-evident truths that are the basis for the rebellion against the English king and the creation of a form of government that is rational. That does not merely perpetuate history, but reflects the application of human reason to human affairs.

So what we've seen here, very briefly sketched, but we're going to pick up on it in the next lectures as we discuss the introduction of print technology into Europe and the Renaissance, the idea of techno-science and the Renaissance. What we've seen here is that the idea of progress begins to emerge in the 14th century through a group of poets, of intellectuals concerned that there is such total aesthetic decay in Europe at this time, and yet we have the example of the Greeks and Romans. We can restore the glory that was Greece and the grandeur that was Rome at least at the aesthetic level if we make our mission to be as good as they were linguistically. It emerges in that context, not them saying, "Look at how much we accomplished over the last 250 years. Human beings are actually living better and are superior to the way human beings were 1,000 years ago." They did not say that.

And that idea then was pursued with vigor by this humanist intellectual community in the 14th, 15th, and 16th centuries, and in the course of the 15th and 16th centuries when, as we will see, European society began to apply knowledge to technology and transformed itself once again into what we now call modern society. Then the idea of progress became associated primarily with science and technology in the 18th century, emerging as the agent of social reform, the basis for social reform. Then we will see how that translates in the 19th century into the driver of social change that still shapes our lives.

Lecture Ten
The Printed Book—Gutenberg to Galileo

Scope:

Printed texts were not new in the West in the 15th century and were more than 1000 years old in China. Printing using movable type was also an old technology when Gutenberg introduced it to Europe, but the response of European societies to his print technology perfectly illustrates the thesis that innovations only open doors; social factors determine if a society enters through them. The impact of printed texts on Western societies was dramatically different from its impact in China or Islam. European culture became "print drunk" instantly. By 1500, some 10 million texts, including 2 million books, had been printed at a time when the literacy rate was very low. The response triggered the creation of a vast system to supply, produce, and distribute texts, and new institutions were created to protect and reward producers and increase literacy, promoting further increases in text production and distribution.

Outline

I. The printed book is an excellent illustration of how technological innovations change the way we live.

- **A.** Books are only the most visible manifestation of a largely invisible, highly complex social-technological system at work.
    - **1.** This is true of artifacts generally, not just of books.
    - **2.** The visibility of artifacts distracts attention from the underlying system of which they are manifestations.
    - **3.** Although artifacts are described as causes of social change, social factors play a central role in deciding if artifacts are to be produced, how and in what form, and how they are to be distributed and used.
- **B.** If an invention such as Gutenberg's printing press only "opens a door," we need to ask what it takes for a society to "cross the threshold."
    - **1.** Gutenberg did not invent printing.
    - **2.** The Chinese were producing block-printed texts by the 6th century, eventually producing multi-block, multi-color texts.
    - **3.** In the 11th century, a Chinese printer developed movable (fired) clay type, and in the 14th century, printers began using movable wooden type, early experiments with metal type having failed.
    - **4.** Between 100 B.C.E. and 105 C.E., paper was invented by the Chinese using vegetable matter as the "pulp," and papermaking technology spread to Korea, Japan, and the Middle East.
    - **5.** These Chinese print technology innovations spread via Korea to Japan by the 12th century and, by 1400, to the West.
    - **6.** The first European paper mills, for example, were built in Islamic Spain in the 12th century and quickly moved north into France, where the pulping process was water-powered, the paper now being rag-based.
- **C.** The invention that triggered the 15th-century book "revolution" was high-volume printing using movable metal type.
    - **1.** Gutenberg was the first successful integrator of movable metal (lead) type, a modified ink with an oil base, and an adaptation to printing needs of oil and linen presses.
    - **2.** Oil-based paints for artists were introduced at about this time in Europe by Jan van Eyck.

3. The impact of this new print-production technology, given the population of Europe and the low literacy rate, was astonishing: By 1500, 2 million books alone had been printed, altogether some 40,000 different titles!
4. Echoing Lynn White's dictum, western European society burst through the door opened by this new technology, but what was required for it to do so?

II. The major elements of the iceberg/system of which the printed book is the "tip" are easily identified.

A. Exploding in just 50 years from a low-volume specialty item to a mass-production commodity, book production required a comparable increase in the production of paper and ink.

1. Scaling production up to the new level demanded by the printing press, however, required a whole new kind of paper industry: more and larger mills, more raw materials, more workers, more investment, increased transportation capacity, scaled-up marketing and distribution, and more complex business organization.
2. All these factors apply to supplying appropriate inks, as well.
3. The print shop needed to be "fed" as the number of presses grew, as markets grew, and as competition increased.
4. Skilled workers were needed to build, operate, and maintain presses and auxiliary equipment.
5. Typecasting was a new job category, as was typeface design, and the demand for lead rippled back to increased mining.
6. Even when printing existing texts, printers needed educated people to prepare the content and copyeditors to check for errors and monitor the accuracy of the production process.
7. Very soon, printers needed authors to provide original content.

B. The printing press also needed to be "fed" and protected at the demand end of the book-production process.

1. A book-*selling* industry—more broadly, a printed-materials-selling industry—was needed that matched demand to the scale of the printed-materials-*production* industry.
2. Printers needed distribution channels that could move inventory more rapidly than medieval-era trade fairs.
3. As the market grew, bookselling became a business in its own right, with an interest in playing printers off against one another.
4. From the beginning, printers, authors, sellers, and the reading public needed protection from "pirated" texts, especially editions that were not accurate replicas of the author's original text.
5. New markets were needed to absorb growing production capacity, which required dramatic increases in literacy.
6. A "literacy industry" arose to increase the scale of education and make more people want to read more.
7. Growth in demand fed back into the production system, promoting further growth!

III. Everyone acknowledges that modern printing exerted a profound impact on Western societies, but why it had that impact and how that impact was effected are little understood, as is the impact of modern printing on modern science.

A. The book as the visible "tip" of a largely invisible socio-technic system reveals an important feature of all such systems.

1. There was no central planning for the creation of this system.
2. No one person or institution orchestrated the complex supply, production, distribution, and demand channels.
3. There is a lesson here in self-organization that we will return to in Lecture Thirty-Four.

B. To understand the impact of printing on Western society, we need to look at the demand side and the content of printed works.

1. The question of *what* to print was initially answered by printing Bibles, religious literature, and Greek and Latin classics.
2. The Humanists became a source of new editions of these classics, but as demand grew, so did the need for original material.
3. As the investment in mass production grew, so did the need for mass "consumption."
4. The size of the market is directly related to the literacy/education rate of the population.
5. Francis Bacon, "father" of the experimental method, was primarily an education reformer, and universal literacy was one of his objectives.

C. The response after 1450 to the possibility of mass production of printed material is revealing in other ways, as well.

1. A positive feedback loop, reminiscent of the impact of the invention of writing, was created, so that production and consumption became mutually reinforcing.
2. The invention of writing was immediately followed by the appearance of vast numbers of documents, as if a dam had burst. So it was with printing.

D. The power and attraction of mass production of texts are not as obvious as they may seem.

1. One view has been that printing authoritatively "fixes" a text, so that authors can be assured that every reader is reading exactly the words they wrote and looking at exactly the same illustrations they provided.
2. In fact, others have argued, this was not at all the case, because of the new ease and commercial attractiveness of plagiarism and pirated versions of "bestsellers."
3. Galileo, for example, carefully produced a "deluxe" edition of a slim book that he hoped would make his fortune, *The Starry Messenger*, describing his telescopic discoveries. Within a year, pirated copies with distorted illustrations were being sold all over Europe.
4. The great Danish astronomer Tycho Brahe attempted total control over the printing and distribution of his books by owning or controlling every step in the process—in spite of which he failed.
5. The new technology thus required the creation of new social institutions to deal with these problems and with the problem of controlling morally, politically, and religiously "subversive" texts.

Essential Reading:

Adrian Johns, *The Nature of the Book*.

Elizabeth L. Eisenstein, *The Printing Revolution in Early Modern Europe*.

Questions to Consider:

1. How does a social-technological system, such as the print industry, come into being without central planning and coordination?
2. What was it about 15^{th}-century Western culture that caused a demand for universal literacy in response to the new print technology?

Lecture Ten—Transcript
The Printed Book—Gutenberg to Galileo

The subject of this lecture is the idea of the book, the invention of the idea of the book. But before we move on to the book, I want to hold on for a moment to the idea of progress from the last lecture and make a kind of an editorial comment. While it is self-evident that every improvement entails a change, not every change implies that we have made an improvement. And it seems to me that the rhetoric of progress, especially in the 19^{th} and 20^{th} centuries, and now at the beginning of the 21^{st} century, often mindlessly identifies change with improvement. It is not clear how in any particular case we are supposed to evaluate whether a change has become an improvement. All we can see is that when we think there have been improvements, then they were always precipitated by some change.

But let's refocus on the idea of the book. Now, on the one hand, you knew that this was coming. You knew that we were going to be talking about the book because of my focus early on in this course on how central writing is to science. Writing is, I said, a necessary condition for the idea of science, and for the practice of science from the rise of modern science to the present. So it was in a certain sense inevitable that somewhere along the line I was going to be talking about the book, about printed texts as the embodiment of writing that modern science was able to assimilate in the 17^{th} century.

On the other hand, one can legitimately say, "But what's the big deal? I don't understand. How do I invent the idea of the book? Since people have been writing texts since antiquity—we talked about books, and correctly so, in the context of Greece in the 5^{th} century B.C.E.—then what do you mean? How can you invent the idea of the book in the 15^{th} century?" I hope that by the end of this lecture you'll see that we take the printed text (I'm going to use "book" as a synonym for "printed text"), we take the book for granted, and don't appreciate the sense in which a book that we may hold in our hands, the book that people held in their hands starting in the middle of the second half of the 15^{th} century, the kind of books they held in their hands, were the most visible expression of a very complex system that I'm going to call a socio-technic system. The kind of a system that became clear in the 19^{th} century.

It was in the 19^{th} century that technological innovations, driven by scientific knowledge, generated these very complex socio-technic systems, of which artifacts and processes were only the most visible elements, analogous to the tip of the iceberg, and the overwhelming majority of the bulk of the iceberg being submerged and roughly speaking invisible. So I want to talk about the book in the context of being an illustration of a socio-technic system, and I'm going to obviously have to flesh that out, but this will be telegraphing a phenomenon that becomes really important in the 19^{th} and 20^{th} centuries.

The book itself, as I say, is only the most visible manifestation of a system that is associated with the creation of books, the production of books, the distribution of books, the marketing of books, and the sale of books. Those are, roughly speaking, invisible aspects of the system when you're just holding the book, and all you're interested in is the content of the book. You're reading the book because you want to know what is inside the book, or because someone has told you that you have to read the book and then you'll be quizzed on the content of the book. But that's what you're interested in. And we tend not to be sensitive to the fact that there is a vast system surrounding that book that enabled that book to be held in my hands, or for that text to be posted on the Internet.

Now we all "know" that Gutenberg invented printing, but Gutenberg, of course, did not invent printing. Not only did he not invent printing, he did not invent printing with moveable type, either. But this is not to take credit away from him. We'll see what credit he deserves in a little while. But the credit for the invention of printing goes to the Chinese, who were block printing text, carving the written writing symbols into wooden blocks, inking the blocks, and then printing block printed texts, back in the 6^{th} century. From approximately the 500s, the Chinese were producing block printed texts, and large numbers of them. It's not as if they did one here, they did one there. Some of the printed works were massive encyclopedias, and collections of religious and politically relevant writings.

And in fact from somewhere around the 11th century they began using moveable type—moveable type originally perhaps in clay, and then in wood, because the clay type tended to break, so wood. This technology of block printing and printing with moveable type migrated from China to Korea, to Japan, and into Islam, and using paper, by the way. The Chinese also invented paper approximately 2,000 years ago. At that time they made paper out of vegetable material, the debris of vegetable material, which they compacted and pounded, and squeezed and flattened, and pressed into paper.

Somehow between roughly 2,000 years ago and 1,000 years ago, this morphed into using rags, and that technology was definitely carried by Islamic culture into Spain, and from Spain into Europe. That was probably in the 13th century when we see rag-based paper first manufactured in Spain. I referred in an earlier lecture to the use of water mills to power the hammers to pulp the rags in order to manufacture the paper. We find the first examples of such paper mills in Spain in the 13th century.

So when we look at Gutenberg in the middle of the 15th century, there already existed in Gutenberg's social milieux printing shops that block-printed texts. Some texts were handwritten, and others were block-printed and hand illuminated, or illustrated, and people were also using paper as a basis for texts. Texts were printed on paper. We weren't using parchment any more, or papyrus, and clay tablets had fallen out of use long before. So what did Gutenberg do?

Well, what Gutenberg did introduce was printing using moveable metal type, which turned out to be much more effective, and much more efficient, than using ceramic or wood moveable type. And the use of moveable metal type required different kinds of ink than block printing required. These kinds of ink used were oil based, olive oil based, and flax oil based, and Gutenberg empirically developed such oils. And you also could not just use a block printing press for this new kind of printing using moveable metal type and these new kinds of inks. You had to modify the press, and he did that, too. So in effect Gutenberg, and there's some argument about whether he, himself, did all of these things or any of these things, but I think that it is reasonable to say that Gutenberg in the middle of the 15th century (approximately 1450) introduced this complex of adapted technologies of printing using moveable metal type, and using new kinds of inks—oil-based inks.

It's interesting, and we'll talk about this in the next lecture a little bit, that at the same time Jan van Eyck had introduced oil-based paints into Europe. Oil-based paints rapidly became almost the universal standard for painters during the Renaissance, giving up tempera egg-based paints and using oil-based paints. So Gutenberg perhaps was reflecting a merging craft knowledge of using oil-based paints for oil-based inks, and modified presses, and started printing texts using moveable metal type.

Now what happened next is not something that Gutenberg could possibly have predicted or anticipated, and so this is another feature of technology that we need to set aside as a generic feature of technology. Namely, that its social impact is unpredictable in advance, that we cannot with confidence predict how a society is going to respond to a technology.

So I said that's another illustration. What was the first one? The first one was, recall, Lynn White's dictum about new innovations opening doors but not forcing a society to go through them; that technological innovations open doors, and furthermore, we cannot predict in advance what the response is going to be. Because what was the response to Gutenberg's innovation? There had been books for centuries in the West, the university system, schools. There had been block-printed books. But all of a sudden, between 1450 and 1500, at least two million books were published in Western and Central Europe—two million books; 40,000 different titles; perhaps as many as 10 million texts, but eight million of them were pamphlets of various kinds.

Consider what the population of Europe was between 1450 and 1500—much, much smaller than today. Consider what the literacy rate was at the time—maybe five percent? That is as close as I could get by asking scholars of this period what they think the literacy rate was. That's an incredible response. There is no way that Gutenberg thought that printing with moveable metal type was going to trigger that kind of a market.

But now, get back to the socio-technic system. I said the book is the most visible manifestation of the socio-technic system. Whoa! Two million books; 10 million texts, all printed on paper. Where is the paper going to come from? Who is going to invest in the paper mills? Who is going to be collecting the rags to pulp into paper? And then the paper has got to be distributed. To where? To print shops. So that means that print shops have to spring up all over the place. Someone has got to manufacture presses, got to manufacture the ink. Someone has got to train the people who will build, operate, and maintain the presses physically, plus someone has got to oversee the process of printing this stuff, and make sure that it's correct. Let's call them editors.

Now, we haven't talked about the content yet. Let's leave the content aside. Because if you're going to print two million books, they can't be blank pages, right? You could save a lot of money on ink and presses if you don't bother to put anything on the page. But let's set the content aside for the moment and think about when you're printing large numbers of texts, what are you going to do with them? Obviously you need to sell them in order to recoup the cost of the printing process so you can pay the people who sold you the paper, and pay the salaries, etc. So you've got to have a distribution system. There had never been such a thing as having to distribute millions of texts. There has to be a marketing system. There has to be a sales system.

Who is going to actually put the text in the hands of the reader? There are no bookstores. How are you going to transfer the books to the reader—the pamphlet, the newspaper, eventually? How are they going to be sold? So you need a sales network, but you also need marketing. Why do you need marketing? Because when books were a luxury item people could charge whatever the market would bear, and there was very little in the way of start-up costs if you were a copyist, a scribe. So you buy some ink, you buy some paper, and you try to get a customer who hires you to make a copy of Aristotle's *Physics*. But if you have invested serious money in a paper mill and you need to sell umpteen pounds of paper a week in order to recoup the cost, let alone make a profit, then you've got to make sure that the demand is always at least equal to the supply. The demand has to pull that supply out. If you're printing two million books, you need to be able to able to sell two million books. But in order to ramp up the system to produce two million books, you can't afford for people to suddenly decide, "You know what? I don't need to read anymore." You can't afford for there to be less than, let's say, 100,000 books a year, or 10,000 books a week, sold.

Now we begin to get some idea of what it means, what the socio-technic system means. That this innovation, printing with moveable metal type—it doesn't really sound that revolutionary or that exotic. But in fact the way that Western society responded to printing with moveable metal type required, elicited, provoked this socio-technic system.

Now, here is another generic feature of technology that we're going to become aware of only in the 19th century; in fact, I would say only in the late 20th century was it taken seriously: there was no central planning here. Nobody sat down and said, "Oh, well, we're going to have to have three more paper mills here. We're going to have to have an army of people collecting rags"—very often, by the way, tragically, from battlefields; an easy way to get rags is to strip them off the bodies of the dead—"and we're going to have to have a system for collecting rags and shipping them to the paper mills. We need 11 paper mills here and three paper mills here." Nobody did that. This is a self-organizing system. And this is another generic feature of the kinds of socio-technic systems that underlay the technological innovations that changed the world. And we'll see this repeatedly in the 19th and 20th centuries, and it becomes finally a branch of a new discipline in science in the late 20th century, but that's down the line for us in this course.

Right now we're looking at the book as the highlight, the star element of a complex socio-technic system, and what we're up to is content. So all of a sudden everybody wants to buy books, two million in 50 years just for the books. Everybody wants to buy books. What are we going to sell to them? Well, Gutenberg started off with the Bible. That's a good deal. It's actually not as good a deal as you might think, because when Gutenberg started printing Bibles, Europe was Catholic. The Catholic Church vigorously opposed the private ownership of the Bible. It was, "You could lose your life for distributing Bibles."

The position of the Church was that it was the Church that disseminated the Word of God. It was part of the Protestant Reformation, which is a 16th century phenomenon, that each family must own its own Bible and must study the Bible every day. The daily study of Bible text, the daily Bible reading within the family, is a Protestant innovation. It is a principle of Protestantism. So, in fact, Gutenberg's Bibles were luxury items. They were not mass-market items. Well, but given a sudden mass market for books, what are you going to print?

Well, the easiest thing to do is to print the golden oldies. Start printing the great works of Greece and Rome, because everybody who can read knows about them. Everybody knows Aristotle. Everybody has heard the name Plato. Everybody has heard the founding fathers of the Catholic Church—people like Augustine. Volumes of sermons; that is perfectly okay. You can print and distribute those. And what you want is stuff that is already available, so you don't have to pay anybody to do it, except you have to pay somebody who will obviously prepare the text to be set in type. But you don't need an author for that; you just need an educated person.

Many, perhaps the bulk, of those two million books, were in fact sort of reprints of golden oldies. And isn't it interesting, and what a coincidence from the last lecture, that the humanists now in the 15th and 16th centuries are flooding the market with new editions of classical texts, of the golden oldies? And so those humanists become a source of classical texts that they have corrected, and that they are editing into original forms as far as possible. And in fact in the 16th century we have an example of the first person that we know of—he claimed it anyway—named Erasmus of Rotterdam, who made a living solely as an author. He was a humanist scholar, although his own books, which were mildly satirical criticisms of Christian life in Western Europe at the time, were bestsellers. He was able to live from the fees that printers paid him as an author, and also as an editor because he was a legitimate humanist scholar. So that was one source.

Okay, but now there is a limit to the golden oldies, too, because the market keeps growing. While there were two million books published between 1450 and 1500, that was nothing compared to the volume of printing from 1500 on. It is a perfect illustration of Lynn White's dictum of a new technology only opens a door. The response of European society to printing using moveable metal type was totally different from the response of Chinese, Japanese, Korean, and Islamic society to exactly the same technology. To look ahead a bit, the response of European society—and those of you who are critical of capitalism may see this in a more negative light; I see it as quite positive—that the socio-technic system, the investment in the production and distribution networks necessary to sustain this kind of a market, whatever was the driver, the response of European society was universal literacy. Make a reader and customer out of everybody.

We see this already. We will see in the second lecture from now that Francis Bacon, one of the founders of modern science, was not a scientist. He was a social reformer and an educational reformer, as his father was before him. And as an educational reformer, Bacon championed the idea of universal literacy in England—especially universal literacy in technology, and secondarily in science as he understood it—because that, he thought, would be the only sound basis for British power and prosperity in the future: universal literacy. So of course the printers loved the idea of universal literacy. It doesn't mean that they lobbied for it or they paid anybody off to get it, and it took centuries to get to, but there was unquestionably an increase in schooling.

We have another example of this positive feedback loop. Just as the invention of writing somehow created a positive feedback loop in which all of a sudden in the 3rd millennium B.C.E. and the 2nd millennium B.C.E. there was a flood of texts. Awkward as it was to write on tablets with cuneiform symbols, awkward as it was to write pictographs on papyri, there were hundreds of thousands of them.

Literally, there are in museums hundreds of thousands of texts that have survived, of tablets, and tens of thousands of papyri with Egyptian hieroglyphics, many of which have not yet been looked at, let alone translated. So that the positive feedback loop here is that people wanted to learn to read; the more people read, the more printing there was. The more printing there was, the greater the pressure for more people to read, so that universal literacy was a realistic notion in this broader cultural context.

Now let's go further with the content idea. It became, until relatively recently, almost a truism among historians of Europe, and especially those who paid attention to print technology, that the power of the printed text, especially for science and technology, science and engineering, lay in the fact that now you could write a book and be sure that there would be no copying errors. You didn't have to worry that some copyist was drunk when he or she did the copying and wrote things that you didn't write or missed important terms. You could be sure that the text was accurate and stable, that everybody who read your book would be reading the words that you wrote. And that especially in science and in the burgeoning niche market for engineering machine design books that we're going to be talking about in the next lecture, in the 16th and 17th centuries especially, that science and engineering texts with their increasingly good illustrations, you could be confident that everybody was going to be reading the same thing that you wrote. And that this was part of the power of the book and it was also the reason why the book became so central to science and to engineering.

This view was articulated by the great historian of science, George Sarton, the man who struggled very hard to establish history of science as a discipline here in the United States against tremendous opposition from the historical community at the time, and more recently by Elizabeth Eisenstein. But I think that the view of an author, Adrian Johns, is more correct in pointing out that as a matter of fact an aspect of the socio-technic system underlying the book that has not been given enough attention is the fact that there were real problems with the content of books, and especially with scientific books. That books were pirated; that they were plagiarized; that cheap knockoffs were made almost immediately; that you could not be confident that because your book was printed that all the copies would say exactly what you had written.

That might be true for the printer where you personally stood over them and saw the book being printed. But once, if you're British, once some Dutch printer sees that the book is selling well and makes a knockoff of it, then you have no control over what they did. You have no control over the quality or the accuracy of the equations and the illustrations by the time we get into the 17th century. For example, Galileo, in 1610, produced a slim book called *The Sidereal Messenger* or *The Messenger from the Stars* that he carefully produced with very good illustrations that he himself prepared, and which he used as his ticket to fame and fortune, by so to speak manipulating the Medici family in Florence, so that he would get the cushiest academic position in Italy of his generation. Within that same year, pirated versions of the text were appearing in Europe, outside of Italy, with increasingly lousy illustrations. Now, there was no way that Galileo could control that.

An even more flagrant illustration that Johns points out is Tycho Brahe, who was an astronomer we'll be talking about in the lecture on Copernicus. Tycho Brahe, the greatest observational astronomer of all times, perhaps, Brahe had a self-contained fiefdom on an island that he was given by the Danish king. He had his own printing presses, he made his own paper, and in fact he was unable to control the production and distribution of his own books. When they eventually were printed, they were not printed by him for distribution and marketing. His attempts to produce his own books and market them and send them to the people that he wanted to have them, knowing that they would be reading what he wrote, failed, and the eventual printing was commercialized. So in fact an aspect of the socio-technic system that we don't pay sufficient attention to is the copyright laws, the institutions that were created to control the content, to prevent piracy, and to prevent subversion. So there are censorship institutions. It's just like the Internet. In one sense there's nothing new under the sun.

There is religious subversion that you have to be concerned about in the 15th, 16th, and 17th centuries. The Catholics have to worry about what became the Protestant religious teachings getting out, and then even in the 16th and 17th centuries, when the Protestants were legitimated, so to speak, there were atheists who might publish criticisms of religion and make fun of religion. You can't allow that. Politically speaking, you don't want people making fun of the king. You don't want them making fun of the nobility. You don't want them publishing seditious stuff.

So creating censorship institutions, creating institutions and laws that attempt to eliminate piracy and plagiarism, they also are part of the socio-technic system which implicates the broader society as a whole. Plus of course commercial institutions that protect the investments and the profit-seeking of the people who not only print books, but the people who sell books, to limit competition so that they can make a profit on the sale of the books, and the people who are making the paper, and all the way down to the people who are making the printing presses, and who are making the oil-based inks. It's a complicated system, and we take it for granted.

The book unquestionably did become—and the illustrations that I gave from Tycho Brahe and Galileo, and I will give more in a subsequent lecture, reinforce this—the book did become critical to the practice of science. That is part of my earlier claim that writing is a necessary condition for science. The writing is captured in the text. The printed text as we have it in the post-Gutenberg era is an essential ingredient for both science and technology, and quickly became one of the cornerstones of the emergence of modern engineering in the 15th and 16th centuries, and we will look into that in the next lecture.

Lecture Eleven
Renaissance Painting and Techno-Science

Scope:

Mathematical physics was the heart of modern science when it was created in the 17th century, and it remains so. That mathematics is the "language" of the reality behind experience was a Pythagorean teaching in antiquity, but it acquired cultural force in the West during the Renaissance in advance of modern science and at the hands of artists, engineers, and innovators in mapmaking, navigation, and commerce. The rediscovery of central-vanishing-point perspective drawing, for example, was immediately and universally acclaimed as the means to "realistic," truthful representation. The application of abstract mathematics to a wide range of practical problems reinforced the correlation, if not the identification, of mathematics with reality. The origins of modern engineering lie in these applications, again, in advance of modern science. They also stimulated the study of mathematics and the production of original mathematics in Christian Europe for the first time since the decline of the Roman Empire.

Outline

I. The Humanists, promoting their own agenda, introduced the idea of progress into European society, which then linked progress to technological innovation and scientific knowledge; Renaissance artists contributed significantly to the resurrection of the idea of techno-science!

- **A.** The Florentine architect-engineer Filippo Brunelleschi's demonstration circa 1415 of central-vanishing-point (CVP) perspective drawing sparked an almost immediate transformation of European art.
  - **1.** For 1000 years, the pictorial art of Catholic Europe did not exploit perspective drawing.
  - **2.** The technique is referred to in general terms (*skenografia*) in Vitruvius's *On Architecture* as if it were familiar to practitioners, and the frescoes unearthed at Pompeii reveal that it was indeed familiar 100 years later.
  - **3.** Centuries before that, Plato had written critically of the painter Zeuxis, much praised for painting so realistically that birds attempted to eat the grapes he depicted.
  - **4.** Nevertheless, paintings in the Byzantine, Romanesque, and Gothic periods were overtly two-dimensional.
- **B.** It is likely that CVP perspective drawing was deliberately rejected by early medieval artists and later became unfamiliar through disuse rather than from ignorance or incompetence.
  - **1.** Perspective drawing is valuable because it allows the artist to depict things as they appear to the physical eye, as they are "naturally." If the goal of the artist is to represent people, objects, and scenes as we experience them visually, "realistically," then CVP perspective drawing is essential to painting.
  - **2.** If, however, the goal of the artist is to use the content of a painting to arouse in the viewer an ideal intellectual or religious response, in the belief that the ideal is superior to, because more real than, the natural, then CVP perspective drawing is not only *not* valuable, but it is a corruption.
  - **3.** Plato thus criticized the painter Zeuxis for using his talent to fool the eye, which led people to identify the real with the material, and this was certainly the sentiment of medieval Christian painters.
  - **4.** Recall that throughout the Middle or Dark Ages, there was virtually no secular art in Catholic Europe.

5. It follows that medieval artists put no value on naturalism or on individuality/particularity, which is a mark of the material, and thus, they could put no value on CVP perspective drawing even if they knew of it.

C. Brunelleschi seems to have rediscovered CVP perspective on a visit to Rome and demonstrated it on his return to Florence by displaying an experimental painting he made of the baptistry in Florence.

1. Around 1425, Masaccio employed the technique in a masterful series of frescoes that attracted great attention.
2. Shortly thereafter, the painter Piero della Francesca, who was also a mathematician, wrote the first of what would be many handbooks for artists explaining the mathematical technique for foreshortening that underlies CVP perspective and makes "realistic" drawing possible.
3. The triumph of this new technique was so complete that we identify Renaissance painting with its use.

D. To embrace perspective drawing as the only way to "truth" in art is to redefine reality for art.

1. CVP perspective drawing allows the artist to depict three-dimensional objects on a two-dimensional surface such that the eye (the mind, of course) responds to the flat visual representation as it does to the material visual object.
2. We should be astonished by the cultural phenomenon that Brunelleschi's introduction of this technique inaugurated: Within 50 or so years of his experimental painting of the baptistry in Florence, CVP perspective drawing was ubiquitous, adopted by artists and public alike as the *only* way to paint.
3. To value CVP perspective so highly is to value the natural as real, to embrace the corporeal as real, to identify truthfulness with accurate representation of the natural, the material, *and the individual*, overturning 1000 years of aesthetic, philosophical, and religious values.
4. Fifteenth-century Europe remained thoroughly Catholic at one level, but the secularism, naturalism, and individualism that had surfaced in the 12^{th}-century renascence now were revealed to have a much deeper hold in society.
5. One manifestation of this hold was the commissioning even by prominent Church officials of paintings depicting scenes from Greek mythology.
6. Another was the aggressive egotism of Renaissance master artists, documented by Giorgio Vasari.

II. CVP perspective drawing was immediately understood to be a technique of mathematics, which was thereby coupled to 15^{th}-century art and its values.

A. That the power of CVP perspective drawing to "capture" nature was a consequence of following a mathematical formula implied that mathematics was intimately connected to nature.

1. This connection echoes the Pythagorean metaphysics that made mathematical form the essence of material objects and the order of nature.
2. Making mathematics the basis of natural philosophy (knowledge of nature) was part of the curriculum at leading medieval and Renaissance universities.
3. Ptolemy's mathematical astronomical theory was required reading for virtually all students, but the recovery by Humanists of his *Geography* exerted a new influence.
4. The *Geography*, whose original maps were lost, described the world as Ptolemy knew it but also the use of mathematics to represent the three-dimensional surface of the Earth accurately on a two-dimensional surface.

B. Throughout the 16^{th} century, the idea that mathematics captured essential features of the real material-physical world spread in concrete ways.

1. Ptolemy's *Geography*, coming at a time when Europeans were embarking on global voyages of exploration, stimulated the rise of schools of mathematical cartography, one exponent of which was Gerard Mercator, famous for his Mercator projection maps.
2. John Dee was an influential 16th-century British mathematician who taught techniques of mathematical navigation to many British ship pilots sailing to the Americas and Asia.
3. From the 15th century on, rival mathematical theories of musical harmony, based on or deviating from Pythagoras's original insight into tone systems, played a central role in music composition and musical instrument design and performance.
4. Galileo's father, Vincenzo Galileo, wrote two books on this subject, rich with experiments of his own design, and Kepler's greatest work in his own eyes was his 1619 *Harmony of the World*, coupling music and astronomy via mathematics.

C. In the course of the 16th century, practical applications of mathematics reinforced the connection to nature forged in painting and created a pillar of the 17th-century Scientific Revolution.

1. By the end of the 16th century, books of machine designs were an established publication genre, and machine designers adopted and adapted CVP perspective drawing.
2. This had the effect of making the depictions of machines more "realistic" and visually intelligible, but they were also made more intelligible mechanically by including cutaway and exploded drawings of details of the mechanisms.
3. This new capability seems to have stimulated the design of more complex machines, because these could now be depicted convincingly and in a mechanically intelligible way.
4. The engineering version of the mathematics underlying CVP perspective drawings is *orthographic projection*—a two-dimensional representation that allows reconstruction of a complex three-dimensional object from that representation.
5. This capability developed in 16th-century machine illustration and achieved formal expression—another linkage of know-how to knowledge—in projective geometry, co-invented by Girard Desargues and Blaise Pascal circa 1640.
6. A fascinating illustration of the new capabilities of Renaissance engineering is Domenico Fontana's account of his contract to move an ancient Egyptian obelisk weighing more than 700,000 pounds some 260 yards to make way for the construction of St. Peter's Cathedral in the new Vatican.

Essential Reading:

Samuel Y. Edgerton, Jr., *The Heritage of Giotto's Geometry*.

William Barclay Parsons, *Engineers and Engineering in the Renaissance*.

Charles Singleton, *Art, Science, and History in the Renaissance*.

Bertrand Gille, *Engineers of the Renaissance*.

Questions to Consider:

1. What do we mean when we call a calculatedly deceptive simulation of the appearance of the subject of a painting "realistic" and "truthful"?
2. Did the monotheistic religious tradition of the West contribute to the scientific idea of an abstract reality behind concrete experience?

Lecture Eleven—Transcript
Renaissance Painting and Techno-Science

You may have thought it ironic that the humanists, concerned with literary and aesthetic sensibilities, were the ones who introduced the idea of progress into modern Western culture, subsequently incorporated by science and technological innovation. And it is perhaps even more ironic that the renascence, the rebirth of the idea of techno-science after approximately 1,200 years from the Roman period until the 15th century, was largely the work of the great painters of the Renaissance. The great painters of the Renaissance, in retrospect, we see that they exploited a mathematical technique for depicting the content of the painting in a way that was then, and we still consider, naturalistic, realistic.

It was that incorporation of mathematics into the "production," if I may use that expression, of art that was associated with, contributed to the renascence of the idea of techno-science. And it didn't leave after the 16th century with the maturation of this artistic technique, and the other forms in which mathematics became increasingly coupled to technological innovation. That is why the idea of techno-science can be seen to be revived in the Renaissance, and applied. It is manifested in the use of mathematics in order to develop new kinds of technologies.

Now the orthodox art historical view is that somewhere around 1450 the Florentine artist and architect, Filippo Brunelleschi, after a trip to Rome, returned to Florence having rediscovered somehow the technique of central vanishing point perspective drawing. That is a mouthful, but we all know what it means. It means a technique for shortening and the convergence of ostensibly parallel lines in a painting so that the eye is fooled into seeing as a depth on the surface of the canvas. When you look at the surface of the canvas you see the scene depicted inside the painting recede into the background, although of course we know it's right there on the surface of the canvas. The way that you do this is by applying a particular mathematical technique.

Brunelleschi brought that technique back to Florence, as I said, and it was subsequently used in a masterful way by Masaccio in a series of frescoes. It caught on, to put it mildly. It spread at least as rapidly as the spread of the printed book in the second half of the 15th century. This is now happening in the second quarter of the 15th century, roughly speaking from about 1425, which is I think when Masaccio painted those frescoes, until by the end of the century, everybody was painting in this style.

The style is a fundamentally mathematical one. We see this, for example, in the fact that the great artist Piero della Francesca, who was also a mathematician, wrote mathematical treatises, but he also wrote a handbook for artists teaching them the mathematical trick—without meaning anything pejorative by that—of how to paint the content of a painting in a way that causes the viewer to see depth. Not just depth, but to see objects depicted as the physical eye sees objects depicted.

The mathematical basis of this technique was then repeatedly the subject of handbooks throughout the century, notably by Leone Alberti and Luca Pacioli. Pacioli was a great friend of Leonardo da Vinci, who was a master of this technique, but by that time everybody was doing it, and you had to be a master to stand out, because everybody who was painting was painting using this technique. At a certain level the technique is mechanical, especially nowadays with the tools that we have available for looking behind the paint on a canvas to the underlying canvas. We can see the grids of lines that the painters made—it's called pentimento—we can see the grids of lines that the painters first laid down, in which each box of the grid as you go up the canvas becomes foreshortened in a strictly mathematically proportioned way in order to create this effect.

Then, of course, there's the additional point: you have to have a central vanishing point in the painting, a point towards which the lines of the painting converge. Painters displayed their talent in this regard by often making paintings in which there were patterned tile floors, say in a cathedral or in a large room, so that you could see alternate black and white tiles. Now we know that at some level these tiles all have parallel lines on their sides, and yet what gives it the impression of depth is that those ostensibly parallel lines in fact converge on the point that the artist wants to depict the scene from, and that the viewer then responds to, by sort of recreating the depth that the artist saw when he or she set up that scene.

So this technique—there's no argument about this—Renaissance painting means the exploitation of central vanishing point perspective drawing. What's interesting about this from our point of view in this course is that there is a real relationship between the adoption of central vanishing point perspective and the rise of modern science. And in particular to the role that mathematical physics played within modern science. Because what's happening here is we are seeing, not just the dissemination of an artistic technique, what we're seeing is an identification of mathematics with reality, and an identification of reality with the material world, with the natural world.

From writings and from the surviving frescoes at Pompeii, we have a very good idea that in the ancient Greek world, and certainly in the Roman world, artists knew how to draw in this way. Plato—or his mouthpiece, Socrates—even in the passage that I read from earlier in this course, Socrates refers to painting as a simulation of reality. Plato and Socrates were critical of painters who represented scenes in a way that fooled the eye into thinking that they were looking at a real scene. Plato refers to the painter Zeuxis, for example, a contemporary painter who was so talented that he painted a bunch of grapes on a painting and birds dropped down out of the sky and tried to snatch the grapes.

Plato refers to the fact that—well, Socrates in the *Dialogue*—refers to the fact that people praise Zeuxis for this, but Socrates thinks this is really terrible. Fooling people into thinking that what is not real is real is a fundamental crime to a philosopher, because what we really need to understand is the nature of what is ultimately real. And for Plato, as you well know by now, the ultimately real is not natural, cannot be captured in the natural. It is supra-natural; it is these ideal forms. And to be fooled into taking as real material objects, that's just a trick, and it's not a very praiseworthy trick at that.

Vitruvius, in his *Ten Books on Architecture*, refers to scene painting in theaters, for example, and I referred to the discipline called *skenographia*, which seemed to rely on this kind of naturalistic depiction. But then we have concrete evidence from the frescoes that have survived at Pompeii, which was inundated with volcanic ash when Vesuvius erupted in August of 79, that the frescoes, many of which exist in museums today and are certainly available for looking at in books, those frescoes are clearly painted using this kind of naturalistic representation in which the eye sees a depth that, of course, is not there.

So there is a question that has to be raised about why, between let's say around the 2nd and 3rd century and the 15th century when Brunelleschi rediscovered this technique, why it disappeared. What happened? "Well, it just disappeared. People forgot how to do it." That's one response. Another is, and I think a somewhat more plausible one is, that the society—especially we're talking now about the Christian society of Europe in the period from the collapse of the Roman Empire until the Renaissance—like Plato, did not attribute ultimate reality to the natural world. It was not praiseworthy to make paintings that depicted the material world in its materiality.

The rise of central vanishing point perspective, and not just the rise, the immediate and almost total embrace of central vanishing point perspective as truth in art, reflects an identification of the natural with the real, and attributes value to the real. It says, "Now I'm going to show things the way they really are."

In Byzantine painting, in Romanesque painting, in Gothic painting, the surface is flat. There is no attempt to fool the eye into thinking that it is looking at a materially real object. It's to get the mind to respond to the symbolism in the painting and to recognize the religious value, to think thoughts that are associated with religious values. And this is clearly reflected in the fact that the faces of people in these paintings are sort of generic faces, and the landscapes are generic landscapes.

There was no attempt by the painters in the 10th, 11th, 12th, and 13th centuries to capture a specific landscape as you would see it if you went out and stood in the spot where the artist stood, or to depict the people in the painting with their specific individuality. When you identify the real with the natural—that means you're identifying the real with the material—then, as we have seen right from the beginning of this course, we're talking about individuality. The forms are universal but the objects of our experience are all characterized by individuality.

The philosophical tradition thought that the individuality could be glossed over because we want to get behind the individual to the universal that allows us to have knowledge even of the individual. Thus, with Aristotle, for example, we talked about his theory that the mind has the ability to identify the universal within the individual. Then you can forget the individual dog or tree or person and philosophize, develop a science based on the universals that you have abstracted from experience. But when you identify reality with the material world, then individuality becomes a value because that's a sign of the new realism.

And in fact this is the case in Renaissance painting, that it becomes intensely individualized on both sides of the equation. The content becomes individualized, and we see portraits of people who are depicted as they, so to speak, really are, often with their flaws. They're not all made beautiful. They are depicted in their individuality.

Landscapes are painted as if you could actually see that scene. Sometimes they are imaginary landscapes, but they are depicted in a way as if you were looking out a window onto a scene. That, by the way, is why paintings developed frames. The frame of a painting originally was supposed to be a window casement, so that when you looked at a painting you could think that you were looking out the window onto a scene that you could see, because it was the kind of thing that you did see when you looked out a window, setting aside the specifics of the content, of course.

So what we're talking about here is not merely an artistic technique. It is the embrace of the artist, just as it was the embrace of printing with moveable metal type that is the social phenomenon that is of interest to us and that is associated with the power of the book in Western society. So it is the response to this technique that needs to make us step back and we have to respond to that response. The technique per se is much less important than the fact that it was essentially universally embraced, which reflects now—I'm returning to a theme that I introduced when we talked about the 12th century Renascence—the theme of secularism, of attributing value to the secular, the natural, the material.

Depicting fabrics with loving accuracy, depicting silks in rich colors, and the folds of the silk exactly the way fabrics drape over the body became an extraordinary skill. This is the way that artists showed how good they were. Leonardo's mastery of light and shadow, the ability to capture the shape of the human body exactly; when you bend an arm, the wrinkles that form, the way the muscles respond, this is a paean. These paintings are poems of praise to materiality. Interesting, and in fact it should be startling to us.

Many of the great paintings of the Renaissance, most of the great painters of the Renaissance, if not all of them, were subsidized, were commissioned by Church officials. And very often it was routine for these officials to commission paintings with pagan content. Scenes from Greek mythology, for example, are in any museum you go to. If you go to see the Renaissance paintings, you will see religious paintings, but you will also see paintings of Greek mythology, and of course, the individual portraits that we saw.

Now that's on the content side of the equation. There was this intense individualism, individuality to the content, and the technique of central vanishing point perspective drawing enabled that, and there was this embrace of the secular, the natural and the material. Again, I'm not denying that the surrounding culture was faith-based, but within that context we again see this aggressive assertion attributing value to the material. It may seem like a small point, but when you think of how much effort and genius is expended on the depiction of the silk cape wrapped around a cardinal's shoulder in a particular Renaissance painting, then the viewer is not responding, "Oh, what a holy man he is," but, "Wow. It almost feels like you could touch that silk. It's almost as if your eye is caressing the folds of that garment. It's so realistic."

From the other side of the equation, the artist's side of the equation, we see the same kind of individuality. Giorgio Vasari, in his very famous and influential *Lives of the Famous Painters, Sculptors and Architects*, Vasari starts off by saying something really incredible has happened to art in our time (in the 15th century), and that is that artists all of a sudden became what I'm going to call egomaniacs. They wanted fame.

In the past artists made great religious paintings and sculptures, and nobody knows who did it. Nobody knows who built the Gothic cathedrals, for example, by and large. And certainly many of the great paintings of the Romanesque and Gothic period that have survived are simply called the Master of X, the master of this painting, the master of that painting. They're not signed. But when you get to the Renaissance the painters want everyone to know, "I painted this painting."

Michelangelo was obsessed with getting credit for his paintings and sculptures. He was not a painter; he was an artist. Michelangelo is expressing here this same attribution of value to the individual. That has subsequent political consequences, but what we're concerned about here primarily is the identification of the real with the nature, and the identification of mathematics as the means by which the natural, the real, can be captured. The natural is the real. Mathematics captures the natural. Mathematics captures the real. Mathematics is the language of reality.

That just seems to be putting a very heavy burden on painting. After all, that doesn't seem like a vehicle that can carry that particular burden. But if that were the only case, then it would be very hard to argue, but as a matter of fact, contemporaneously reinforced by the legacy of the medieval university curriculum at the University of Oxford and the University of Paris and the University of Padua, especially the idea of applying mathematics to the study of natural phenomena, that was part of the legacy of the educated 15th and 16th century person. But there were the humanists that were feeding in texts of Vitruvius, and not just Ptolemy's astronomy, which everybody knew about, had known about before, but now they had rediscovered Ptolemy's geography.

Now, Ptolemy's geography, which had been unavailable for over 1,000 years, Ptolemy's geography had a profound influence, because in that book not only do we see that the Romans had what are described in the book (because they didn't survive) detailed maps of the world extending from England to India, but Ptolemy describes in there how to depict on a two-dimensional map the three-dimensional surface of the earth in a way that preserves the spatial relationships. So that when you look at the relationship between London and Rome on the flat map, it reflects the actual relationship of London and Rome on the surface of the earth, which of course is a sphere, as I mentioned before, everybody knew.

So that is an interesting technical problem. How do you depict accurately on a two-dimensional surface—a flat map—how do you depict three-dimensional spatial relationships? That, too, turns out to be a mathematical technique. And in the 16th century, as Ptolemy's geography book was disseminated, and for the Portuguese voyages of discovery, subsequently the Spanish and the British voyages of discovery, and the French and Italian in the early 16th century, people needed better maps. And they needed maps of areas that nobody knew about before. So mathematical cartography became a cottage industry in the 16th century.

The most famous illustration of that for us, the one that we tend to be most familiar with, is the map of Gerardus Mercator. The Mercator projection is an adaptation of Ptolemy's technique for depicting the curved surface of the earth, three-dimensional, accurately on a two-dimensional surface. Now, it turns out there's no one projection that will satisfy everybody's needs. In a Mercator projection, of course, you essentially flattened out the globe in a certain way so at the poles the relationships on the map bear no connection to the relationships on the surface of the earth; but for the latitudes that are most important to human beings who are traveling, so between roughly speaking the Arctic Circle and the Antarctic Circle, those are pretty accurate.

And so Mercator's projection became one of the standard projections for navigators, for people who were traveling, and especially traveling by sea. So mathematical cartography was another illustration of how mathematics is capturing reality. Now, Mercator tried to keep his technique a secret, but eventually it leaked out, and the technique of doing this in a kind of a simple way, of depicting the surface of a sphere on a two-dimensional surface was developed in the early 17th century, was published in the early 17th century in England. That sort of took the whole trick away, and then anyone could make such a map.

Mathematical cartography goes together with mathematical navigation. We're sailing all over the world now. The first round-the-world voyage was around 1522 by Ferdinand Magellan. Now, when you're sailing in the open ocean you're not sailing along the coastline as before the centrally-mounted stern rudder was introduced. When you're sailing in the open ocean you need navigational tools, and the navigational tools are mathematical. They're derived from astronomy.

In fact, the great 16th century British or English voyagers of discovery, the pilots of those ships were all trained—well, many of them were trained—by a man named John Dee, who was one of these Renaissance humanists, but who subscribed to the sort of magical tradition. He was one of the leading mathematicians in England at the time. He was responsible for the first English translation of Euclid's geometry. It was paid for by a businessman named Henry Billingsley, but Dee was the guy who actually did it, and Dee also designed machines for theatrical performances along the lines of the ancient Greeks. He recovered that knowledge described in Hero's *Pneumatica*, and other books by Hero of Alexandria that I mentioned in an earlier lecture, and designed such machines. Dee trained, was known to the Crown and was hired to train navigators, pilots, to use the techniques of mathematical navigation.

Concurrently, there is a revival of mathematical music theory in the 15th, 16th, and 17th centuries. So to the extent that we now have during the Renaissance period a revival of this Pythagorean notion, that music and the mathematical structure of music somehow reveal the secret structure of nature and ultimately of the universe (and that is a very real theme in Renaissance and early modern thought) then the revival of mathematical musical theory—I mentioned, for example, Galileo's father Vincenzo—was centrally involved in these controversies which were raging at the time. Almost everybody who was anybody intellectually and scientifically and mathematically had something to say on this subject.

Kepler's greatest book in his own eyes was his *Harmonies of the World* of 1619, which explicitly tries to actually compose the musical chords that are sounded by the planets, given their mathematically correct relationships. So this was another way in which mathematics—borderline magical, mystical—another way in which mathematics was perceived to be connected to reality.

Concurrently there was, I believe stimulated by central vanishing point perspective drawing, a renaissance of machine design books. Remember in antiquity—I referred to the fact—that from about the 3rd century B.C.E. until about the 3rd century C.E., there was a flurry of books by people like Ctesibius and Philo of Alexandria and Strato of Lampsacus (who was associated with a book that used to be attributed to Aristotle), and Archimedes, Vitruvius, Frontinus's book on the aqueducts of Rome, Hero of Alexandria's machine design book (the *Pneumatica*, that I read the opening paragraph from), and Pappus's book sort of summarizing the machine design books of his predecessors. There was a flurry of these machine design books, and then that particular genre sort of disappeared.

In the 15th and 16th centuries machine design books, now using the new techniques of central vanishing point perspective, became popular again. And people that we would now call predecessors of modern engineers, or early modern engineers, if you like—people like Agostino Ramelli and Mariano Taccola and Domenico Fontana—published books of machines with exploded and cut-away views so that you could actually, if you were a mechanic, you could take that drawing and make a copy of that machine, because you could now see the machine in its three-dimensionality.

This application of central vanishing point perspective drawing to engineering quickly became formalized mathematically. The idea that this is a mathematical technique that engineers and mechanics need in order to build the more complicated machines that technology was capable of allowing people to build, became formalized as early as 1629 in what's called projective geometry, a mathematical theory of the depiction of three-dimensional objects so that the complexity of a three-dimensional object can be depicted in a series of two-dimensional drawings. What we roughly mean by engineering drawing.

Blaise Pascal and another Frenchman named Girard published books that gave the mathematical theory, so to speak, of engineering drawing. And from then on that's what guided engineering drawing; but that emerges out of the application of the central vanishing point perspective technique to designing machines. And then you could invent all kinds of machines in your head. Some of them maybe could be built, some not. Look at Leonardo. I mean, Leonardo's notebooks are filled with imaginary machines, almost none of which were ever built—effectively none of which were built. Some of them would work; some of them wouldn't work. The fact is, nobody knew about them at the time.

So this was another area in which mathematics became coupled to physically real things. You can't get much more real than machines that work in the society in which you live. I mentioned Domenico Fontana, for example. Domenico Fontana was given the contract to move—one of the greatest construction projects in Europe of all time was the creation of the Vatican and St. Peter's Cathedral, so one of the things that got in the way of building the Cathedral was a gigantic obelisk that the Roman emperors had shipped from Egypt where it had been erected in approximately 900 B.C.E. It weighs over 700,000 pounds. They had it shipped to Rome and the Emperor Caligula had it put up in Rome, and there it stood. But now it was in the way of St. Peter's Cathedral, so it had to be moved. It had to be moved approximately 260 yards, so let's call it 800 feet. But it weighs 737,000 pounds, approximately.

So Domenico Fontana got the contract to do this, and he did it using a series of machines that he adapted to this purpose, and without a knowledge of mathematics this could not have been done. And we know from the book that he wrote describing this whole process how carefully he made his calculations, which involved in the end over 900 men and 40 windlasses pulled by it seems approximately four horses per windlass. This had to be coordinated precisely, because that obelisk, if it breaks, there's no second chance.

So to summarize, what we see initiated by Renaissance artists with the recovery of central vanishing point perspective drawing, by the response of the society, by painters and the society, the values that they placed on this depiction of nature as the real, we see the introduction of an identification with mathematics with reality that flourishes, that becomes a foundation of modern science in the 17th century.

Lecture Twelve
Copernicus Moves the Earth

Scope:

The idea that the Earth is motionless at the center of a large but finite Universe that revolves around the Earth matches our commonsense experience of the motions of the Sun, Moon, planets, and "fixed" stars. By contrast, we have no sensation whatsoever of any motion of the Earth. Furthermore, that the Earth is the center of the Universe fits very well with religious and mystical philosophical teachings that the Universe was created for the sake of mankind and that human beings play a central role in a cosmic drama of creation and salvation/ damnation. Ptolemy's mathematical model of such an Earth-centered Universe thus anchored a conception of the Universe as both manifestly and anthropocentrically ordered. Copernicus's theory, in addition to violating common sense by attributing multiple concurrent motions to the Earth, undermined the anthropocentricity of the cosmic order and, ultimately, the manifest orderliness of the cosmos itself.

Outline

I. Copernicus did not just disturb the Renaissance Universe, but he redefined it, and after 150 years, his new definition stuck but only for 200 years.

- **A.** The Renaissance Universe incorporated two overlapping but distinctive lines of thought, one astronomical, the other religio-metaphysical.
  1. The most vivid expression of the latter was Dante's epic poem subsequently named *The Divine Comedy*.
  2. Literally, the poem recounts a descent into hell within the Earth, followed by an ascent from the Earth through the physical heavens to the abode of the saints in God's presence.
  3. Throughout, Dante displays a sophisticated grasp of contemporary astronomical theory, which he used selectively for poetic effect, but what is most important about the astronomy in the poem is the symbolism.
  4. Symbolically, the surface of the Earth, on which the human drama is played out, is poised midway between hell and heaven.
  5. The descent into hell is the mirror image of the ascent to heaven, which emphasizes the idea that the ultimate order of the cosmos is centered on mankind and his spiritual destiny.
- **B.** Parallel to Dante's religious-symbolic expression of the centrality of the Earth in the Universe, there was the dominant "professional" Earth-centered astronomical theory: Ptolemy's.
  1. Ptolemy's theory reigned for some 1,400 years, but he never intended it to be understood as physically real or physically true.
  2. His theory was strictly mathematical, its purpose to deduce the observed but merely apparent motions of the Sun, Moon, and planets from their real motions.
  3. These "real" motions had to satisfy Pythagoras's criteria, which on mathematical-metaphysical grounds, required that heavenly bodies move only in circular orbits at uniform speeds.
  4. Ptolemy's model is extremely complicated, but it works quite well for naked-eye observations.
  5. That is, using his theory, one can calculate in advance where each planet will be in the night sky as a function of time with an accuracy of about 1/6 of a degree.
  6. Note well: The order of the Universe for theoretical astronomers is mathematical, hence, accessible only to the trained mind, visible only to the mind's "eye."

7. The Universe visible to the body's eye is only apparently orderly but in fact is confused, misleading, and disorderly.

II. This was the Universe that Nicolaus Copernicus inherited, then transformed.

A. Copernicus was theologically orthodox but intellectually radical.

1. Copernicus was a university-trained Polish Catholic priest who then spent years studying in Humanist Renaissance Italy before returning to Poland and a career in the Church.
2. Reading Archimedes, he found a reference to an idea of Aristarchus of Samos that the Sun was the center of the cosmos and the Earth just another planet (an idea treated dismissively by Archimedes!).
3. Some ancient, some Islamic, and some late-medieval Christian writers referred to this or similar ideas, but no one had acted on them: Copernicus did.
4. Copernicus devoted himself to astronomy and, by 1512, was committed to working out a theory in which the Sun was stationary at the (near-)center of the Universe, while the Earth moved around it on a circular path at a uniform speed, as Pythagoras's mathematical metaphysics required.

B. The practical motivation for such a theory, quite apart from the philosophical motivation, was calendrical.

1. Calculating in advance the positions of the planets in the night sky served important "industries": almanacs for farmers, travelers, and sailors; and charts for both astrologers and astronomers.
2. A byproduct of these calculations was more accurate determination of the length of the solar year, which was of great importance to the Catholic Church in setting the date of Easter.
3. Copernicus enjoyed a growing reputation as an astronomer when the Church was forced to recognize that Julius Caesar's calendar reform of 46 B.C.E. caused Easter to come far too early.
4. A papal commission was appointed that led to the Gregorian calendar reform implemented in Catholic countries beginning in 1582, later in Protestant countries, and still not completely by Russian Orthodox communities even today.

C. In 1543, the year he died, Copernicus finally published his theory in his great work *On the Revolutions of the Heavenly Spheres*.

1. He was goaded into publishing by a young astronomer named Rheticus, who learned of Copernicus's radical new theory and came to him to learn it.
2. This book works out in full mathematical detail an alternative to Ptolemy's theory, one in which the Earth moves around the Sun.

D. Although Copernicus is universally hailed as the founder of modern astronomy and, in a sense, he was, his theory of the Universe and even of (what we call) the Solar System is completely wrong.

1. First of all, he had virtually no observational data that had not been available to Ptolemy or that could not have fit perfectly into Ptolemy's theory.
2. Thus, Copernicus's theory is an alternative interpretation of the same data available to Ptolemy's theory: The data do not distinguish between the two theories.
3. Second, the planets do not move in circular orbits or at uniform speeds.
4. Third, there is no pre-telescopic observational evidence to support the claim that the Earth moves around its own axis in 24 hours or around the Sun in a year. On the contrary, observational evidence works against the theory.
5. Finally, because he accepted circular orbits and uniform speeds and had to place the Sun slightly off-center, Copernicus, like Ptolemy, had to use epicycles. For this reason, his theory is almost as complicated to use for calendrical calculations as Ptolemy's and no more accurate: both are off by about 10 minutes of arc.

III. Copernicus, almost certainly unintentionally, instigated a cultural revolution at the metaphysical level, as well as an astronomical revolution.

- **A.** Unlike Ptolemy, Copernicus insisted that his theory was physically real.
  - **1.** Copernicus's book appeared with a preface describing his theory as mathematical only. Ostensibly, this preface was by Copernicus, but in fact, it was written by a Protestant editor seeking to protect Copernicus from a charge of heresy.
  - **2.** The assertion that the theory was mathematical only would allow for the Earth "really" to be stationary, the position the Church insisted was mandated by the Bible.
  - **3.** But Copernicus's text does not support that reading, and subsequent Copernicans, such as Kepler and Galileo, took the theory to be intended as a mathematical expression of physical truth.
- **B.** In spite of being wrong from the perspective of the subsequent history of science, Copernicus's theory occasioned a re-conception of the Universe and the Earth's place in the Universe.
  - **1.** Again using Lynn White's phrase, Copernicus opened a door for Western intellectuals, who were so anxious to get through it that they modified the theory freely.
  - **2.** Where Copernicus thought that the Universe was compact, prominent Copernicans proclaimed it to be infinite.
  - **3.** The symbolic significance of removing the Earth from the center of the Universe is profound but becomes still more profound if the Universe is infinite.
  - **4.** Many professional astronomers used and taught Copernicus's theory, thus disseminating his ideas, but withheld support for its physical truth.
  - **5.** Kepler abandoned circular orbits and uniform speeds, which made the orderliness of the Universe still more abstract and intellectual than in Pythagoras's original version.
- **C.** Kepler and Galileo were the leading champions of Copernicus's theory, which remained a minority view until Newton's *Principia Mathematica*.
  - **1.** Kepler fundamentally altered Copernicus's theory, introducing forces that bound the planets to the Sun and caused them to rotate as they did, but he still considered himself to be a follower of Copernicus.
  - **2.** Tycho Brahe rejected Copernicus's moving Earth and developed a theory of his own that was preferred by many if not most educated people well into the 17th century.
  - **3.** Kepler worked as Brahe's assistant, ostensibly to work out the mathematics of Brahe's theory but, in reality, to get access to Brahe's new observational data.
  - **4.** Using instruments of his own design, Brahe compiled the most accurate planetary position observations ever made. When Brahe died, Kepler seized the data and used them to support his own version of Copernicus's theory.
  - **5.** Galileo was an "orthodox" Copernican, rejecting Kepler's modifications (which turned out to be correct!) and Brahe's theory, even though it fit his telescopic observations as well as Copernicus's.

Essential Reading:

Nicolaus Copernicus, *On the Revolution of the Heavenly Spheres*, book 1.

Thomas Kuhn, *The Copernican Revolution: Planetary Astronomy in the History of Western Thought*.

Questions to Consider:

1. What are the implications for scientific theories of the fact that Copernicus based his theory of the heavens on essentially the same facts Ptolemy used?

2. In the absence of any empirical evidence whatsoever for the Earth's motion, either on its axis or around the Sun, why did anyone adopt Copernicus's theory?

Lecture Twelve—Transcript
Copernicus Moves the Earth

The subject of this lecture is the reconceptualization of the universe that took place in the 16th and 17th centuries with Copernicus's theory of a moving earth and its verification, if we can use that term, by Isaac Newton in 1687 in his *Mathematical Principles of Natural Philosophy,* which contained his universal theory of gravity, from which it is a logical consequence that the planets move in elliptical orbits around the sun.

Now, this is, in a sense, finally a solidly scientific idea, and in a certain sense it begins to bring us within the framework of modern science. Although Copernicus's theory as it stood in 1543 when he published it in a full book-length version, was well developed, it really is not a very modern scientific theory, and I hope that we'll get to see that as well.

But let's understand what the universe was that the Renaissance inherited—what conception of the universe there was at the time that Copernicus did his astronomical theorizing. There were really two notions of the universe that were extant.

There was a kind of religious metaphysical view of the universe, which is beautifully described by Dante in his *Divine Comedy*. *The Divine Comedy* is composed of three books: Dante's descent into *Hell,* guided by the Roman poet; and then his ascent from the very depths of Hell to *Purgatory* first, at which the Roman poet drops off; and then his ascent to *Heaven,* which is guided by the woman that he adored, platonically, Beatrice. And as he ascends to Heaven he ascends through the concentric spheres of the planets and the fixed stars, giving us a brilliant and quite accurate poetic account of this sort of religious metaphysical conception of the earth as at the center of the universe with God's Heaven on the periphery, God beyond that Heaven. And as we ascend we go to the moon, to the sun, to Mercury, to Venus, to Mars, to Jupiter, to Saturn (the only planets known at that time), to the sphere of the fixed stars, and then to the Empyrean, to sort of the inner surface of God's presence where Dante has this vision of the mystical rose, of all of the saved souls that are singing praises to God. God's presence is signified at the very end of the poem by an incredibly bright spark of light, a minute opening through which this incredible effulgence of light takes place. And then Dante wakes up back in the world.

This is, I believe, a brilliant poetical, and also astronomical (Dante knew his astronomy) depiction of the earth as the center of the universe created by God, and in which the earth is the location of a cosmic drama. It is the drama of human beings living out their existence as souls contained within bodies and having to identify their real being with their souls, in which case they ascend to Heaven, or identifying with materiality, with their bodies, in which case they get dragged down into Hell.

And in the first book, *The Inferno,* the descent into Hell is the mirror image of the ascent into Heaven. The concentric spheres of Hell through which Dante descends, in which the sinners become increasingly sinful, until at the very center of the earth, which is also the center of hell, you have the absolute frozen waste in which the worst sinners and the devil are contained.

So this is one view of the universe that was extant in the Renaissance, and it captured a kind of a, let's call it a simplistic cosmology that existed from the Pythagoreans on, which was simply that the earth is the center of the universe and the planets and the stars move around the earth in concentric spheres.

Now, there was also a conception of the universe which was astronomical; namely, Ptolemy's theory, which was a mathematical theory that allowed you to say that behind the appearance of the earth being the center of the universe and the sun, the planets and the stars moving around the earth at uniform speeds in circular orbits, how you can possibly have that appearance of what we see, given let's call it the mathematical reality behind the appearances. Because the appearances when looked at closely don't support the idea of uniform motion in circular orbits, so we need to understand how can that happen, and give the appearances, even though really what's happening is that the planets and the stars move at a uniform speed in circular orbits. This is the mantra of astronomy for 2,000 years. Uniform speeds, circular orbits—does it look that way? How can we account for it?

Meanwhile, sort of religiously, metaphysically, we think that all that matters is the earth is at the center, and that's because we're special. We are the products of the creator God, and for some reason or other God has created us in order to live out this drama of choosing spirit over flesh.

From an astronomical point of view, what's important is trying to understand how those appearances can be generated given that the ultimate reality is this mathematically inspired one that I attributed to the Pythagoreans of the circular orbits at uniform speeds. Ptolemy did that, but as he himself points out, his model is mathematical; it is not physical. His model, which is incredibly complicated and which uses epicycles in various complicated patterns in order to generate the actual appearances of the planets moving across the night sky. The epicycle is a little circle whose center moves on the circumference of a larger circle. If you play around with the number of epicycles and the relative sizes of the epicycle as a small circle and the big circle, then you can actually get a pretty accurate—empirically accurate—model of how the planets move across the sky, including how the planet continues to move in one direction, but some planets look like they're moving backwards at certain times, the so-called retrograde motion of the outer planets: Mars, Jupiter, and Saturn.

So Ptolemy's model was a mathematical model. Ptolemy never claimed that it was physically real, and in fact, it doesn't really make any sense. It's not possible for it to be physically real; it's mathematical, it's ideal. The mind can appreciate it, but it has nothing to do with matter.

So in the 16th century when Copernicus was doing his astronomizing, this was the inherited universe: relatively compact, centered on the earth. The orderliness of the universe is a mathematical order; physically it doesn't look as orderly as it is. The order is mathematical, and it is keyed to humans being on earth.

Along comes Copernicus. Copernicus is a Polish priest, definitely not a radical, an orthodox person (not Greek Orthodox—he's a Catholic priest; but orthodox in the sense he's very traditional). He has a university degree, studying at Krakow, and he goes to Italy where he spends years studying; called back to Poland by an uncle who's a higher church official. He goes back to Italy again because he really loves it in Italy, and studies medicine, and studies literature, becomes adept at Greek, translates some Greek poetry into Latin, and becomes involved in Ptolemaic astronomy. And in the course of his studies in mathematics and astronomy, discovers in Archimedes's book, *The Sand-Reckoner*, that Aristarchus of Samos approximately 700 years before had speculated that maybe the earth is just another planet and the sun is the center of what we call the solar system, and that the earth circles the sun, and the sun does not circle the earth.

That idea is referred to and dismissed by Archimedes in that particular work, but Copernicus said that that's where he first heard of this idea. It's fascinating that we have no really solid basis for saying that anyone else in the 2,000 years between Pythagoras and Copernicus had thought of this or offered it as a hypothesis. There are some suggestive passages in some late medieval writers, especially Nicole Oresme at the University of Paris and some Islamic writers, but no real proposal.

Copernicus himself became known as being knowledgeable in astronomy, and was even approached to be a member of the commission that the papacy formed in the 16th century to reform the calendar—very important to the Church, because Easter has to come out at a particular time; it has to come out in the springtime. It has to actually come out after the first full moon after the onset of spring (what we would consider March 21st). And because the Julian calendar—the calendar that Julius Caesar was responsible for having implemented in Rome, and which was still being used in the 16th century in Europe—defines the year as 365 ¼ days, by the 16th century there had been an accumulated error of 10 days because that's not an accurate figure. So what happened was that Easter was coming out earlier and earlier, and if they don't do anything about it, pretty soon Easter's not going to be in the springtime at all, which is clearly contrary to the Biblical story, because Easter has to come out after the onset of Passover, which is required to be in the springtime.

So the Pope forms a commission, and eventually, in 1582, the Pope pronounces that the day after October 4th in 1582 will be October 15th—not October 5th, 6th, 7th, 8th, 9th, 10th, 11th, 12th, 13th, 14th, and if you paid rent for the month of October, tough on you, because the next day after the 4th is going to be the 15th. And that became the Gregorian Calendar Reform, which is key to the idea that the year is not 365 ¼ days long, but 365 days, 5 hours, 48 minutes, and 20 seconds. That was the definition that the astronomers of the day recommended to the Pope based on the latest observations and measurements that they were able to make in the mid-16th century.

This calendar adjustment, by the way, was adopted in all the Catholic countries almost immediately because the Pope said so. The Protestant countries did not adopt this mostly until the 18th century. In Germany, for example, it was not fully adopted by the Protestant communities in Germany until 1775. Russia, being under the sway of the Russian Orthodox Church, the Orthodox Church has never accepted this, and still doesn't accept the Gregorian Calendar Reform, but in Russia the reform was only implemented when the Communists took power in 1917, and at that time the discrepancy was about 13 or 14 days. So what they call the October Revolution was November everywhere else in the world.

So Copernicus was recognized as an astronomer of note in the 16th century, but he was sort of a theoretical astronomer. He was not noted for being an observational astronomer, and in 1512 he circulated to a limited degree, only among a very closed circle, an initial version of, "Here's an idea worth considering—that the earth moves around the sun." And what would follow from that?

Now, over the next 30 years approximately, Copernicus had lots of things to do as a church official in Eastern Poland. He was approached, however, late in his life by a young astronomer named Rheticus who really urged Copernicus to complete his detailed account of his new theory. In 1543, the very year in which Copernicus died—we have no idea whether he saw the book before he died—with the assistance of Rheticus (mainly as a goad), Copernicus published a book that worked out in tremendous detail a mathematical model of the heavens in which the sun is stationary (so it's a heliostatic theory) and in which the earth and all the other planets move around the sun in circular orbits at uniform speeds.

Now, we don't need to say that this was a big deal. It is, however, important to step back and realize that, first of all, Copernicus did not have any evidence for this theory. He did not have any observations that had not been available 1,000 years before, had not been available to Ptolemy 1,300 years before. It's not that new evidence suggests that we need a new theory. This is a reinterpretation of existing evidence.

Secondly, Copernicus is quite wrong. The theory is quite wrong in the sense that the planets do not move in circular orbits and they do not move in uniform speeds. Furthermore, there is no supporting evidence once you hear this hypothesis to say, "Oh, let's go test it." Any attempt to test Copernicus's theory in the 16th century was doomed to failure, and in fact failed, because the earth does not seem to be rotating at its axis 1,000 miles an hour. It's easy to make fun of this, right? Birds don't get blown backwards when they fly up into the air. But if he's right and the earth rotates on its axis once every 24 hours approximately, and the earth is approximately 25,000 miles in circumference, then at the equator the earth is moving 1,000 miles an hour. That's a heck of a wind. Not there.

If the earth is really moving around the sun—and while they didn't know exactly how far the earth was from the sun, it's a substantial distance—then in December and in June there's a very wide let's call it a baseline between the earth's position relative to the sun in December and six months later, and so if you looked at stars in the night sky, two stars that seem to be in a straight line in June should not be in a straight line in December. That's called parallactic displacement. They should no longer be in a straight line, because the angle at which you are viewing them has changed dramatically.

And yet we don't see such a displacement. So in fact the obvious experimental tests of Copernicus's theory are wrong. And furthermore, Copernicus made no attempt to say, "Well, what forces are responsible for the motions of the planets? Why are the planets in the positions that they are in, and why are they moving at the speeds with which they are moving?" This is a completely kinematic description. It's merely a description. It is a model.

Furthermore, since he was wrong about circular orbits and uniform motion, then his detailed version of the theory had to be dramatically complicated in order to do the same thing that Ptolemy had had to do. How do the planets actually move in order to generate the appearances that we see, which are not uniform, not circular? So he's got to use epicycles also. So the first book makes it sound like we can finally get out from under Ptolemy's model, and here we have a theory that has almost as many epicycles—it has fewer, but it still has a lot of epicycles. And the calculations are complicated, and in fact they are not significantly, and according to some, they are no more accurate predictively than Ptolemy's. They are accurate within several minutes of arc, but not any better accuracy. Some easier calculation.

But—and here's where you might say again, "Well, history is illogical; human beings are illogical"—Copernicus's theory in some sense precipitated a reconceptualization of the universe. For one thing, in spite of a preface that was added to the book, apparently by a Protestant sympathizer of Copernicus's who didn't want him to get into trouble, and at the printing press put in a preface saying, "This is merely a mathematical model," Copernicus himself clearly believed and said that he believed that this was the physical model of what we will call the heavens—what we call the solar system—that the earth really does move around the sun, and that all of the planets move around the sun. And the sun is slightly off center, but the center of the universe is the center of the earth's orbit.

This was substantially metaphysically and somewhat religiously motivated, but it was not in the end from what we would recognize as a scientifically proposed theory. If you take it as such a theory, then it's easy to say that no person who considered themselves to be scientifically sophisticated in the 16th century should have paid any attention to this theory, because every attempt to confirm it, to test it experimentally, failed.

But the cultural response over the next century or so was that indeed Copernicus had opened the door to a new conception of what the universe was; because very quickly after Copernicus, the people who considered themselves Copernicans dramatically transformed Copernicus's theory. Some of the Copernicans, for example, including most notably Giordano Bruno, who was executed in 1600 as a heretic, Giordano Bruno argued that the universe was infinite.

Copernicus didn't think that. Copernicus thought that the universe was larger, in terms of miles in diameter, than it was thought to be by the Greeks in order to explain why you don't see this parallactic displacement. But he thought that all of the fixed stars were in a kind of a thin band a couple of Polish miles in diameter (that was a measure of the day), and so they were all about the same distance from the earth, and far enough away so that the radius of the earth's orbit was like a point. The whole radius of the earth's orbit was like a geometric point compared to the size of the universe.

These Copernicans, among them Bruno, argued that the universe was, in fact, infinite, and that there were an infinite number of stars, and that there may be an infinite number of planets—many of them inhabited, who knows? Now that changes the orderliness of the universe completely. Copernicus's universe is still strictly ordered. Okay, the order is not the obvious one, because the obvious one is that the earth is stationary. Now the order is much more abstract, but it's an orderly, highly structured universe, but the earth has been snatched out of its central role.

The centrality of the earth is now metaphysical and conceptual. The center of the earth's orbit is the center of the universe. The sun is a little bit off to the side to account for the non-circularity of the planetary orbits. Nevertheless, it's reasonably close to the Ptolemaic, although I believe that conceptually this is a major shift because now the earth's centrality in the cosmic drama of the Judeo-Christian tradition is no longer obvious. You can believe in it, but it is not manifested by the visible structure of the universe as conceived in the Renaissance cosmology before Copernicus.

The Copernicans, however, by making the universe infinite, by making the number of stars and planets infinite, totally changed the concept of the orderliness of the universe. That was one response to Copernicus. The professional astronomers read the book, taught the theory sometimes. Johannes Kepler was taught Copernicus's theory at the university by his teacher of astronomy, Michael Maestlin, but Maestlin to the end of his life did not agree that the Copernican theory was true even though Kepler kept him up to date on everything that Kepler was doing.

Other professional astronomers used the Copernican system without claiming that it was true in order to produce more accurate tables of planetary and star positions in the night sky to be used in almanacs, also very useful for navigational purposes by sailors. The so-called Prutenic tables generated by an astronomer named Erasmus Reinhold openly and explicitly used Copernicus. The book was originally approved by the Pope at the time, and so there was no conception at the time that this was heretical or threatening.

Kepler transformed the theory. Kepler considered himself to be a loyal Copernican. He always depicted himself as a Copernican. In fact, one of his late books is called *Epitome of the Copernican Astronomy*, but what you find in that book is Keplerian astronomy, because over a period of decades what Kepler worked out using data that had been made available to him by the great Danish observational astronomer, Tycho Brahe, Kepler worked out that the planets move in elliptical orbits at non-uniform speeds. And furthermore, Kepler developed a conception of the solar system mainly as a system of forces centered in the sun that caused the planets to occupy the orbital positions that they did, and to move with the speeds that they did.

Now, using some of the new scientific discoveries of the time—for example, that the sun rotates on its axis; based on the observation of sunspots and how they move, it was decided that the sun rotates on its axis—he thought that somehow the sun had a gravitational force that kept each planet in its orbital distance. And that as the sun rotated, then it radiated a gravitational force that whipped the planets around in their orbits, and the reason why the planets moved faster the closer they were to the sun, slower the further away, is because this gravitational force, these whips, were weaker and weaker as you got away from the sun in inverse proportion to the distance.

Now, this is incorrect, but it reflected the latest thinking of the time, which was that magnetic spherical bodies, like the earth, automatically rotated. Any spherical magnet would rotate on its axis, it was decided by William Gilbert, who published a book on the subject in 1600. And so Kepler thought that if you put Gilbert together with the sunspots, the sun rotates on its axis, radiates magnetic lines of force—as we came to say in the 19th century—and they somehow pushed the planets around.

Isaac Newton, later in that century, then, based on his idea of a universal law of gravity, or a universal law of universal gravity, showed that as a matter of fact, that law of gravitation implies as a deductive logical consequence that planets have to move in elliptical orbits at the non-uniform speeds that Kepler had already identified. So in a certain sense Newton validated Kepler's transformation of Copernicus's theory.

Where's Galileo in this story? Galileo was a truly orthodox Copernican. That is to say, in spite of some correspondence with Kepler, being quite familiar with what Kepler was doing—we look back at Kepler and say Kepler proved that the planets moved in elliptical orbits at non-uniform speeds. Nonsense. Galileo in his great work, *The Dialogue Concerning the Two Great World Systems*, the one that got him into so much trouble, is an orthodox Copernican. There is no evidence whatsoever that he ever accepted elliptical orbits or the non-uniform speeds.

Galileo was a strictly orthodox Copernican and was only interested in the conceptual shift to a moving earth, an earth that now is just one of the planets. And if there's anything special about the earth, then that's something that you believe with regard to religious teachings, but that specialness is not manifested to an observer flying by who takes a look at the solar system. That observer would not see anything particularly special about the earth. We say, "Oh, yes. Today it's blue and green and none of the other planets are." But it's not sacred. It does not occupy a sacred spot.

And what about Tycho Brahe? What happened to him? I've referred to him several times now as perhaps the greatest observational astronomer of all time. Well, we don't have time to go into Tycho's personal life—and it was extraordinarily fascinating, combining some noble features and many, many ignoble ones—but Brahe was quite familiar with Copernicus's theory and rejected it, and was a careful enough observer, generating the most accurate observations of the planetary positions as a function of time in the night sky, to see that the Copernican predictions were just as bad as the Ptolemaic ones. So why should he accept the theory?

In a certain sense, Brahe was the scientist. He's said, "Where's the meat? Where are the facts that support the theory?" And the facts are not there. So he offered an alternative theory, which almost never is referred to in popular books about science, like when you get a paragraph in the history of science in high school science or college science; but Brahe's theory, until Newton, was the one that was considered most probable by people knowledgeable about astronomy.

Brahe's theory was that the earth is indeed the center of the solar system, and is motionless at the center of the solar system. The sun does indeed rotate around the earth. Mercury and Venus orbit around the sun as it orbits around the earth, the way, for example, our moon, from a Copernican perspective, the moon orbits the earth as the earth orbits the sun, so Mercury and Venus orbit the sun as the sun orbits the earth, and that explains the peculiar phenomenon that Mercury and Venus always seem to be close to the sun in rising and setting. And then Mars, Jupiter, and Saturn orbit around the sun as they orbit around the earth. Their orbits enclose the sun even as they are really orbiting around the earth. And what Brahe argued, and he's quite correct, is that this is observationally indistinguishable from Copernicus's theory, and doesn't suffer from the flaws that Copernicus's theory had.

At the end of his life, Kepler, who was desperate for data because he wanted to prove Copernicus was right, joined Brahe's entourage in order to get access to Brahe's data. Brahe wanted Kepler, saw that Kepler was brilliant enough to pull off proving the truth of Brahe's theory, and when Brahe died before any of this happened, Kepler snatched the data and ran for it. Eventually by analyzing that data—an excruciatingly tedious process in those days without calculators or without even slide rules (which were being invented at the time, but Kepler didn't have one; no calculator, although he got one later in his life, he was sent one later in his life), having to work out thousands and thousands of trigonometric calculations—Kepler came to the conclusion that the planetary orbits are not circular, they're elliptical.

And now we have, especially when we come to Newton's validation of Kepler's transformation of Copernicus's theory, now we have a conception of the universe that lasted until Einstein's general theory of relativity and Edwin Hubble's announcement that the universe is much greater than the Milky Way and it's expanding. A conception of the universe as infinite in space, finite in matter, and one in which the orderliness of the universe is strictly abstract and mathematical. Only a person trained in mathematics can appreciate it. And in which the earth really is, as John Donne had said prematurely, it really is lost, and it's nowhere special. And the fact that the earth is nowhere special suggests neither are we.

Timeline

9000 B.C.E.	Domestication of grains and fruits begins
7000 B.C.E.	First evidence of copper smelting; evidence of drilled teeth
6000 B.C.E.	Earliest evidence of wine making; large-scale settlements in the Middle East
4500 B.C.E.	Horizontal loom weaving
4000 B.C.E.	Modern wooly sheep
3500 B.C.E.	Sumerian cuneiform writing
3000 B.C.E.	Beer brewing in Sumer; earliest gold jewelry; twill weaving using warp-weighted loom
2800 B.C.E.	Bronze in use in Sumer; Egyptian hieroglyphic writing
2000 B.C.E.	Spoked-wheel chariots
1800 B.C.E.	Egyptian medical and mathematical papyri; Babylonian Code of Hammurabi; alphabetic writing in Ugarit
1500 B.C.E.	Iron manufacturing; cast bronzes in China; vertical loom weaving
1300 B.C.E.	Earliest Chinese inscriptions; Phoenician alphabetic writing
1250 B.C.E.	Glass manufacture in Egypt
1000 B.C.E.	Steel making on a limited scale
800 B.C.E.	Hellenic Greeks adopt Phoenician alphabet
700 B.C.E.	Homeric epics written down
500 B.C.E.	Cast iron in use in China
5th century B.C.E.	Thales, Pythagoras, Parmenides, Heraclitus, Anaxagoras, Empedocles
4th century B.C.E.	Plato, Aristotle, Euclid, Epicurus
3rd century B.C.E.	Roman conquest of Greece; Archimedes, Apollonius, Aristarchus
2nd century B.C.E.	Antikythera machine
1st century B.C.E.	Vitruvius; Chinese invention of paper
1st century C.E.	Pompeii buried by Vesuvian ash; Frontinus on aqueducts of Rome
2nd century C.E.	Hero of Alexandria’s book of machines; Baths of Caracalla in Rome; watermill complex near Arles; Ptolemy and Galen
451	Conquest of Rome by Goths
521	Justinian closes Athenian philosophy schools
1086	Domesday Book inventory of England
1092	Start of the First Crusade
1170	Universities of Bologna and Paris founded
1268	First weight-driven mechanical clock
1329	Start of the Hundred Years’ War between England and France

1347 ....First outbreak of plague in Europe

1350 ....Petrarch founds the Humanist movement/idea of progress

1415 ....Brunelleschi rediscovers perspective drawing

1425 ....Jan van Eyck introduces oil-based paints

1453 ....Gutenberg introduces printing with movable metal type

1487 ....Vasco da Gama sails around Africa to India

1492 ....Columbus's first voyage to the New World

1512 ....Michelangelo completes the Sistine Chapel ceiling painting

1515 ....Ferdinand Magellan begins first around-the-world voyage

1543 ....Copernicus's *On the Revolutions of the Heavenly Spheres*; Vesalius's *On the Structure of the Human Body*

1554 ....Gerard Mercator's mathematics-based maps of Europe

1600 ....William Gilbert's *On the Magnet*; Giordano Bruno burned at the stake in Rome

1609 ....Kepler's *New Astronomy* claims elliptical planetary orbits

1610 ....Galileo's telescope-based *Sidereal Messenger*

1618 ....Start of the Thirty Years' War

1619 ....Kepler's *Harmony of the World*

1620 ....Francis Bacon's *New Organon*

1628 ....William Harvey's *On the Motion of the Heart and Blood in Animals*

1632 ....Galileo's *Dialogue Concerning the Two Chief World Systems*

1637 ....René Descartes introduces algebraic geometry

1638 ....Galileo's *Discourses on Two New Sciences*

1648 ....Treaty of Westphalia ends the Thirty Years' War

1660 ....Royal Society of London founded

1665 ....Robert Hooke's *Micrographia*

1666 ....French Royal Academy of Science founded

1673 ....Anton Leeuwenhoek's first published microscope observations

1684 ....Leibniz's first calculus publication

1687 ....Newton's *Principia Mathematica*

1704 ....Newton's *Opticks*; Newton's first calculus publication

1709 ....Jacob Bernoulli introduces modern probability theory

1750 ....Thomas Wright's Newtonian cosmology

1758 ....John Dollond patents color-corrected microscope lens

1767 ....James Hargreaves's spinning jenny

1771 ....Richard Arkwright's water-powered spinning "frame"

1776 ..............................U.S. Declaration of Independence; Adam Smith's *The Wealth of Nations*

1776 ....Watt-Boulton steam engines commercially available

1782 ....Lavoisier discovers oxygen, initiates chemical revolution

1789 ....French Revolution

1794 ....Erasmus Darwin's poem *The Botanic Garden*

1799 ....Laplace's *Celestial Mechanics*

1800 ....Volta invents the electric battery

1807 ....John Dalton introduces modern atomic theory; 1807

1807 ....Georg Friedrich Hegel's *Phenomenology of the Spirit*

1807 ....Robert Fulton's *Clermont* steamboat

1809 ....Jean-Baptiste Lamarck's *Zoological Philosophy*

1822 ....Joseph Fourier's analytical theory of heat published

1824 ....George Boole's laws of thought; Sadi Carnot's *Reflections on the Motive Power of Heat*

1828 ....George Stephenson's *Rocket* steam locomotive

1830 ....Michael Faraday invents the dynamo

1835 ....Charles Darwin returns from his global voyage on H.M.S. *Beagle*

1835 ....Adolphe Quetelet founds social statistics

1838 ....Friedrich Bessel measures the distance to star Cygnus 61

1838/39 ....Mathias Schleiden and Theodore Schwann's cell theory of life

1844 ....Samuel F. B. Morse's pilot installation of an electric telegraph

1845 ....Faraday introduces the field concept

1847 ....Hermann Helmholtz proclaims conservation of *Kraft* (meaning "force" or "power"); the term "energy" would be introduced in 1850

1849 ....Louis Pasteur discovers two forms of tartaric acid crystals

1850 ....William Rankine coins *energy* for *Kraft*; Rudolph Clausius founds thermodynamics, coins the term *entropy*

1851 ....William Thomson proclaims the arrow of time

1856 ....William Perkin discovers the first synthetic dye

1857 ....Pasteur's essay on fermentation founds the germ theory of disease

1858 ....Alfred Russel Wallace's essay on evolution by natural selection

1859 ....Darwin's *On the Origin of Species*

1862 ....Morrill Land Grant Act triggers growth of engineering education in the U.S.

1865 ....Mendel publishes results of his researches

1865 ....Maxwell's *A Dynamical Theory of the Electromagnetic Field*

1865 ....Auguste Kekule announces the ring structure of the benzene molecule

1865 ....First effective transatlantic telegraph cable

1877 ....Robert Koch isolates the cause of anthrax

1879 ....Pasteur introduces modern vaccination

1882 ....Koch isolates tuberculosis bacterium and, a year later, cholera

1882 ....Thomas Edison inaugurates centrally generated electricity

1885 ....Pasteur shows that dead bacteria confer immunity

1895 ....Roentgen discovers X-rays

1896 ....Henri Becquerel discovers radioactivity

1898 ....Marie Curie names *radioactivity*, isolates polonium, then radium

1897 ....J. J. Thompson discovers the electron

1900 ....Hugo de Vries and others rediscover Mendel’s results; Max Planck’s quantum hypothesis

1903 ....De Vries’s *The Mutation Theory*; William Bateson coins the term *genetics*

1903 ....Ernest Rutherford and Frederick Soddy determine lawful randomness of radioactive decay

1905 ....Einstein’s “miracle year” of publication

1910 ....Thomas Hunt Morgan localizes the “gene” for fruit-fly eye color

1910 ....Ernest Rutherford’s Solar System model of the atom

1912 ....Henrietta Leavitt Swann’s variable-star cosmic “ruler”

1913 ....Niels Bohr’s quantum theory

1914 ....World War I begins

1915 ....Einstein’s general theory of relativity

1918 ....World War I ends

1923 ....Edwin Hubble announces that Andromeda is a galaxy

1925 ....Heisenberg and Schrödinger found quantum mechanics

1926 ....Heisenberg uncertainty principle; statistical interpretation of quantum mechanics

1929 ....Hubble announces the expanding Universe; Paul Dirac founds quantum electrodynamics

1931 ....Electron microscope invented

1935 ....Karl Jansky detects radio signals from the Sun

1935 ....First virus “seen” using electron microscope

1936 ....Alan Turing publishes his principle of the universal computer

1938 ....Warren Weaver coins the term *molecular biology*

1939 ....World War II begins

1945 ....First atomic bombs; World War II ends; ENIAC becomes operational

1947 ....Transistor invented at Bell Labs

1947–1949 ....George Gamow and colleagues propose the Big Bang theory

1948 ....John von Neumann constructs EDVAC; Claude Shannon founds mathematical information theory

1953 ....Watson and Crick announce the double-helix structure of DNA

1956 ....Dartmouth conference on artificial intelligence

1957 ....*Sputnik I* orbits the Earth

1958 ....Jack Kilby and Robert Noyce invent the integrated circuit

1963 ....Penzias and Wilson detect microwave background radiation; Edward Lorenz triggers chaos theory

1964 ....Murray Gell-Mann and George Zweig found quantum chromodynamics

1969 ....Neil Armstrong walks on the Moon

1971 ....First test of ARPANet, leading to the Internet in the 1990s

1971 ....Electro-weak unification wins acceptance

1972 ....Recombinant DNA research begins

1973 ....DEC introduces first “mini-computer” PDP-8

1973 ....Standard model of quantum field theory formulated

1980 ....Alan Guth’s inflationary theory of the Universe; dark matter proposed

1981 ....IBM PC introduced

1984 ....String theory becomes “respectable” in physics

1989 ....Disintegration of the Soviet Union

1990 ....Hubble Space Telescope launched into orbit

1991 ....Tim Berners-Lee introduces the World Wide Web

1995 ....Sixth quark, called *top*, discovered

1998 ....Dark energy proposed

2000 ....Human genome decoded

Glossary

aether: In 19^{th}-century physics, a name for a universal space-filling form of matter or energy that served as the medium for immaterial fields of force.

algorithm: A series of well-defined operations that, if followed precisely, is guaranteed to solve a specified problem.

alphabetic: A name for a writing system that constructs the words of a language out of intrinsically meaningless symbols, in contrast with syllabic or ideographic writing systems.

amino acid: Typically in biology, this refers to one of 20 variants of a complex molecule—in which an NH_2 grouping of atoms shares a carbon atom with a so-called carboxyl group—out of which living cells construct proteins.

analytic geometry: Using algebraic equations to represent geometric forms and to solve problems in geometry or problems in algebra that previously had been solved using geometry, a Greek preference that was still common through the 17^{th} century.

axiom: A statement whose truth is self-evident, hence, can be used for purposes of inference without requiring a proof that it is itself true. Sometimes used loosely for a statement that we are to take as true without further proof because true statements can be inferred from it deductively.

binary system: In arithmetic, a number system employing only two symbols, 0 and 1, to represent all possible numbers and the results of all arithmetic operations; more generally, any strictly two-place characterization of phenomena: for example, on-off or true-false.

block printing: Printing texts by carving the writing symbols into a block of wood that is then inked and pressed onto the writing surface.

cartography: Mapmaking.

central-vanishing-point perspective: A technique for creating the illusion of depth on a two-dimensional surface, for example, a wall or a canvas, such that the viewer "sees" the content of a painting as if the depth were real.

chromatic aberration: Distortion that worsens as magnification increases, caused by the fact that the focal point of a lens is a function of the frequency of the light rays striking it, while natural light contains multiple frequencies, leading to multiple foci and blurry images.

classification problem: Identifying classification categories that organize some set of objects into groups in ways that reflect features of those objects rather than values projected by the classifier.

coal tar: The residue, long considered waste, from burning coal in a closed vessel in order to generate a flammable illuminating gas that was sold for lighting (gaslight) and for cooking and heating.

coke: Burning piles of coal in a controlled way, such that only the outer layer of the pile is consumed, converts the inner material into coke, which can substitute for charcoal in iron-making, dramatically lowering costs.

concrete: A construction material composed of a binder or cement; an aggregate, typically sand and/or gravel; and water. Modern concrete, so-called Portland cement, is very similar to Roman cement, which used quicklime, pozzolana (volcanic ash soil), gravel, and water. The strength of concrete comes from the chemical combination of the water with the binder.

contingent: Dependent, for example, on context, time, or circumstances, hence, not necessary.

conventionalism: The view that classification categories—*tree*, *fish*, *planet*—have no reality apart from the individual objects being classified and reflect features of those objects that have attracted the selective attention of the classifier.

cosmos: Ancient Greek name for the Universe as an ordered whole, though not all Greek philosophers meant by *cosmos* everything that is, as we do.

cuneiform: A way of writing in which the symbols of a writing system are inscribed into a medium, for example, into clay tablets using a stylus.

deduction: A form of reasoning in which the truth of an inferred statement, the conclusion of a logical argument, is guaranteed, that is, follows necessarily, from the truth of some other statements, the premises of that argument.

demonstration: Literally, a "showing," but in reasoning, a deductive logical argument.

dialectic: In Greek logic, a form of reasoning in which the premises of an argument are not known to be true—either self-evidently or deductively—but are assumed to be true in order to explore their logical consequences.

digital: In modern technology, the representation of any phenomenon in discrete numerical terms, typically binary, in contrast with continuous analog representations. Where analog computers are customized to specific problems, digital computers have a universal character (if the numerical representation is valid!).

double-entry bookkeeping: Introduced to the West from Islam circa 1200 and popularized during the Renaissance, this method of record-keeping allowed precise tracking of debits and credits at a time when the scale and complexity of commerce were growing.

dynamo: A machine, commercialized from the 1870s, based on Michael Faraday's dynamo principle of about 1830, in which an electric current flows in a conductor as the result of the relative mechanical motion of the conductor and a magnet.

electrochemistry: Using electric currents to dissociate chemical compounds into their constituent elements, thereby identifying the constituents and permitting the study of "pure" elements.

electro-weak theory: The 1960s theory developed by Sheldon Glashow, Abdus Salam, and Steven Weinberg that unified the electromagnetic force, exerted by photons, and the so-called weak nuclear force, exerted by a family of particles called intermediate vector bosons, that is associated with radioactivity but also affects the electron family of particles, quarks, and neutrinos.

emergent property: A property of a whole that is not displayed by the individual parts of the whole *and* has causal consequences of its own.

empiricism: The view that all knowledge claims are ultimately validated by observational experience.

engineering drawing: A means of exhaustively characterizing the form of a three-dimensional object, however complex, using two-dimensional drawings. Renaissance engineers adapted perspective drawing to achieve this end and invented cutaway and exploded representations to show how machines were built; later, engineers and architects adopted orthogonal projections as a standard.

Enlightenment: A name given by 18^{th}-century intellectuals to their age as one in which reason was used to improve mankind's physical, moral, social, and political condition.

enzyme: Enzymes are proteins that function as catalysts in metabolic processes; that is, they enable reactions but are not consumed in those reactions. Like all proteins, they are composed of amino acid complexes.

epicycles: A name for hypothetical centers of uniform circular motion for the planets to account for the fact that, viewed from the Earth, the planetary motions seem to be neither uniform nor circular.

ether: See **aether**.

feedback: A term popularized by Norbert Wiener's cybernetics theory in the 1940s, feedback refers to returning a portion of the output of a system or process to its input. Positive feedback reinforces the input, leading to a continually increasing output up to the limits of a system; negative feedback reduces the input and can, thus, be used to regulate the ratio of output to input.

floating point arithmetic: A scheme for representing numbers of any size compactly for purposes of automated calculation, as in a computer.

fractal: A name coined by the mathematician Benoit Mandelbrot to describe a family of shapes that occur throughout nature and are describable by a particular family of highly abstract mathematical functions. These shapes violate the traditional conceptualization of objects as being one, two, or three dimensional.

germ plasm: In the 1880s, August Weismann argued that sexually reproducing organisms inherit their distinctive character through a line of sexual cells, the germ plasm or germinal plasm, that is wholly isolated from the life experiences of the organism—hence, no inheritance of acquired characteristics, contra Lamarck. For us, DNA is the germ plasm.

hieroglyphics: An ideographic writing system, such as the one initially used by the ancient Egyptians in the 3rd millennium B.C.E. It evolved over the next 2000 years into increasingly stylized symbols that eventually represented syllables rather than ideas.

hydrostatics: The study of floating bodies in equilibrium, whose principles were first formulated by Archimedes in the 3rd century B.C.E. He also studied hydrostatics, the behavior of fluids, for example, water, in motion and the pressures they exert, which is directly relevant to the design and construction of water clocks and water- and air-powered machinery.

ideographic: A writing system in which each symbol, typically pictorial, expresses an idea.

induction: A form of reasoning in which the truth of some statement follows only with some probability from the truth of other statements; hence, it may be false even if those other statements are true, in contrast with deductive reasoning.

innovation: Not a synonym for invention but the form in which an invention is realized in the course of a process that integrates invention, engineering, and entrepreneurship.

kinetic theory of gases: The mid-19th-century theory developed especially by Clausius, Boltzmann, and Maxwell that the observable properties of gases—pressure, temperature, and viscosity—and relations among them are the result of, and are explained by, the motions of vast numbers of unobservable atoms or molecules of which they are composed; furthermore, these motions have only a statistical description.

logic: The name given to the study of forms of reasoning and their rules, independent of what the reasoning is about.

logical proof: See **proof**.

metaphysics: The study of the ultimately real, as opposed to what only appears to be real. The term occurs first as a description of an otherwise unnamed text of Aristotle's that deals with the first principles of being.

modern science: A name for an approach to the study of natural phenomena that emerged in the 17th century, was extended to social phenomena in the 18th century, and is considered to have developed into what we mean by *science* today.

mutation: A discontinuous variation typically in some heritable attribute of a cell, organism, or today, a DNA molecule, by comparison with its "parent." Hugo de Vries made mutations the basis of his 1901 theory of inheritance and of evolution, replacing natural selection with mutations.

nanotechnology: The manipulation of matter and the creation of structures on a molecular scale, with features measured in nanometers, billionths of a meter, or about 10 angstroms on an alternative scale. A DNA molecule is about 4 nanometers wide, and the read/write head of a state-of-the-art hard drive floats about 3 nanometers above the disk.

naturalism: The view that nature is the sum total of what is real, a view espoused by Aristotle against Plato's view that the ultimately real were supra-natural forms.

nucleosynthesis: The synthesis of the rest of the elements out of the hydrogen that is assumed to have been the universal form of matter in the early Universe.

perspective drawing: See **central-vanishing-point perspective**.

plasm: See **germ plasm**.

polymer chemistry: The study and manipulation of the properties of large molecules built on long, linear chains of carbon atoms. Plastics are polymers.

population genetics: Statistical models of the distribution of genes in large populations of randomly breeding individuals. Conceptually, the development of population genetics in the 1920s echoes the ideas underlying the kinetic theory of gases, statistical mechanics, and thermodynamics and the statistical laws of radioactivity and quantum mechanics.

process metaphysics: The view that reality is ultimately characterized by, and is to be explained in terms of, rule-governed processes, as opposed to the substance metaphysics view.

proof: A proof is a logical argument in which the truth of the statement to be proven is shown to follow necessarily from statements already accepted as true, hence, a deductive logical argument.

proteins: Complex, typically very large molecules made up of combinations of the 20 amino acids living cells manufacture, each protein possessing a distinctive spatial arrangement, or folding, of its components. Proteins, which determine cell metabolism, are manufactured on molecules called *ribosomes* in response to instructions from DNA via messenger RNA.

quantum chromodynamics (QCD): The quark theory of matter that developed in the 1960s in which hadrons, protons, neutrons, and all other particles that respond to the so-called strong nuclear force—thus, not electrons and neutrinos—are built up out of some combination of six quarks held together by gluons. Quarks and the electron-neutrino family of particles, called *leptons*, are now the *really* elementary forms of matter.

quantum electrodynamics (QED): The theory that developed in the 1940s out of Paul Dirac's 1929 quantum theory of the electromagnetic field. It describes the interaction of electrons, protons, and photons and is, thus, the quantum analogue of Maxwell's electromagnetic field theory.

rationalism: The view that deductive reasoning is both the only route to truth and capable of discovering all truths.

reverse engineering: Decomposing an artifact or a process in order to identify its components and mode of operation.

rhetoric: In ancient Greece, techniques of persuasive arguing that use the power of speech to win arguments, as opposed to the use of logical reasoning to prove the point.

science: Literally, knowledge, but for mainstream Western philosophy since Plato, it means knowledge that is universal, necessary, and certain because what we know is deducible from universal problems, not from individual facts.

semiconductor: A substance that is capable of being either a conductor of electricity or an insulator, depending on certain subtle and controllable changes in its makeup. Virtually all electronics technology since the 1960s has been based on semiconductor materials, especially silicon.

skeptics: Philosophers who deny the possibility of universal, necessary, and certain truths about nature; hence, they deny the very possibility of knowledge à la Plato-Aristotle and that anyone has achieved it.

spectroscope: An optical device that separates the many individual frequencies that make up the light incident upon it. Because the atoms of each element, when excited, radiate a distinctive set of frequencies, the elements in starlight and in laboratory specimens of matter can be identified.

spinning jenny: The name given to the single-operator–multi-spindle machine invented by James Hargreaves in the 1760s that revolutionized the production of cotton thread.

spontaneous symmetry breaking: An idea adopted by physicists in the 1960s to explain how a uniform state of affairs can evolve into a non-uniform one.

standard model: The name for the quantum theory that unified the electro-weak theory and quantum chromodynamics, hence, the electromagnetic, weak, and strong forces. Since the 1970s, this theory has matured into our most powerful theory of matter and energy.

statistical mechanics: An extension of the ideas underlying the kinetic theory of gases by Boltzmann, Maxwell, and J. Willard Gibbs and developed further by others in the 20th century, including Einstein, for deriving observable properties of systems of material bodies from statistical models of the behavior of their parts.

statistical thermodynamics: The development of the kinetic theory of gases led Boltzmann and Maxwell to apply statistical models to the laws of thermodynamics and, thus, to energy flows.

stereochemistry: The study of molecular properties that derive from the spatial arrangement of the atoms in a molecule, as distinct from the properties that derive from the atomic composition of the molecule.

string theory: The name given to one approach to the final step in unifying the four fundamental forces in nature by uniting the standard model of quantum theory with the force of gravity, now described by the general theory of relativity, which is not a quantum theory. String theory proposes that all forms of matter and energy at all levels are variations on fundamental entities called *strings* that vibrate in 11-dimensional space-time.

substance metaphysics: The view, tracing back to the teachings of Parmenides, obscure even in antiquity, that the ultimate constituents of reality are timeless, changeless "things" with fixed properties, out of which all changing things are constructed and by means of which all change is to be explained.

syllabary: A writing system in which each symbol stands for a syllable in that language and the set of symbols/syllables allows the construction of all words in that language.

symbolic logic: A symbolic notation for recording and analyzing logical arguments and their properties, developed in the 19th century and leading to a revolution in logical theory and to the creation of a new discipline: mathematical logic.

symmetry: Initially descriptive of properties of mathematical forms, in the 19th and, especially, the 20th centuries, it was made into a fundamental principle of the physical world in physics, chemistry, and biology. In physics, symmetry plays a central role in so-called gauge theories, which attempt to unify the four fundamental forces in nature by supposing that they are the "debris" of symmetries that defined

uniform forces in the very early history of the Universe but fragmented as the Universe cooled. See **spontaneous symmetry breaking**.

system: An ordered whole of mutually adapted parts keyed to the functionality of the whole.

taxonomy: A taxonomy is a systematic classification scheme that may be explicitly artificial, such as the familiar public library Dewey decimal system for classifying books (*not* created by the philosopher John Dewey!), or it may be natural. See **classification problem**.

techno-science: A name for technologies whose design and effective operation are dependent on scientific knowledge. Historically, technological innovations were quite independent of scientific theories, but this situation began to change in the 19th century. The commercial exploitation of these technologies led to the systematic coupling of science and engineering in industrial corporations, research labs, and academe.

temperament: See **tuning system**.

transistor: A device, invented at Bell Labs in 1948 by William Shockley, John Bardeen, and James Brattain, that exploits the properties of simple solid semiconductors to perform electronic functions then performed by much larger, less reliable, more expensive, and more power-consuming vacuum tubes.

tuning system: In music, a set of mathematical relationships among the notes of the octave that, when applied to the construction of musical instruments, maintains harmonies among the notes and minimizes dissonances. Tuning systems were inspired by Pythagoras's insight that mathematical relationships distinguish music from noise, but no one has discovered a single temperament or tuning system that is dissonance-free. Western music over the past 200 years employs equal temperament, a system in which the octave is divided into 12 equally spaced tones.

verisimilitude: Renaissance Humanist idea of the truthfulness of history writing that employs imaginative reconstructions and, by extension, the truthfulness of paintings that obviously are not what they seem to be.

water frame: A name given to the large water-powered version of Hargreaves's spinning jenny built by Richard Arkwright; together with related water-powered machinery for carding and weaving, the water frame initiated the mass-production era, setting the stage for the steam-power-based Industrial Revolution.

Biographical Notes

abu-Kamil (c. 850–930). Early Islamic algebraist, born in Egypt, and author of an influential text translated during the Renaissance containing 69 algebraic problems and their solutions.

al-Khwarizmi (c. 780–c. 850). The earliest known Islamic algebraist. His book of problems and solutions, along with that by abu-Kamil, influenced the shift of European mathematics from geometry to algebra.

Anaxagoras (c. 500–428 B.C.E.). Greek philosopher who proposed that all material objects were composed of a vast number of atoms of many different properties.

Archimedes (c. 287–212 B.C.E.). Greek mathematician and physicist whose combination of deduction and experiment influenced Galileo and Newton. He formulated a mathematics-based theory of the so-called simple machines and founded the science of hydrostatics.

Aristarchus of Samos (c. 320–c. 250 B.C.E.). Greek mathematician and astronomer who used trigonometry to estimate the distances to the Sun and Moon and proposed a Sun-centered Solar System that Copernicus read about in a text by Archimedes.

Aristotle (384–322 B.C.E.). Greek philosopher born in Macedonia, where his father was physician to the king. He studied with Plato for many years but then founded his own rival school, also in Athens. His comprehensive writings, especially on logic and nature, and his metaphysics, were extremely influential for more than 2000 years.

Avery, Oswald (1877–1945). American bacteriologist (born in Canada) who, together with Colin MacLeod and Maclyn McCarthy, argued in the early 1940s, based on their experiments with pneumonia bacteria, that DNA was responsible for inheritance.

Avicenna (980–1037). Islamic philosopher (Aristotelian) and physician, whose masterwork, *The Canon of Medicine*, became a standard text, alongside Galen's, for more than 500 years in European medical schools.

Bacon, Francis (1561–1626). English educational reformer; also reformer and "father" of the experimental method in modern science described in his book *The New Organon* (1620); and political opportunist. Became Lord High Chancellor under King James but was convicted of bribery.

Bernard of Clairvaux (1090–1153). Extremely influential 12th-century French theologian and Church leader, head of the Cistercian order of monasteries that extended over much of Europe. He opposed the rising secular intellectualism that became institutionalized in the emerging universities and especially persecuted the philosopher Peter Abelard.

Bernard, Claude (1813–1878). French biologist, founder of experimental medicine, and an extremely prolific author of research publications, many of whose results remain valid today. He was a positivist, favoring facts over concepts, and championed a homeostatic view of metabolism.

Bernoulli, Jacob (1654–1705). Swiss mathematician, member of a family of outstanding mathematicians in the 17th and 18th centuries, whose posthumously published *The Art of Conjecturing* pioneered probability theory and its application to political and commercial decision-making.

Bohr, Niels (1885–1962). Danish physicist, deeply philosophical as well, whose 1913 proposal to quantize the orbital motion of electrons became the foundation of quantum mechanics. In the late 1920s, with Werner Heisenberg, he formulated the Copenhagen Interpretation of quantum mechanics.

Boltzmann, Ludwig (1844–1906). Austrian physicist who founded statistical mechanics and statistical thermodynamics, posited the kinetic theory of gases (with James Clerk Maxwell), and insisted on the physical reality of atoms.

Boole, George (1815–1864). British mathematician who founded modern mathematical logic by introducing a symbolic notation for logical reasoning. His 1854 book, *An Investigation into the Laws of Thought*, was of immense influence in the history of information theory, computers, and artificial intelligence research, as well as in mathematical logic.

Boyle, Robert (1627–1691). Irish natural philosopher, heir to the title earl of Cork, and member of the Oxford group of natural philosophers that founded the Royal Society of London. Boyle conducted experiments with Robert Hooke, using an air pump of their design, on the physical properties of air; these were considered exemplary of the experimental method of the study of nature. He was an atomist and an early "scientific" chemist.

Brahe, Tycho (1546–1601). A Danish astronomer, the greatest observational astronomer of the pre-telescope era, who used instruments of his own design in an observatory funded by the Danish king. He rejected Copernicus's theory for his own version of an Earth-centered Universe. His data were used by Johannes Kepler to support Kepler's claim that the planets move in elliptical orbits.

Brunelleschi, Filippo (1377–1446). Italian painter, sculptor, and architect; famous for his rediscovery of perspective drawing and his innovative design and construction plans for the cathedral in Florence with its vast dome and cupola.

Bush, Vannevar (1890–1974). American engineer, science administrator, head of the World War II Office of Scientific Research and Development, author of the report that launched large-scale postwar federal support for research, and computer pioneer.

Cardano, Jerome (Girolamo) (1501–1576). Italian mathematician, physician, and founder of probability theory applied to gambling games. He promoted the study of algebra and published Tartaglia's solution to the cubic equation.

Clausius, Rudolf (1822–1888). German physicist and a founder of thermodynamics, Clausius introduced the concept of entropy, implying the irreversibility of time and the "heat death" of the Universe. With Maxwell and Boltzmann, he also created the kinetic theory of gases.

Comte, Auguste (1798–1857). French social and political philosopher and philosopher of science; founder of positivism—basing knowledge on facts, not ideas—and of sociology.

Copernicus, Nicolaus (1473–1543). Polish astronomer and physician whose theory of a moving Earth eventually redirected astronomy. Copernicus spent years studying in Italy after graduating from Jagiellonian University in Krakow and became proficient in Greek, translating into Latin the work of an ancient Greek poet recovered by the Humanists. It is interesting that Copernicus used virtually the same data that Ptolemy used yet reached dramatically different conclusions.

Crick, Francis (1916–2004). English physicist. After working on radar and magnetic mines during World War II, Crick collaborated with James Watson on the spatial arrangement of the atoms in DNA molecules; the two shared the Nobel Prize for that 1953 discovery.

Ctesibius (3rd century B.C.E.?). A Greek "mechanic," son of a barber, who invented a wide range of useful machines, including a complex water clock and a water organ, that were developed further by others over the next 300 years.

Curie, Marie (1867–1934). Born in Warsaw, Curie moved to Paris with a newly married older sister in 1891 and married Pierre Curie in 1895. They shared a Nobel Prize in physics in 1903 with Henri Becquerel for the discovery of radioactivity, named by Marie in 1898. After Pierre's death in 1906, Marie became the first woman professor at the Sorbonne, and in 1911, she was awarded the Nobel Prize in chemistry for her isolation of radium.

Dalton, John (1766–1844). Not the first atomist of modern times—Boyle and Newton were among his many predecessors—Dalton's *New System of Chemical Philosophy* (1807) became the foundation of 19th-century atomic theories of matter, first in chemistry, later in physics.

Darwin, Charles (1809–1882). Born into a wealthy English family, Darwin married a cousin, Emma Wedgwood, and devoted his life to biological science. In addition to his theory of evolution, Darwin published extensively on many subjects and would be considered a major 19th-century scientist independent of evolution.

Darwin, Erasmus (1731–1802). Charles Darwin's paternal grandfather and author of several once-popular (although later mocked) epic poems on nature that incorporated evolutionary ideas of his own.

Davy, Humphrey (1778–1829). An English physicist/chemist, Davy was extraordinarily productive in both "pure" and applied research, pioneering electrochemistry and discovering the elements sodium and potassium, as well as inventing a safety lamp for coal miners, an electric arc lamp, and a process for desalinating seawater.

Dee, John (1527–1608/09). English mathematician and mystical nature philosopher. Dee was actively involved in training ship pilots in the new mathematical techniques of navigation and in mathematical cartography, as well as promoting mathematics literacy for the public. He designed "magical" stage machinery for plays and made the first translation into English of Euclid's *Elements*.

Descartes, René (1596–1650). Descartes was a founder of modern science, modern philosophy, and modern mathematics. He promoted a deductive method for acquiring knowledge of nature and developed a rigorously mechanical philosophy of nature in which only contact forces were allowed: no action at a distance. He made epistemology (the theory of knowledge) central to philosophy, and he invented analytic geometry, making algebra central to mathematics.

De Vries, Hugo (1848–1935). Perhaps the leading figure in founding modern genetics, De Vries, a Dutch botanist, rediscovered Mendel's ignored earlier work after developing his own similar theory and gave the credit to Mendel. He developed an influential theory of mutations as the "engine" of evolution.

Dirac, Paul (1902–1984). Trained initially as an engineer at Bristol University in England, Dirac became one of the greatest theoretical physicists of the 20th century. His 1929 relativistic theory of the electron became the cornerstone of quantum electrodynamics, the most important theory in physics in the mid-20th century.

Dolland, John (1706–1761). An English weaver by training, Dolland became a self-educated scientist, developing and patenting the first compound microscope lenses corrected for chromatic aberration.

Dumas, Jean Baptiste (1800–1884). A French chemist who developed a technique for calculating relative atomic weights, Dumas also pioneered structuralism in chemistry through his theory of substitution of atoms in geometric "types" of molecules.

Einstein, Albert (1879–1955). Given all that has been written about him, perhaps the most amazing fact about Einstein is that, in 1904, no one, with the exception of his closest friend and sounding board, Marcel Grossmann, would have predicted his subsequent accomplishments. In spite of his epochal 1905 papers, his reputation flowered only from 1911. He was appointed director of the Kaiser Wilhelm Institute for Physics in 1914 and, in 1915, published the general theory of relativity. He resigned in 1933 and settled at the Institute for Advanced Studies in Princeton, which was created in part to provide a "home" for him.

Empedocles (c. 490–430 B.C.E.). An early Greek natural philosopher who formulated a four-element theory of matter—earth, air, fire, water—that, together with attractive and repulsive forces, lasted into the 18th century.

Epicurus (341–270 B.C.E.). A Greek moral philosopher primarily, who adopted Democritus's atomic theory of matter and adapted it to his moral and social views. Against Anaxagoras, he held that atoms differed only in size, shape, and weight and that all properties of material objects derived from diverse configurations of their constituent atoms.

Erasmus of Rotterdam (1466–1536). One of the great Humanist scholars and the first author, it is said, to live wholly off his fees from publishers based on the sale of his books, especially his bestselling *In Praise of Folly*.

Euclid (c. 300 B.C.E.). A Greek mathematician, whose synthesis of 200 years of Greek mathematics into an axiomatic system in his book, *The Elements*, was of incalculable influence in Western philosophy, mathematics, and science, right down to the present day. Almost nothing is known of his personal life.

Euler, Leonhard (1707–1783). One of the greatest mathematicians of all time and, perhaps, the most productive. Born in Basel, he lived most of his adult life in Germany or Russia, writing on pure and applied mathematical problems even after he became blind. He encompassed all of mathematics but contributed especially to "analysis," another name for algebra, and made important contributions to astronomy, optics, mechanics, and engineering mechanics: the rigorous solution of engineering problems.

Faraday, Michael (1791–1867). A gifted and highly prolific experimental physicist and chemist, Faraday was effectively wholly self-educated, though he was never proficient in mathematics. He became Humphrey Davy's assistant at the Royal Institution in London through an accident, and he was later Davy's successor. He discovered the dynamo principle in 1830, and invented the concepts of electric and magnetic fields and lines of force, predicting that light was an electromagnetic phenomenon. He rejected the atomic theory.

Fischer, Emil (1852–1919). A German organic chemist famous, first, for his synthesis of sugars and, later, for synthesizing amino acids, then combining them to form proteins. His lock-and-key metaphor for how enzymes act on cell molecules was and remains a powerful heuristic in molecular biology.

Fourier, Joseph (1768–1830). French mathematical physicist whose *Analytical Theory of Heat* was extremely influential, both in terms of its equations and in separating descriptive physics from metaphysics. His use of simple trigonometric functions to model any periodic behavior, however complex, remains one of the most powerful tools in science and engineering.

Francesca, Pierro della (1420–1492). One of the great Renaissance painters, he was also a mathematician and wrote perhaps the first account of perspective drawing as a mathematical technique, *De prospectiva pingendi*. This then became a staple of 15th-century artist's manuals, especially after Leone Alberti's influential *Della pittura* (1436).

Galen (c. 129–199). Greek physician and medical theorist, prolific writer and experimenter, and physician to various Roman emperors. Galen was to medieval and Renaissance medicine what Aristotle was to philosophy: the authority. His theory of health as a balance among four humors was influential into the 19th century, though his anatomy and physiology were overthrown in the 16th and 17th centuries.

Galilei, Galileo (1564–1642). Italian mathematical physicist and founding "father" of modern science, combining deductive reasoning and extensive experimentation à la Archimedes. Born in Pisa, he became a professor of mathematics first there, then in Padua, after his telescope-based observations of the Moon's irregular surface and Jupiter's moons made him famous. His condemnation for teaching Copernicus's theory as true came in 1633.

Galilei, Vincenzo (1520–1591). Galileo's father; Vincenzo was a musician and a music theorist at a time of intense controversy over tuning systems and their mathematical models. He broke with his teacher, Zarlino, who defended an expanded Pythagorean system, in favor of equal-temperament tuning. Vincenzo's books reveal clever experimentation to support his claims.

Gamow, George (1904–1968). Born in Russia, Gamow moved west after earning his Ph.D., studying the new quantum physics first in Germany, then with Bohr in Copenhagen, before settling in the United States. He predicted the quantum tunneling effect in 1929; proposed the Big Bang theory of cosmology in the late 1940s, predicting the microwave background radiation detected in 1963; and proposed that the sequence of bases in the Watson-Crick DNA model was a code for producing proteins out of amino acids.

Gutenberg, Johann (c. 1397–1468). Widely but by no means unanimously considered the inventor of movable-metal-type printing. Almost nothing about Gutenberg's life and work is free of uncertainty except that he was born in Mainz on the Rhine River, apprenticed as a goldsmith but became a printer, and printed a number of deluxe copies of the Bible using metal type in the early or mid-1450s.

Guth, Alan (1947–). American physicist who, in 1980, proposed the inflation model of the Universe, preceding Gamow's Big Bang. Subsequent refinement by others, as well as by Guth, and detailed observation of the microwave background radiation's minute non-uniformities led to a consensus in favor of the inflation model.

Hegel, G. F. W. (1770–1831). A German philosopher, Hegel was the single most influential philosopher of the 19th century, the creator of a system that integrated deduction, history, and time. He held that reality is the deterministic unfolding in time of reason, which manifests itself as nature and as the human mind.

Heisenberg, Werner (1901–1976). A German physicist, Heisenberg invented, in 1925, what was later called "quantum mechanics." Over the next five years, he formulated the famous uncertainty principle and, in collaboration with Bohr, an interpretation of quantum theory that was probabilistic and strictly empirical. Bohr broke with Heisenberg over the latter's role as head of Germany's wartime atomic bomb research effort.

Helmholtz, Hermann (1821–1894). A physicist and pioneering neuro-physiologist, Helmholtz was Germany's leading scientist in the second half of the 19th century. He formulated the scientific principle of the conservation of energy, studied the transmission of signals in nerves, and developed a theory of hearing that became the basis for designing stereo audio equipment.

Heraclitus (c. 540– c. 480 B.C.E.). Other than that he lived in the Greek city of Ephesus in what is now Turkey and probably wrote before Parmenides, not after, nothing is known about Heraclitus. That he wrote one or more works on philosophy is known, and in these, he clearly insisted on the reality of change, suggesting that the object of knowledge is the *logos*, or orderliness, of processes, not timeless objects and their properties.

Hero (or Heron) of Alexandria (flourished c. 60). A Greek "engineer" before the term existed, Heron created a school for engineering in Alexandria and left behind a number of books describing mechanical and optical machines based on physical principles, including the action of compressed air, water, and steam.

Hertz, Heinrich (1857–1894). A German physicist who, in the 1880s and independently of Oliver Lodge in England, confirmed the prediction of Maxwell's theory of electromagnetic waves traveling freely through space. This finding became the basis for the broadcast radio technology developed 10 years later by Guglielmo Marconi.

Hippocrates (c. 460–377 B.C.E.). A Greek physician, medical theorist, founder of a medical school, and teacher. His school was on the island of Kos, where he was born, and pioneered a wholly naturalistic approach to illness and treatment.

Hoffman, August (1818–1892). An eminent German organic chemist, Hoffman was called to London by Prince Albert to teach at the new Royal College of Chemistry, where his student William Perkin synthesized the first artificial dye from coal tar. Hoffman later returned to Germany, founded the German

Chemical Society, and played an active role in German chemists' dominance of the commercial dye industry and the many important industrial applications of coal-tar chemistry.

Holland, John H. (1929–). American computer scientist and creator of "genetic" algorithms: computer programs based on Darwinian evolution and genetic theory that display adaptation. Holland is a theorist of complex systems and self-organization and was actively involved with the Santa Fe Institute and World Economic Forum, in addition to teaching computer science at the University of Michigan.

Hooke, Robert (1635–1703). An English natural philosopher, Hooke collaborated with Robert Boyle on experiments to determine the properties of air, studied the properties of metallic springs, and invented a spiral spring-controlled balance wheel for a watch (replacing the pendulum). He was a pioneering microscopist, invented numerous scientific instruments, attempted a theory of gravity, and played a leading role in the rebuilding of London after the great fire of 1665.

Hoyle, Fred (1915–2001). An English physicist, Hoyle, together with Herman Bondi and Thomas Gold, proposed the Steady State theory of the Universe as a counter to Gamow's Big Bang theory, a name mockingly assigned by Hoyle. Hoyle also wrote science fiction and argued that life came to Earth from space.

Hubble, Edwin (1889–1953). Hubble was a midwestern American astronomer who became director of the Mt. Wilson observatory in 1919 and, with its 100-inch reflecting telescope, soon discovered that the sky was filled with galaxies, contrary to the consensus view that the Milky Way was the Universe. In 1929, Hubble announced the expansion of the Universe and devoted the rest of his life to observations aimed at determining its size and age.

Huygens, Christiaan (1629–1675). A Dutch mathematical physicist, mathematician, and astronomer, Huygens was a central figure in the creation of modern science, first to demonstrate that curved motion required a force and to recognize Saturn's rings as such. He developed a wave theory of light; made important contributions to algebra, probability theory, optics, and mechanics; developed accurate pendulum clocks and their theory; and independently of Hooke, invented a spring-balance wheel-driven watch.

Joule, James Prescott (1818–1889). An English physicist whose experiments on the quantitative relationship of mechanical motion and heat led, in the hands of others, to the idea of conservation of energy and the creation of thermodynamics.

Kekule, Friedrich August (1829–1886). A German organic chemist, Kekule is best known for his contributions to structural chemistry, especially the hexagonal ring structure of benzene and his prediction of the tetrahedral form of the carbon atom's valence bonds, which became the basis of polymer chemistry in the 20^{th} century.

Kelvin, Lord/William Thomson (1824–1907). An Irish-born mathematical physicist, Thomson was knighted for designing and overseeing the laying of the first successful transatlantic telegraph cable in 1866. He played key roles in the development of thermodynamics and electromagnetic field theory but was wedded to the reality of the aether and believed that the Earth was probably only 100 million years old and, thus, too young for Darwin's theory of evolution to be correct.

Kepler, Johannes (1571–1630). A German astronomer who first formulated the modern conception of the Solar System, which is very different from that of Copernicus. The data Kepler used came from Tycho Brahe, whose assistant he became when Brahe relocated to Prague. When Brahe died, Kepler took the data and applied them, first, to a Pythagorean theory of his own that failed to match the data; he then let the data guide his theorizing, arriving at elliptical orbits, not circular ones.

Khayyam, Umar (1048–1131). Islamic mathematician, astronomer, and poet who had effectively achieved a general solution to the cubic equation centuries before Tartaglia, and whose text *Algebra* anticipates Descartes' invention of analytic geometry.

Koch, Robert (1843–1910). A German biologist who, with Louis Pasteur, founded bacteriology and formulated the germ theory of disease. His Nobel Prize was for discovering the bacterium that causes tuberculosis, then rampant, but he developed methodologies for isolating microorganisms that resulted in his discovery of anthrax and cholera bacteria, as well.

Lamarck, Jean-Baptiste (1744–1829). Lamarck was almost 50, with very modest credentials as a botanist, when in 1793 the committee running the French revolutionary government made him a national professor of invertebrate zoology. His theory of the emergence of all life forms from a common ancestor by natural forces was an important predecessor of Charles Darwin's theory, and one of which Darwin was acutely aware.

Laplace, Pierre-Simon (1749–1827). A French mathematical physicist and theoretical astronomer of great influence who managed to prosper under Louis XVI, the revolutionary government, Napoleon, and the restored Bourbon monarchy! He proved the long-term stability of the Solar System under Newtonian gravitation, developed a mathematical theory of the origin of the Solar System out of a cloud of gas, published an important essay on probabilities, and championed a rigorous materialistic determinism.

Laurent, Auguste (1807–1853). At one time a graduate student of Dumas (above) contemporary with Pasteur, Laurent seems first to have developed a theory that the spatial arrangement of atoms in a molecule determines properties of the molecule. His "nucleus" theory was subsequently overwhelmed by Dumas' extension and adaptation of it, a source of some bitterness to Laurent.

Lavoisier, Antoine de (1743–1794). Unlike Laplace, Lavoisier did not survive the French Revolution. His research led him to believe that combustion involved combination with one component of air, which he named *oxygen*. This led him to propose a "revolution" in chemistry, one that laid the foundation for the modern theory of elements. His widow married Benjamin Thompson (below).

Leavitt, Henrietta Swan (1868–1921). An American astronomer, Leavitt graduated from what became Radcliffe College and became a human "computer" at Harvard College Observatory, eventually rising to head of a department there. Her specialty was variable stars, and she identified 2400 new ones, especially the Cepheid variables that she recognized as providing a cosmic "ruler" for measuring absolute cosmic distances.

Leibniz, Gottfried (1646–1716). A German philosopher, mathematician, and physicist, Leibniz, like Descartes, was influential in all three of those areas. He formulated a rationalist, deterministic but anti-materialistic philosophy; invented the calculus independently of Newton (publishing first), using a notation that has become universal; anticipated late-19th-century topology and symbolic logic; and first called attention to the quantity in mechanics that we call kinetic energy.

Liebig, Justus von (1803–1873). A German chemist of enormous influence, partly through his own mechanistic theories of chemical reactions, but largely through the many subsequently prominent students trained in his laboratory. Liebig studied the chemistry of fermentation long before Pasteur and never accepted that the cause was a living organism (yeast). He also dismissed the significance of atomic structure within molecules and the early germ theory of disease.

Linnaeus, Carl (1707–1778). Swedish botanist whose binomial system for classifying plants based on their sexual organs became universally adopted. An aggressive proponent of his system as a natural one, he was forced to acknowledge late in life that it seemed to be conventional, which implied that species and genera were conventional, not immutable features of reality.

Lucretius (c. 99/94–c. 55/49 B.C.E.). Roman poet and natural philosopher whose epic poem in hexameters, *On the Nature of Things*, disseminated Epicurus's atomic theory of matter and morality, somewhat modified by Lucretius.

Mach, Ernst (1838–1916). An Austrian experimental physicist of note but remembered mostly for his theory of scientific knowledge as based on perceptual experience and incapable of penetrating to a reality behind experience, which is why he opposed the reality of atoms.

Maxwell, James Clerk (1831–1879). One of the greatest of all mathematical physicists, Maxwell was born in Edinburgh. He became, in 1871, the first professor of experimental physics at Cambridge University and established the Cavendish Laboratory there. Under the leadership of Lord Rayleigh, J. J. Thomson, and Ernest Rutherford, the laboratory became a leading center for important new developments in physics into the 1950s.

Mendel, Gregor Johann (1822–1884). An Austrian monk and botanist, Mendel lived in the Augustinian monastery in Brünn (Brno) effectively for the last 40 years of his life, becoming abbot in 1868, which ended his experimental work on plants. Mendel twice failed to pass the exams for an advanced teaching license. In between failures, he spent three years at the University of Vienna studying science and mathematics and, on returning to the monastery in 1854, began the years-long breeding experiments that resulted in his posthumous fame.

Mercator, Gerard (1512–1594). Mercator was born in Flanders and, after a religious crisis that led to his becoming a Protestant, studied mathematics in order to apply it to geography and cartography. He migrated to the Lutheran town of Duisberg in Germany in 1552, living there for the rest of his life and producing the first modern maps of Europe over the next 10–15 years. In 1569, he produced a map of the Earth based on his projection of its surface onto the inner surface of a cylinder. He coined the term *atlas* for a collection of maps.

Morgan, Thomas Hunt (1866–1945). An American geneticist, Morgan began his career as an embryologist, studying fertilization at the cell level. In 1907, after becoming a professor at Columbia University, he shifted his research to the mechanism of heredity. Initially critical of the gene concept, he became a major proponent of it after 1910 and trained a number of influential students, among them, Hermann Muller (below).

Morse, Samuel F. B. (1791–1872). Morse was a financially unsuccessful American artist who, returning from Europe in 1832 after a three-year stay, learned about electromagnetism from a fellow passenger. Morse became obsessed with the idea of an electric telegraph and, eventually, with advice from the physicist Joseph Henry, among others, succeeded in getting Congress to fund a pilot line from Baltimore to Washington in 1843. This inaugurated the commercialization of the telegraph using Morse's code.

Muller, Hermann Joseph (1890–1967). Born in New York City, Muller attended Columbia University and received his Ph.D. under Thomas Hunt Morgan's direction in 1916, by which time he was Morgan's active collaborator in research and publication. His Nobel Prize–winning discovery of genetic mutations induced by X-rays was made while he was at the University of Texas, but he spent the mid-1930s at the Institute of Genetics in the Soviet Union, leaving because of his opposition to Lysenko's anti-Mendelian theories, which were approved by Stalin. He returned to the United States in 1940.

Müller, Johannes (1801–1858). Müller was a German physiologist who was committed to the vitalist view of life and to Romantic nature philosophy, yet his research laboratory, first at the University in Bonn, then in Berlin, was the training ground for an extraordinary group of influential life scientists, virtually all of whom were mechanists!

Newton, Isaac (1642–1727). Great both as an experimental and as a theoretical physicist, Newton's "miraculous year" was 1665, when an outbreak of plague caused Cambridge University to close and he went home. In notebooks he kept then, there are the clear antecedents of most of his great ideas in

mechanics, optics, mathematics, and astronomy. Newton devoted much of his time (and the bulk of his surviving writing) to biblical chronology and interpretation and alchemical researches, yet he was the single most important architect of modern science. He was autocratic as warden of the Royal Mint and as president of the Royal Society, and suffered a mental breakdown in the early 1690s, perhaps poisoned by his alchemical experiments.

Pacioli, Luca (1445–1517). Renaissance mathematician, befriended by Piero della Francesca, and tutor to, and friend of, Leonardo da Vinci. Pacioli published a summary of 15th-century mathematics in 1494 that included an extensive description of double-entry bookkeeping and commercial arithmetic generally. His 1509 book, *On the Divine Proportion* (the famous Greek "golden ratio"), was written in Italian and illustrated by Leonardo. It describes the application of mathematical proportions to artistic depictions, for example, of the human body.

Parmenides (born c. 515 B.C.E.). One of the earliest and most influential Greek philosophers, in spite of the fact that his only work is lost, a poem of some 3000 lines, apparently, of which 150 are known because they are cited by other Greek philosophers. Parmenides's rigorously logical characterization of the concepts of being and becoming provoked atomistic theories of nature, in contrast to Heraclitus's process approach and influenced the view, dominant since Plato and Aristotle, that reality was timeless and unchanging and that knowledge and truth were universal, necessary, and certain.

Pascal, Blaise (1623–1662). A French mathematician and physicist, in 1654, Pascal had a vision that led him to cease almost all secular intellectual activity, although he designed a public transportation system for Paris that was built the year he died. He made important contributions to projective geometry and probability theory before turning to philosophical and theological themes. His *Pensées* has been in print since publication.

Pasteur, Louis (1822–1895). A French chemist, Pasteur became the very embodiment of the natural scientist, for the French at least. With Robert Koch, he formulated the germ theory of disease, but he also contributed to the creation of stereochemistry and established the value of chemical science to industry through his work on fermentation, pasteurization, vaccination, and silkworms.

Petrarch (1304–1374). An Italian poet, born in Arezzo, Petrarch was named Poet Laureate of Rome in 1341, largely because of an epic poem in Latin on the great Roman general Scipio Africanus, who defeated Hannibal. He was a great admirer of Dante, whose *Comedy* (called "divine" by Petrarch's admirer Boccaccio) was in Italian, not Latin. Petrarch instigated the Humanist movement and the collection of ancient manuscripts in order to recover models of the best writing, feeling, and thinking.

Planck, Max (1858–1947). The German physicist who initiated the quantum physics "revolution" with his 1900 solution to the black-body radiation problem. Planck remained in Germany in spite of his outspoken opposition to Nazi policies, and his only surviving son was gruesomely executed as an accomplice to an assassination plot on Hitler. After World War II, the Kaiser Wilhelm Institute was renamed the Max Planck Institute(s).

Plato (428–347 B.C.E.). The quintessential Greek philosopher from the perspective of the subsequent history of Western philosophy, Plato was one of Socrates's students and the teacher of Aristotle. "Plato" was his nickname—his given name was Aristocles—and he was initially a poet and, as a young man, a competitive wrestler. He was an elitist by birth and inclination, and the relationship between the "real" Socrates and the character in Plato's dialogues is, at best, loose.

Prigogine, Ilya (1917–2003). A Russian-born chemist who was raised, educated, and rose to fame in Belgium. He moved to the United States in 1961, first to the University of Chicago, then to the University of Texas, while retaining his Belgian academic affiliation. He demonstrated that many far-from-equilibrium physical and biological systems were self-organizing and stable and displayed adaptation.

Pythagoras (c. 572–c. 479 B.C.E.). A Greek philosopher and mathematician with a strong metaphysical/mystical bent. Pythagoras promoted a total lifestyle conception of wisdom and created schools and self-contained communities in which people could live in accordance with his teachings. His most enduring accomplishments are the idea of deductive proof, which essentially created mathematics as we know it, and the idea that mathematical forms are the basis of all natural order.

Quetelet, Adolphe (1796–1874). A Belgian astronomer-in-training whose lasting achievement was social statistics, especially the idea of statistical laws, which challenged the prevailing belief that laws were necessarily and exclusively deterministic.

Rumford, Count/Benjamin Thompson (1753–1814). A Royalist, Thompson fled the colonies to England in 1776, returning to the colonies as a British officer, then went to Europe after the war. He distinguished himself in Bavaria as minister of war and minister of police, becoming de facto prime minister, and was made count of the Holy Roman Empire in 1791. He instituted workhouses for the poor and new uniforms, marching formations, diet, and weapons for the army. In addition to his experiment in 1799, which proved that heat was motion, he founded the Royal Institution in London to teach science to the public, enjoyed a short-lived marriage to Lavoisier's widow, and endowed a science professorship at Harvard.

Rutherford, Ernest (1871–1937). Born in New Zealand, Rutherford went to Cambridge in 1895 to study with J. J. Thomson, then to McGill in Montreal as professor of physics, before returning for good to England in 1907. He was professor of physics in Manchester until 1919 when he moved to the Cavendish Laboratory at Cambridge as J.J. Thomson's successor. His 1908 Nobel Prize was in chemistry for his work on radioactivity, but he and his students made many fundamental contributions to atomic and nuclear physics.

Schleiden, Mathias (1804–1881). A German botanist who, with Theodor Schwann proposed the cell theory of life. Schleiden was originally a lawyer who turned to the study of botany after a failed suicide attempt. In 1838, he published an essay in a journal edited by Johannes Müller, proposing that cells are the basis of all plant life and are formed in a process that begins inside the nucleus of a progenitor cell. In an 1842 text, he argued that a single, mathematically describable physical force underlies all natural phenomena, including life.

Schrödinger, Erwin (1887–1961). Schrödinger was born in Vienna and received his Ph.D. there, in physics. He was an Austrian artillery officer during World War I and became a professor of physics in Zurich in 1921. It was at Zurich in 1925 that he developed his version of what was called "quantum mechanics," which unlike Heisenberg's version, was based on 19th-century deterministic wave physics and was interpretable as offering a conceptual "picture" of microphysical nature. Succeeding Max Planck as professor of theoretical physics in Berlin in 1927, he fled the Nazi takeover in 1933 for London; he returned to Vienna in 1936, only to flee again, this time, to Ireland until 1956 and yet another return to Vienna.

Schwann, Theodor (1810–1882). Schwann was born and educated in Germany and served from 1834–1838 as Johannes Müller's laboratory assistant in Berlin, but after a paper on yeast as a factor in fermentation was derided, he accepted a professorship in Belgium, where he spent his entire academic career. It was his 1839 book, *Microscopical Researches on the Similarity in the Structure and Growth of Animals and Plants*, that proposed the cell theory as the universal basis of both plants and animals, hence, of all life forms. Schwann thus extended Schleiden's cell theory of plant life, with which he was quite familiar; for this reason, the universal cell theory is attributed to them jointly.

Shannon, Claude (1916–2001). Shannon was born in Michigan and did his graduate work at MIT, receiving his master's and Ph.D. in mathematics in 1940 (with these in two different areas of applied mathematics). He joined Bell Labs in 1941. During the war, he worked on mathematical models for predictive antiaircraft firing. The technological applications of Shannon's theories in computer logic

circuit design, telephone switching circuits, computer networks, and electronic and optical information transmission and storage devices have had an incalculable social impact.

Shapley, Harlow (1885–1972). An American astronomer, Shapley originally planned to become a journalist after attending a new university journalism program in his home state of Missouri. He became an astronomer because the program was delayed and he chose to take astronomy courses while he waited! At Princeton from 1911 to 1914, Shapley did important observational work on double stars and variable stars and was, thus, well positioned, after his move to Mt. Wilson Observatory in 1914, to use Leavitt's variable-star–based cosmic "ruler" to estimate the size of the Milky Way and distances to the Magellanic Clouds.

Swift, Gustavus (1839–1903). Born and raised on Cape Cod, Swift dropped out of school after eighth grade and, at the age of 16, had his own butchering business, which prospered and expanded with each relocation. He and his partner moved to Chicago in 1875, and in 1878, he went his own way, commissioning the first successful refrigerated rail car. It was delivered in 1880, and a year later, he had 200 cars carrying 3000 dressed beef carcasses a week to New York City.

Tartaglia, Niccolò (aka Niccolò Fontana) (1499–1557). Tartaglia was a mathematician and engineer; as a boy, he was slashed through the cheek by a French knight, hence, his nickname, "stammerer" ("Tartaglia"). He discovered the general solution to the cubic equation (though Khayyam may have anticipated him, independently) and the parabolic trajectory of cannonballs. He made the first Italian translations of Euclid and Archimedes.

Thales (c. 624/620–c. 570/546 B.C.E.). According to Aristotle, Thales was the first Greek natural philosopher, speculating that water or some fluid was the universal "stuff" out of which all material objects were composed.

Thompson, Benjamin. See **Count Rumford**.

Thompson, Joseph John (1856–1940). Thompson was born near Manchester in England and planned on studying engineering, but because the family could not afford the apprenticeship fees for engineering training, he switched to physics, winning a scholarship to Cambridge—where he spent the rest of his life—and a Nobel Prize (in 1906). In 1884, he succeeded Lord Rayleigh, who had succeeded Maxwell, as Cavendish Professor of Physics and was succeeded in turn by Ernest Rutherford when he resigned in 1919 to become Master of Trinity College. His Nobel Prize was for discovering the electron and for studies of the conduction of electricity in gases, establishing the electron as a particle. (Thompson's son George won the Nobel Prize for physics in 1937 for showing that electrons behaved like waves!)

Thomson, William. See **Lord Kelvin**.

Virchow, Rudolf (1821–1902). A German biologist and another student of Johannes Müller's, Virchow focused his research on the cell, especially cellular pathologies, which he believed to be the basis of all disease. In the mid-1850s, he insisted on the principle that cells arise only from other cells by a process of division, utterly rejecting the possibility of spontaneous generation or other cell formation theories current at the time, among them, Schleiden's. His text *Cellular Pathology* was influential, and its ideas were the basis of his rejection of the Pasteur-Koch germ theory of disease. Like most biologists prior to the mid-1870s, Virchow defended the inheritance of acquired characteristics.

Vitruvius (fl. 1st century B.C.E.). Almost nothing is known about Vitruvius's personal life (even his full name is conjectural!), but the influence of his *On Architecture* since the Renaissance has been immense. The book was discovered in 1414 by the Humanist scholar Poggio Bracciolini and popularized by Leone Alberti in a major work on art and architecture, *On the Art of Building* (1452), that was dedicated to Pope Nicholas V, who initiated the construction of the Vatican complex.

Wallace, Alfred Russel (1823–1913). Wallace was born into a poor Welsh family and left school at 14 to become a surveyor under an older brother. Self-educated by local standards, he became a teacher at a workingman's school in 1844 when he met a young naturalist, Henry Bates, and discovered his true vocation. They traveled to Brazil together in 1848 to gather specimens for wealthy British collectors, and Wallace returned to England with crates' worth, all of which were lost when the ship sank approaching the English coast. He then spent 20 years, from 1842–1862, in the Malay Peninsula, collecting specimens and studying the distribution of plants and animals; this led to the essay proposing evolution by natural selection that he sent to Darwin in 1858 for his advice as to publication. Wallace became one of England's greatest naturalists, but he never accepted the extension of evolution to man. He was an aggressive supporter of radical social reform and of "scientific" spiritualism, believing in life after death.

Watson, James (1928–). Watson studied zoology at the University of Chicago and received his Ph.D. from Indiana University in 1950, where he was influenced by T.H. Morgan's former student Hermann Muller. Watson's Ph.D. thesis, under Salvador Luria, was on the effect of X-rays on bacterial cell division. In 1951, he met Maurice Wilkins, who had with him copies of X-ray diffraction patterns of DNA crystals, and Watson decided to spend time at the Cavendish Laboratory at Cambridge studying them. There he met Francis Crick and began their epochal collaboration.

Watt, James (1736–1819). A Scottish mechanic and instrument maker who opened a shop in Glasgow circa 1756 and began working for faculty members at Glasgow University. While repairing a Newcomen engine, Watt saw that the efficiency would be improved dramatically by separating the cylinder and the condenser. He built a crude working model in 1765, but a reliable engine for commercial application required solving problems involving valves, precision machining (for the day), and lubricants. Watt's partnership with Mathew Bolton from 1774 was heaven-sent, initiating the steam-power–based Industrial Revolution of the 19th century and freeing Watt to develop progressively more efficient and more useful designs that Bolton put into production.

Bibliography

Agricola, Georgius (Georg Bauer). *De Re Metallica*. Herbert Hoover, trans. New York: Dover, 1950. Bauer was a sort of chief medical officer for the Fugger mines in the 16th century, and this is a translation—by Herbert Hoover before he became president—of his survey of contemporary technologies related to mining, including medical technologies, of course.

Allen, Garland. *Life Science in the Twentieth Century*. Cambridge: Cambridge University, 1981. A solid history of biology in the first half of the 20th century.

Aristotle. *The Complete Works of Aristotle*. Jonathan Barnes, ed. Princeton: Bollinger, 1982. Aristotle's logical works include the *Prior* and *Posterior Analytics* and the *Rhetoric*. His scientific works include *On the Heavens*, *On Physics* (nature), *On the Soul*, *On Generation and Corruption*, and the *Generation of Animals*.

Augustine. *Confessions*. London: Penguin Books, 1961. Book 11 contains his penetrating analysis of time, and his style of writing reveals how intertwined his religious commitments were with his reasoning.

Bacon, Francis. *The New Organon*. New York: Bobbs-Merrill, 1960. Part 1 is the account of what we think of as the modern experimental method. Important and very readable.

Baeyer, Hans Christian von. *Information: The New Language of Science*. New York: Phoenix Press, 2004. A short, clear, current account of the emergence of information as a feature of reality on a par with matter or even superior to it as the "stuff" of reality.

Baird, Davis. *Thing Knowledge: A Philosophy of Scientific Instruments*. Berkeley: University of California Press, 2004. A provocative monograph on the connections among ideas, the artifacts we call instruments, and knowledge claims.

Barabasi, Alberto-Laszlo. *Linked: The New Science of Networks*. Cambridge, MA: Perseus, 2002. This book is a joy to read, and without having to confront an equation, you will learn a great deal about how mathematical forms can have properties that affect physical systems—here, networks, which are, of course, relational structures. Very highly recommended.

Barber, Elizabeth Wayland. *The Mummies of Urumchi*. New York: Norton, 1999. Barber is a historian of ancient textiles, and this analysis of what we can learn from the clothing on a mummified, 3200-year-old Caucasian family found in central Asia is fascinating. Highly recommended.

Barbour, J. Murray. *Tuning and Temperament*. New York: Dover, 2004. A clear and correct account of the responses of musicians, composers, musical instrument makers, and philosophers to Pythagoras's claim that musical harmonies are mathematical. Recommended.

Bernoulli, Jacob. *The Art of Conjecturing*. Edith Dudley Sylla, trans. Baltimore: Johns Hopkins University Press, 2006. Sylla's introductory chapter to Bernoulli's 1709 text is a wonderful essay on the early history of applying mathematics to real-world decision-making. Recommended.

Bernstein, Peter. *Against the Gods: The Remarkable Story of Risk*. New York: Wiley, 1998. A well-written and highly informative popular history of practical applications of probability theory. Recommended.

Bertalanffy, Ludwig von. *General Systems Theory*. New York: George Braziller, 1976. A reprint of Bertalanffy's pioneering text on the systems idea. Dated, of course, but reading it puts you in touch with original thinking.

———. *Problems of Life*. New York: Dover, 1952. Here, Bertalanffy focuses on applying the systems concept in biology but also makes connections to other sciences.

Billington, David P. *The Innovators: The Engineering Pioneers Who Made America Modern*. New York: Wiley, 1996. An easy-to-read, insightful series of vignettes about the commercialization of key technological innovations in the 19th century. Recommended.

———, and David P. Billington, Jr. *Power, Speed and Form: Engineers and the Making of the Twentieth Century*. Princeton: Princeton University Press, 2006. Billington and his historian son extend the earlier model to eight key 20th-century innovations.

Biringuccio, Vannoccio. *Pirotechnia*. New York: Dover, 1990. Like Agricola's book, this is a 16th-century survey of technologies available to "engineers" of the period, focusing on uses of fire, heat, and explosives but ranging more widely.

Bolter, J. David. *Turing's Man*. Chapel Hill: University of North Carolina Press, 1984. Bolter was a humanist scholar responding to the very early stages of the computer's penetration of society, but his book remains a valuable reflection on a socially transformative technology.

Braudel, Fernand. *The Wheels of Commerce: Civilization and Capitalism, 15th–18th Century*. New York: Harper and Row, 1979. This is the second volume of a magisterial three-volume work of social history. Highly recommended.

Buchwald, Jed Z., and Andrew Warwick, eds. *Histories of the Electron*. Cambridge, MA: MIT Press, 2001. A first-rate professional history of science, this collection of essays examines in detail the discovery of the electron in 1897, the response of physicists to that discovery, and the impact of the electron on physics theory.

Carroll, Sean B. *Endless Forms Most Beautiful: The New Science of Evo Devo*. New York: Norton, 2005. Evolutionary development, the *Evo Devo* of the title, is a leading expression of Darwinian theory today, and this book describes it very well.

Cercignani, Carlos. *Ludwig Boltzmann: The Man Who Trusted Atoms*. Oxford: Oxford University Press, 1998. A new, very good biography of Boltzmann by a physicist; describes his contributions to physics, among them, to the physical reality of atoms. Recommended.

Ceruzzi, Paul. *A History of Modern Computing*. Cambridge, MA: MIT Press, 2003. A good history by a professional historian of technology.

Chandler, Alfred D., and James W. Cortada. *A Nation Transformed by Information*. Oxford: Oxford University Press, 2000. The authors examine the impact of information technologies on U.S. society.

Cline, Barbara Lovett. *Men Who Made a New Physics*. Chicago: University of Chicago Press, 1987. Very readable, short intellectual biographies of a handful of physicists who fashioned relativity and quantum theory in the first half of the 20th century. Recommended.

Cohen, I. Bernard. *The Birth of a New Physics*. New York: Norton, 1985. Cohen was a great historian of early modern science; this short monograph is an account of mechanics emerging as the foundation of physics in the 17th century. Recommended.

Cohen, Jack, and Ian Stewart. *The Collapse of Chaos*. New York: Viking, 1994. This lively book focuses on the maturation of chaos theory into complexity theory, carrying James Gleick's earlier book *Chaos* into the early 1990s.

Coleman, William. *Biology in the Nineteenth Century*. Cambridge: Cambridge University Press, 1977. An excellent, short history of major ideas at the heart of 19th-century biological theories. Highly recommended.

Cooper, Gail. *Air-Conditioning America*. Baltimore: Johns Hopkins University Press, 1998. A good history of the co-evolution of air-conditioning technology and its commercial, industrial, and residential applications.

Copernicus, Nicolaus. *On the Revolutions of the Heavenly Spheres*. New York: Prometheus, 1995. You can—and should—read book 1 of this epochal work to experience Copernicus's revolutionary idea firsthand. (The rest of the book requires serious effort!)

Cortada, James W. *Before the Computer*. Princeton: Princeton University Press, 2000. An interesting history of calculator and tabulator technologies in the 19th and early 20th centuries and how they affected the conduct of business and business strategies.

Cutcliffe, Stephen H., and Terry Reynolds. *Technology and American History*. Chicago: University of Chicago Press, 1997. An excellent collection of essays from the journal *Technology and Culture* on how technologies have changed American society. Recommended.

Darwin, Charles. *On the Origin of Species*. Cambridge, MA: Harvard University Press, 1966. Reading Darwin's argument for what we call evolution is a powerful experience. Highly recommended, as is comparing it to Alfred Russel Wallace's essay "On the Tendency of Varieties to Diverge Indefinitely from Their Type" (download it from the Internet).

———. *The Descent of Man*. London: Penguin, 2004. The extension of evolution to mankind came 12 years after *Origin* (and Wallace rejected it!). Highly recommended.

Debus, Alan. *Man and Nature in the Renaissance*. Cambridge: Cambridge University Press, 1978. A classic monograph in a wonderful series of history-of-science monographs by Cambridge University Press. Recommended.

Dennett, Daniel C. *Darwin's Dangerous Idea*. New York: Simon and Schuster, 1996. Provocative, even controversial, but Dennett is a leading philosopher and a defender of a strict, strictly atheistical reading of Darwinism.

Descartes, René. *Discourse on Method* and *Rules for the Direction of the Mind*. London: Penguin, 1999. These two short works are Descartes' prescriptions for a deduction-based methodology as the foundation for modern science.

———. *The Geometry*. New York: Dover, 1954. Title notwithstanding, this long essay, published in 1637, proposes substituting algebra for geometry as the basis of mathematics.

Dohrn-van Rossum, Gerhard. *History of the Hour*. Chicago: University of Chicago Press, 1996. An excellent history of the weight-driven clock and its impact on late-medieval and Renaissance society. Highly recommended.

Drachmann, A. G. *The Mechanical Technology of Greek and Roman Antiquity*. Madison: University of Wisconsin Press, 1963. A scholarly monograph reviewing just what the title promises. Out of print but available used.

Drake, Stillman, and I. E. Drabkin. *Mechanics in Sixteenth-Century Italy*. Madison: University of Wisconsin Press, 1969. The authors, leading historians of early modern science, give a detailed account of the state of the art in which Galileo was trained. Modest mathematics required, but very informative.

Edgerton, Samuel Y., Jr. *The Heritage of Giotto's Geometry: Art and Science on the Eve of the Scientific Revolution*. Ithaca: Cornell University Press, 1994. Out of print, but a good introduction to the idea that Renaissance painting techniques contributed to the rise of modern science. Highly recommended. Edgerton's *The Renaissance Discovery of Linear Perspective* covers the same material.

Einstein, Albert. *Relativity: The Special and General Theory*. London: Penguin, 2006. In his own words, writing for a general audience, Einstein describes relativity theory, aiming at a broad conceptual understanding. Highly recommended.

Eiseley, Loren. *Darwin's Century: Evolution and the Men Who Discovered It*. New York: Anchor, 1961. Eiseley wrote beautifully about science, and the virtues of this book include its clarity and readability. Recommended in spite of many more recent works on this topic.

———. *The Firmament of Time*. New York: Atheneum, 1960. Here, the writing is center stage. The theme is the naturalization of time and man in the 19th century. Highly recommended.

Eisenstein, Elizabeth L. *The Printing Revolution in Early Modern Europe*. Cambridge: Cambridge University Press, 2005. An important scholarly study of the social impact of print technology—this is an abridged and illustrated edition of Eisenstein's two-volume *The Printing Press as an Agent of Social Change* (1984)—attributing that impact primarily to features of the technology. Adrian Johns's book (below) takes issue with this view.

Eldredge, Niles. *Darwin: Discovering the Tree of Life*. New York: Norton, 2005. Eldredge is an important evolutionary biologist. Here, he traces the development of the ultimate unity of all life forms in Darwin's thinking.

Elkana, Yehuda. *The Discovery of the Conservation of Energy*. Cambridge, MA: Harvard University Press, 1974. A very good, nontechnical history of the idea of energy and the foundation of thermodynamics. Recommended.

Euclid. *Euclid's Elements*. Dana Densmore, ed. T. L. Heath, trans. Santa Fe, NM: Green Lion Press, 2002. You probably hated it in high school, but this is one of the truly great works of the mind, exemplifying reason and knowledge for mainstream Western intellectuals right down to the present. Read it to appreciate the mode of reasoning it exemplifies. Highly recommended.

Galen of Pergamon. *On the Natural Faculties*. New York: Putnam, 1916; in the Loeb Classical Library series and reprinted by Kessinger in 2004. In this work, Galen pulls together many strands of Greek and Graeco-Roman medical thought and theory, as Euclid did for Greek mathematics and Aristotle for Greek logic.

Galilei, Galileo. *Dialogue Concerning the Two Chief World Systems*, 2nd rev. ed. Berkeley: University of California Press, 1962. This is the book that caused Galileo's trial for heresy. Did he advocate the view that the Earth moved around the Sun? Is this a "fair" scientific treatment of a controversial issue? Highly recommended.

Gamow, George. *Thirty Years That Shook Physics*. New York: Anchor, 1966. Gamow remains one of the least known of the great 20th-century physicists. This is a wonderful autobiographical memoir, often funny and somewhat irreverent, of the creation of quantum mechanics. Very highly recommended.

Gille, Bertrand. *Engineers of the Renaissance*. Cambridge, MA: MIT Press, 1966. Newer complement to Parsons (below) by a good French historian of technology; out of print but available used.

Gimpel, Jean. *The Medieval Machine: The Industrial Revolution of the Middle Ages*. New York: Holt, Rhinehart and Winston, 1976. Gimpel was an "amateur" historian in the best sense and an enthusiast for medieval and Renaissance technology as both beautiful and socially important. Easy to read yet packed with information. Highly recommended.

Gingrich, Owen. *The Book Nobody Read*. New York: Walker and Company, 2004. Gingrich is a leading historian of astronomy. Here, he traces the fate of copies of Copernicus's masterwork in the decades after its publication in 1543 as a way of assessing its influence.

Grafton, Anthony. *Leon Battista Alberti: Master Builder of the Italian Renaissance*. New York: Hill and Wang, 2000. Grafton is an intellectual historian, and this book, like his earlier biography of Jerome Cardan, gives an appreciation of the social-cum-intellectual context of a man who was at the center of art, business, and engineering in the late 16th century. Recommended.

Grant, Edward. *Physical Science in the Middle Ages*. Cambridge: Cambridge University Press, 1977. A very good, short monograph that surveys the major ideas, people, and places. A good source of leads to reading in greater depth about medieval nature philosophy as a seedbed of modern science.

Grattan-Guinness, Ivor. *The Norton History of the Mathematical Sciences: The Rainbow of Mathematics*. New York: Norton, 1997. Grattan-Guiness is the encyclopedic historian of mathematics, and this is a rich general reference to the subject.

Greene, Brian. *The Fabric of the Cosmos*. New York: Norton, 2004. A popular treatment of late-20th-century cosmology by a Columbia University physicist. Very well written. Recommended.

———. *The Elegant Universe*. New York: Norton, 1999. All you want to know about string theory and more at the turn of the 21st century. Well and clearly written.

Grendler, Paul F. *The Universities of the Italian Renaissance*. Baltimore: Johns Hopkins University Press, 2002. A scholarly study, narrow in scope, but this is the stuff of good history writing.

Ghiselin, Michael T. *The Triumph of the Darwinian Method*. Chicago: University of Chicago Press, 1984. A prize-winning monograph on the logic of Darwin's argument in the *Origin* and his methodology. Recommended.

Hacking, Ian. *The Taming of Chance*. Cambridge: Cambridge University Press, 1991. Very good social-intellectual history of probability theory. Well written and, like all of Hacking's books, insightful. Recommended.

Hall, Marie Boas. *The Scientific Renaissance, 1450–1630*. New York: Dover, 1994. For today's historians of science, this is a dated book, but it is enjoyable to read, highly informative without being stuffy, and not wrong. A good lead-in to Westfall's *Construction* (below).

Hankins, Thomas L. *Science and the Enlightenment*. Cambridge: Cambridge University Press. An excellent, short book on science in the 18th century, with an emphasis on science as an agent of social reform through its connection to the ideas of rationality and progress. Highly recommended.

Harman, P. M. *Energy, Force and Matter: The Conceptual Development of Nineteenth-Century Physics*. Cambridge: Cambridge University Press, 1982. A very good, tightly focused book. Highly recommended.

Harris, William V. *Ancient Literacy*. Cambridge, MA: Harvard University Press, 1989. A valuable, detailed study of literacy in ancient Greece and Rome; the spread of writing in law, politics, and daily life; and the emergence of a commercial book trade. Recommended.

Harvey, William. *On the Motion of the Blood in Man and Animals*. New York: Prometheus, 1993. This remains one of the most readable of all primary source works in early modern science, arguing in 1628 for the circulation of the blood driven by the heart. Recommended.

Haskins, Charles Homer. *The Renaissance of the Twelfth Century*. Cambridge, MA: Harvard University Press, 2005. A classic essay, now reissued, that remains a joy to read as a general introduction to a field now dominated by specialists. Highly recommended.

———. *The Rise of Universities*. New York: Transactions, 2001. Again, a reissued early study. Recommended.

Hero of Alexandria. *Pneumatica*. New York: American Elsevier, 1971. Always in print, this little book, written in the 2nd century, is a collection of ideas for machines. A fascinating insight into one facet of Graeco-Roman technology, but note that the illustrations are not original. Recommended.

Hesse, Mary. *Forces and Fields: The Concept of Action at a Distance in the History of Physics*. New York: Dover, 2005. A valuable and insightful historical study of recourse by natural philosophers and modern scientists to forces acting at a distance, as opposed to mechanical contact forces, in order to explain natural phenomena without invoking magic or spiritualism. Highly recommended.

Hodges, Andrew. *Alan Turing: The Enigma*. New York: Simon and Schuster, 1983. An excellent biography of Alan Turing and a clear treatment of the intellectual context out of which the idea of the computer emerged. Recommended.

Holland, John H. *Hidden Order: How Adaptation Builds Complexity*. Boston: Addison-Wesley, 1996. Short monograph on self-organization by a pioneer of complexity theory and creator of the computer program Life. Highly recommended.

———. *Emergence: From Chaos to Order*. New York: Perseus Books, 1999. Holland gives scientific content to the cliché that the whole is greater than the sum of its parts. Recommended.

Hughes, Thomas P. *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970*. Chicago: University of Chicago Press, 2004. Very good, very readable analysis of the relationships among technology, politics, and social values from the mid-19th through the mid-20th centuries. Recommended.

———. *Networks of Power*. Baltimore: Johns Hopkins University Press, 1983. Hughes is a dean of American historians of technology and this book shows why. It traces the relationships among invention,

innovation, commerce, politics, science, and society in the creation of America's electrical networks. Recommended.

Johns, Adrian. *The Nature of the Book*. Chicago: University of Chicago Press, 1998. Johns argues at length in this big book, with lots of supporting detail, that print technology enabled authoritative, uniform versions of a text only after an extended social struggle to create institutions that protected profit and reduced pirated editions and plagiarism. Recommended.

Jones, Richard A. L. *Soft Machines: Nanotechnology and Life*. Oxford: Oxford University Press, 2004. The commercial exploitation of nanotechnology and that of molecular biology in the early 21st century are converging; this popular account of the convergence is timely.

Kelley, Donald. *Renaissance Humanism*. New York: Twayne, 1991. A good introduction to the Humanist movement by a major scholar. Recommended.

Klein, Jacob. *Greek Mathematical Thought and the Origin of Algebra*. New York: Dover, 1992. An original analysis and survey of Greek mathematics, which was, after all, a decisive influence on modern science.

Kramer, Samuel Noah. *Sumerian Mythology*. Philadelphia: University of Pennsylvania Press, 1972. Kramer was one of the pioneers of the study of Sumerian texts. This book presents deciphered Sumerian religious texts.

Kuhn, Thomas. *The Copernican Revolution: Planetary Astronomy in the History of Western Thought*. Cambridge, MA: Harvard University Press, 1992. An excellent, important analysis of the intellectual legacy of Copernicus's astronomical ideas. Highly recommended.

Lamarck, Jean-Baptiste. *Zoological Philosophy*. Chicago: University of Chicago Press, 1976. Lamarck was a far more important figure than most 20th-century biologists are willing to allow. Read this for yourself and see that Lamarck is more than just the inheritance of acquired characteristics!

Landels, J. G. *Engineering in the Ancient World*. London: Chatto and Windus, 1978. Easier to find than Drachmann's book (above), though also out of print. Both are the real thing: Engineering-knowledgeable authors use surviving texts and artifacts to reveal what the Graeco-Romans knew how to do with machinery. Sounds stuffy, but it's fascinating detective work.

Lefevre, Wolfgang. *Picturing Machines, 1400–1700*. Cambridge, MA: MIT Press 2004. A collection of essays that survey the evolution of machine drawing during the Renaissance and its implications for machine design and construction and, more broadly, for technological innovation as a social force. Recommended.

Levere, Trevor. *Transforming Matter*. Baltimore: Johns Hopkins University Press, 2001. Histories of chemistry are rare, and readable ones (to non-chemists), rarer still; thus, Levere's book is recommended.

Lewontin, Richard. *The Triple Helix*. Cambridge, MA: Harvard University Press, 2000. Lewontin is a major figure in evolutionary biology, and in these four lectures, he describes what he thinks is wrong with the current linkage of evolution to molecular biology and genetics. Recommended (but be prepared for its relentless negativism!).

Lindberg, David C. *The Beginnings of Western Science*. Chicago: University of Chicago Press, 1992. A fine example of history-of-science writing and scholarship, surveying the Greek, Roman, Islamic, medieval, and early Renaissance antecedents of modern science. Recommended.

Lindley, David. *Boltzmann's Atom*. New York: Free Press, 2001. Where Cercignani's book focuses on Boltzmann and his scientific accomplishments, Lindley focuses on the idea of the atom in the 19th century and the context within which Boltzmann championed its reality.

Lloyd, Seth. *Programming the Universe*. New York: Knopf, 2006. Lloyd is a pioneer of the quantum computer and here describes, in nontechnical terms, his conception of the Universe as a quantum computational information structure. Recommended.

Lucretius. *On the Nature of the Universe*. London: Penguin, 1994. An important and, from the Renaissance on, influential statement of Epicurus's atomism that made the armature of a philosophy of nature and of man.

Mandelbrot, Benoit. *The Fractal Geometry of Nature*. San Francisco: W.H. Freeman, 1983. Mandelbrot pioneered the field of fractional dimensionality. This is a stimulating, accessible description of what fractals are and why they matter. Subsequently, they have become important tools in applied mathematics. Recommended.

Mann, Charles C. *1491: New Revelations of the Americas Before Columbus*. New York: Knopf, 2005. Mann is a journalist, synthesizing primary source material, and his claims are controversial, but they reflect the opinions of a growing number of scholars that the inhabitants of the Americas before 1492 were far more numerous and far more sophisticated than we have been taught.

Marenbon, John. *Later Medieval Philosophy*. London: Routledge, 1991. A good introduction to the knowledge issues in medieval philosophy, but this source also describes the rise of the universities and the translation of Greek and Roman texts from Arabic into Latin. Recommended.

Mayr, Ernst. *The Growth of Biological Thought*. Cambridge, MA: Harvard University Press, 1982. Mayr was one of the great evolutionary biologists of the 20th century and was still publishing as he approached 100! This is an excellent history of the great 19th-century ideas in biology. Recommended.

McClellan, James E., III, and Harold Dorn. *Science and Technology in World History: An Introduction*. Baltimore: Johns Hopkins University Press, 2006. Excellent social-historical interpretation of how technology and, later, science-through-technology have changed the world. Recommended.

Melsen, A. G. van. *From Atomos to Atom: The History of the Concept Atom* New York: Harper, 1952. A dated but charmingly literate monograph on the atomic idea from the Greeks to the 20th century. Out of print but available used. See Pullman below.

Misa, Thomas J. *A Nation Transformed by Steel*. Baltimore: Johns Hopkins University Press, 1995. An excellent example of the placement of history of technology in its social context. The displacement of iron by steel implicated science, technology, finance, industry, government, and society, and Misa does justice to them all. Highly recommended.

Morange, Michel. *A History of Molecular Biology*. Cambridge, MA: Harvard University Press, 1998. If you're going to read just one book about molecular biology, make it this one. Morange is a biologist, not a historian, so the focus is on the science, but the writing makes it very accessible.

———. *The Misunderstood Gene*. Cambridge, MA: Harvard University Press, 2001. Highly recommended critique of the still-prevalent view that genes do it all. What genes are and how they act is still being discovered.

Newton, Isaac. *The Principia*. I. Bernard Cohen and Anne Whitman, trans. Berkeley: University of California Press, 1999. This is one of the most influential science texts ever published, and in this new translation with extensive commentary, the general reader can learn directly from Newton! Highly recommended.

Nisbet, Robert. *A History of the Idea of Progress*. Piscataway, NJ: Transaction, 1994. Intellectuals have been critical of the idea of progress for most of the 20th century, but it remains a core public value and central to science and technology. Nisbet's book takes a positive view of progress and is a successor to J. B. Bury's classic *The Idea of Progress*. Recommended.

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*. New York: Twayne, 1996. A good short history of physical science as it became a driver of social change. Highly recommended.

Overbye, Dennis. *Lonely Hearts of the Cosmos*. Boston: Little, Brown and Co., 1999. A wonderful book that uses people, their ideas, and relationships as a means of describing the development of ideas about

the origin of the Universe since the 1950s. Highly recommended. (Read the revised 1999 edition or a later one.)

Parsons, William Barclay. *Engineers and Engineering in the Renaissance.* Cambridge, MA: MIT Press, 1968. A classic study of what the title promises. Still good enough after its original publication in the late 1930s to remain in print for decades, and now available used at reasonable prices. A big book.

Pesic, Peter. *Abel's Proof*. Cambridge, MA: MIT Press, 2003. Very short, very good (and nontechnical) account of how Niels Abel's proof of a negative about algebraic equations led to major innovations in 19th-century mathematics and in late-20th-century symmetry-based physics.

Plato. *Plato: The Collected Dialogues*. Edith Hamilton and Huntington Cairns, eds. Princeton: Bollingen, 1978. The dialogue *Phaedrus* contains Socrates's argument against writing; the dialogues *Thaeatetus* and *Timaeus* relate to knowledge of nature.

Porter, Roy. *The Rise of Statistical Thinking, 1820–1900*. Princeton: Princeton University Press, 1986. An excellent book; nicely complements Hacking (above), with a narrower focus.

Prager, Frank D., and Gustina Scaglia. *Brunelleschi: Studies of His Technology and Inventions.* New York: Dover, 2004. Brunelleschi not only reintroduced perspective drawing, but his dome for the cathedral in Florence was an epochal technological achievement, and he invented numerous machines to enable its construction. Recommended.

Prigogine, Ilya. *Order Out of Chaos*. New York: Bantam, 1984. A philosophical reflection on the challenge of process thinking to atomistic thinking. Highly recommended. (His later *From Being to Becoming* is more challenging technically.)

Provine, William. *The Origins of Theoretical Population Genetics*. Oxford: Oxford University Press, 2003. Ignore the forbidding title: This is an excellent book that exposes how Darwinian evolutionary theory was resurrected in the 1920s. Highly recommended.

Pugsley, Alfred, ed. *The Works of Isambard Kingdom Brunel*. Cambridge: Cambridge University Press, 1976. Brunel, typically for engineers, is unknown in spite of being one of a small community of men (including his father, Marc) responsible for making the world "modern." This is a collection of short essays (search for it used online) that reveal how much one of these men accomplished while knowing so little theory!

Pullman, Bernard. *The Atom in the History of Human Thought*. Alex Reisinger, trans. Oxford: Oxford University Press, 2001. A history of the atom from the Greeks to the 20th century. Given that the author was a professor of chemistry at the Sorbonne, this is a scientist's view of the history of a core scientific idea.

Raby, Peter. *Alfred Russel Wallace: A Life*. Princeton: Princeton University Press, 2001. A good biography of Wallace, who is still damned with faint praise by biologists. A leading scientist, a social reformer, and a spiritualist, Wallace deserves our attention. Recommended.

Randall, Lisa. *Warped Passages*. New York: Harper, 2005. If you're interested in learning about string theory, this is one breezily written option by a string theory researcher. I prefer Brian Greene's *The Elegant Universe* on this subject.

Ratner, Mark, and Daniel Ratner. *Nanotechnology: A Gentle Introduction to the Next Big Idea*. Upper Saddle River, NJ: Prentice Hall, 2002. Nanotechnology research, development, and commercialization, along with safety and health issues, are evolving at a breakneck pace, so consider this a good introduction to the underlying ideas and read the newspaper.

Robb, Christina. *This Changes Everything: The Relational Revolution in Psychology*. New York: Farrar, Straus and Giroux, 2006. Robb is a Pulitzer Prize–sharing journalist; this book describes how acknowledging the reality and causal efficacy of relationships affected clinical and theoretical psychology.

Rocke, Alan J. *Chemical Atomism in the 19th Century: From Dalton to Cannizaro.* Columbus: Ohio State University Press, 1984. An in-depth study of the early history of the atomic theory of matter, when it was mostly a theory for chemists.

Rudwick, Martin J. S. *The Meaning of Fossils*. Chicago: University of Chicago Press, 1985. All of Rudwick's books are excellent, and his most recent, *Bursting the Limits of Time*, is most relevant to the reconceptualization of time in the 19th century, but it is massive. This book is a gentler yet still highly informative study of the same subject. Highly recommended.

Scaglia, Gustina. *Mariano Taccola and His Book* De Ingeneis. Cambridge, MA: MIT Press, 1972. This is a very good edition, with scholarly commentary, of a Renaissance-era machine design book, symptomatic of the emergence of modern engineering. See Prager and Scaglia (above) and Scaglia's *Francesco di Giorgio*, a beautiful collection of Renaissance machine drawings with extensive commentary by Scaglia. Recommended.

Seife, Charles. *Decoding the Universe*. New York: Viking, 2006. A very readable account by a science journalist of how information has become physically real for many scientists. Recommended.

Shapin, Steven and Simon Schaffer. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life*. Princeton, New Jersey: Princeton University Press, 1985. A modern classic that exposes the equivocal character of experimental research using newly devised instruments by way of Thomas Hobbes' criticism of Robert Boyle's "discoveries" and the Royal Society as an institution. Recommended.

Singleton, Charles. *Art, Science, and History in the Renaissance*. Baltimore: Johns Hopkins University Press, 1968. An alternative to Edgerton (above); also out of print but available used at more reasonable prices.

Smolin, Lee. *The Trouble with Physics: The Rise of String Theory, the Fall of Science, and What Comes Next*. Boston: Houghton Mifflin, 2006. One of several recent attacks on string theory by physicists who claim that it is a dead end and bad science. I admire Smolin's earlier books, especially *Three Roads to Quantum Gravity*, and his criticisms are legitimate, but the book's primary value is as one skirmish in a "war" within physics.

Sorabji, Richard. *Matter, Space and Motion: Theories in Antiquity and Their Sequel*. Ithaca: Cornell University Press, 1988. A survey by a philosopher of materialist theories of nature from the earliest Greek philosophers through the 6th century. This complements Lindberg's book, above.

Stachel, John. *Einstein's Miraculous Year*. Princeton: Princeton University Press, 1998. Stachel is the editor of the Einstein papers and here offers the historic 1905 articles in translation with enough commentary for anyone to follow their arguments. Highly recommended.

Stephenson, Bruce. *The Music of the Heavens: Kepler's Harmonic Astronomy*. Princeton: Princeton University Press, 1994. Here, you can see the authority given to the Pythagorean idea that mathematical form was the indwelling order of nature underlying its expression in matter and that this order was fundamentally musical. Recommended.

Strogatz, Steven. *SYNC: The Emerging Science of Spontaneous Order*. New York: Hyperion, 2003. A readable book for a general audience on self-organization, bringing Prigogine's early ideas up-to-date. Strogatz is himself a researcher in this field.

Susskind, Leonard. *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design*. Boston: Little, Brown and Co., 2006. As if to counter Smolin's rant against string theory, one of its architects describes the theory as if its triumphant completion and confirmation were imminent! Stranger than science fiction. Recommended.

Swade, Dorn. *The Difference Engine*. London: Penguin, 2002. An excellent book that makes reading about Charles Babbage's failed quest to build a computer in the mid-19th century fun. The effort and its failure reveal much about the science-technology-society relationship. Highly recommended.

Taylor, George Rogers. *The Transportation Revolution*. New York: Harper, 1968. A solid history of the 19th-century transportation technology innovations that literally changed the world.

Travis, Anthony. *The Rainbow Makers*. Bethlehem, PA: Lehigh University Press, 1983. The fascinating story of how a teenager discovered the first synthetic dye and triggered the first "Silicon Valley" phenomenon, in which chemical science, industry, and government created enormous wealth and power. Recommended.

Uglow, Jenny. *The Lunar Men: Five Friends Whose Curiosity Changed the World*. New York: Farrar, Straus and Giroux, 2002. Wonderful account of the interactions of a group of thinkers and doers at the turn of the 19th century whose members included James Watt and Mathew Boulton, Erasmus Darwin and Josiah Wedgwood (both of them Charles Darwin's grandfathers!), and Joseph Priestley. Highly recommended.

Vitruvius. *The Ten Books on Architecture*. New York: Dover, 1960. More than 2000 years old, still in print, and still worth reading!

Watson, James D. *The Double Helix*. New York: Signet, 1968. No scientist had written such a tell-it-all account of how his research was done before this book. Highly recommended.

———. *DNA*. New York: Knopf, 2003. Now an honored senior, Watson describes the state of our understanding of how DNA works for a general audience. Recommended.

Webster, Charles. *The Great Instauration*. London: Peter Lang, 2002. Webster describes the social context of 17th-century England—especially the religious, political, social reform, and medical contexts—in which early modern science took root.

Weinberg, Steven. *Dreams of a Final Theory*. New York: Pantheon, 1992. Weinberg shared a Nobel for the first step in the unification of the four fundamental forces of nature and here anticipates the implications of full unification. Not dated because there has been little progress since 1992!

Westfall, Richard S. *Never at Rest: A Biography of Isaac Newton*. Cambridge: Cambridge University Press, 1980. The definitive personal and intellectual biography of Newton. Highly recommended.

———. *The Construction of Modern Science*. Cambridge: Cambridge University Press, 1989. Short, excellent introduction to the ideas at the heart of 17th-century science and its accomplishments. Highly recommended, as are all the monographs in the Cambridge History of Science series.

White, Lynn. *Medieval Technology and Social Change*. Oxford: Oxford University Press, 1966. White describes the social impact of the stirrup, wind power, and agricultural innovations, overstating the case but calling attention to technology as a force driving social change when most historians ignored it.

Williams, Trevor. *A History of Invention*. New York: Checkmark Books, 1987. It looks like a coffee table book, but Williams is a scholar and the book is filled with lots of valuable information without reading like an encyclopedia.

Wilson, Catherine. *The Invisible World: Early Modern Philosophy and the Invention of the Microscope*. Princeton: Princeton University Press, 1995. An important study of the interaction of ideas and instruments, theories of nature and observations. Recommended.

Worboys, Michael. *Spreading Germs: Disease Theories and Medical Practice in Britain, 1865–1900*. Cambridge: Cambridge University Press, 2000. An account of the response of the British medical community to the germ theory of disease as that theory evolved. Recommended.

Zachary, G. Pascal. *Endless Frontier: Vannevar Bush, Engineer of the American Century*. Cambridge, MA: MIT Press, 1999. A good biography of the man who was the "czar" of harnessing science and technology to the World War II effort and who promoted the postwar policy of federal support for scientific research.

Zagorin, Perez. *Francis Bacon*. Princeton: Princeton University Press, 1998. A very good biography of Bacon, doing justice to him as a social reformer, political opportunist, and philosopher of nature. Recommended.

Internet Resources:

Stanford Encyclopedia of Philosophy. A superb resource for the history of philosophy, of uniformly high quality, guaranteed to illuminate and please. Includes outstanding entries on many science topics—try advanced search. http://plato.stanford.edu.

University of Delaware Library. *Internet Resources for History of Science and Technology*. A "super" site for exploring the history of technology and of science from antiquity to the present. www2.lib.udel.edu/subj/hsci/internet.html.

Ancient Languages and Scripts. An informative site on the history of writing. www.plu.edu/~ryandp/texts.html.

The Labyrinth: Recourses for Medieval Studies. A "super" site listing resources for exploring Medieval culture. http://labyrinth.georgetown.edu.

The Art of Renaissance Science. A rich, multi-disciplinary site created by Joseph Dauben on the relationships among art, mathematics and science in the Renaissance. www.mcm.edu/academic/galileo/ars/arshtml/arstoc.html.

The Galileo Project. An excellent resource site for everything to do with Galileo's life, works and ideas. http://galileo.rice.edu.

The Newton Project. A similar, and similarly excellent resource, for the life, works and ideas of Isaac Newton. www.newtonproject.ic.ac.uk.

University of St. Andrews School of Mathematics and Statistics, *The MacTutor History of Mathematics Archive*. A very good resource for the history of mathematics; the Biographies on the site offer a comprehensive history of mathematicians and their accomplishments. www-history.mcs.st-and.ac.uk/.

Selected Classic Papers from the History of Chemistry. An outstanding collection of the full text of classic papers in the history of chemistry. http://web.lemoyne.edu/~giunta/papers.html.

The Nobel Foundation. Official web site offering access to all Nobel Prize winners, their biographies and accomplishments, and their acceptance addresses; a rich and fascinating history of science resource. http://nobelprize.org.

The History of Computing. An excellent collection of materials and links for exploring the history of computers and computing. http://ei.cs.vt.edu/~history/.

NASA History Division. A central site for aerospace history. http://history.nasa.gov.

The Official String Theory Website. The "home page" for accessible accounts of string theory. http://superstringtheory.com.

Sunny Y. Auyang. “Scientific convergence in the birth of molecular biology.” Very good essay on the history of molecular biology. Other articles available on this idiosyncratic yet interesting website by a respected scientist address engineering, including a useful history of engineering, biomedicine, and physics. www.creatingtechnology.org/biomed/dna.htm.

National Nanotechnology Initiative. The official Web site for federally funded nanotechnology research and development. www.nano.gov.

Great Scientific Ideas That Changed the World

Part II

Professor Steven L. Goldman

THE TEACHING COMPANY ®

PUBLISHED BY:

THE TEACHING COMPANY
4151 Lafayette Center Drive, Suite 100
Chantilly, Virginia 20151-1232
1-800-TEACH-12
Fax—703-378-3819
www.teach12.com

Printed in the United States of America

ISBN 978-1-59803-305-2

Steven L. Goldman, Ph.D.
Departments of Philosophy and History, Lehigh University

Steven Goldman has degrees in physics (B.Sc., Polytechnic University of New York) and philosophy (M.A., Ph.D., Boston University) and, since 1977, has been the Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University. He has a joint appointment in the departments of philosophy and history because his teaching and research focus on the history, philosophy, and social relations of modern science and technology. Professor Goldman came to Lehigh from the philosophy department at the State College campus of Pennsylvania State University, where he was a co-founder of one of the first U.S. academic programs in science, technology, and society (STS) studies. For 11 years (1977–1988), he served as director of Lehigh's STS program and was a co-founder of the National Association of Science, Technology and Society Studies. Professor Goldman has received the Lindback Distinguished Teaching Award from Lehigh University and a Book-of-the-Year Award for a book he co-authored (another book was a finalist and translated into 10 languages). He has been a national lecturer for Sigma Xi—the scientific research society—and a national program consultant for the National Endowment for the Humanities. He has served as a board member or as editor/advisory editor for a number of professional organizations and journals and was a co-founder of Lehigh University Press and, for many years, co-editor of its Research in Technology Studies series.

Since the early 1960s, Professor Goldman has studied the historical development of the conceptual framework of modern science in relation to its Western cultural context, tracing its emergence from medieval and Renaissance approaches to the study of nature through its transformation in the 20th century. He has published numerous scholarly articles on his social-historical approach to medieval and Renaissance nature philosophy and to modern science from the 17th to the 20th centuries and has lectured on these subjects at conferences and universities across the United States, in Europe, and in Asia. In the late 1970s, the professor began a similar social-historical study of technology and technological innovation since the Industrial Revolution. In the 1980s, he published a series of articles on innovation as a socially driven process and on the role played in that process by the knowledge created by scientists and engineers. These articles led to participation in science and technology policy initiatives of the federal government, which in turn led to extensive research and numerous article and book publications through the 1990s on emerging synergies that were transforming relationships among knowledge, innovation, and global commerce.

Professor Goldman is the author of two previous courses for The Teaching Company, *Science in the Twentieth Century: A Social Intellectual Survey* (2004) and *Science Wars: What Scientists Know and How They Know It* (2006).

Table of Contents
Great Scientific Ideas That Changed the World
Part II

Great Scientific Ideas That Changed the World

Scope:

It is easy to fall into one of two traps in dealing with ideas: either to dismiss them as abstractions and, thus, of less consequence than concrete things, such as swords, plowshares, and factories, or to glorify them *as* abstractions, as creative inventions of the mind, and thus, praiseworthy independent of any practical consequences whatsoever. Ideas are, nevertheless, as concrete as swords and plowshares because they are always tied to a concrete context of values, actions, beliefs, artifacts, and institutions out of which they arise and on which they *may* act. The concreteness of ideas derives from their being produced not only *within* a particular cultural context but *out* of that context, and it is because ideas are produced out of a particular context that ideas are able to influence and even to reshape that context. Treating ideas out of context, then, treating them as if their existence were, in principle, independent of any particular context, deeply distorts the reality of ideas and obscures their power to affect the world.

Ideas and their contexts interact in complex, *mutually* influential ways such that the resultant effect on society of introducing a new idea is unpredictable. The evolution of the Internet from a modest computer networking project funded by the U.S. Department of Defense to a global technology transforming commerce, industry, politics, warfare, communication, education, entertainment, and research illustrates the unpredictability of the idea-social context interaction. The still-unfolding consequences of a small number of innovative ideas introduced to solve technical problems posed by enabling different kinds of computers in different locations to share information in real time continue to surprise, confound, and disturb us!

Unpredictable though it may be, however, for 200 years now, the interaction of science and technology with society has been the primary driver of social and cultural change, first in the West, then globally and at an accelerating rate. During this period, social and personal values and relationships; social, political, and economic institutions; and cultural values and activities have changed and continue to change almost beyond recognition by our great-grandparents. What is it that has enabled such deep transformations of ways of life that have been entrenched for centuries and even millennia?

Certainly, we can identify artifacts—the telephone, the automobile, airplanes, television, the computer—that *appear* to be causes of social change. But identifying artifacts does not reach down to the *causes* of innovation itself, nor does it expose those features of the sociocultural infrastructure that enable innovations to be causes of social change. Artifacts, in spite of their high visibility, are symptoms of causes at work; they are not themselves causes. It is not television or automobiles or the Internet that have changed society. Instead, forces at work within the network of relationships that we call society are causing television and automobiles and the Internet to take the changing forms that they take. One of these forces is ideas, explicitly in the case of new scientific ideas and implicitly in the case of ideas in the past that have been internalized selectively by society, thereby shaping both the sociocultural infrastructure and the lines along which it is vulnerable to change.

The objective of this course is to explore scientific ideas that have played a formative role in determining the infrastructure of modern life through a process of sociocultural selection. But we shall interpret the term *scientific idea* broadly. There is, after all, no sharp distinction between ideas that are classified as scientific and those that are classified as philosophical or mathematical or even between scientific ideas and political, religious, or aesthetic ideas. Alfred North Whitehead, for example, famously linked the emergence of modern science in the Christian West to Judaeo-Christian monotheism: to the belief in a single, law-observing creator of the Universe.

The idea that there are laws of nature at least *seems* to reflect a political idea, while there can be no doubt that mathematical and aesthetic ideas were central to the 17th-century Scientific Revolution. Furthermore, distinguishing science and technology is fuzzy, too, especially since the second half of the 19th century,

when scientific knowledge and technological innovation were systematically coupled in industrial, academic, and government research laboratories.

With this in mind, we will begin our discussion of influential scientific ideas with the invention of writing, which may not seem a scientific idea at all. There is, nevertheless, a profound idea underlying the invention of writing, and a controversial one, as reflected in Socrates's argument *against* writing in Plato's dialogue *Phaedrus*. Writing is also a technology, of course, and thus, serves as an initial example of how technologies embody ideas that we tend to ignore because our attention is almost always drawn to *what* technologies do, to *how* they do it, and to what the consequences are of what they do.

By the time of the earliest written records that have been discovered so far, humans already had embodied, through their invention of a breathtaking range of physical, social, and cultural "technologies," an equally breathtaking range of ideas implicit in those technologies. Lecture One looks back at what humans had accomplished in the way of know-how by the 4th millennium B.C.E., while Lecture Two discusses the invention of writing and the spread of writing systems and texts from about 3500 B.C.E. to the beginning of classical antiquity, circa 500 B.C.E.

Between approximately 500 B.C.E. and 300 B.C.E., Greek philosophers developed highly specific concepts of knowledge, reason, truth, nature, mathematics, knowledge of nature, and the mathematical basis of knowledge of nature in ways that continue to inform the practice of science to the present day. Lectures Three through Five are devoted to these ideas and their legacy. Lecture Six discusses the first appearance in Western history, perhaps in world history, of the idea of techno-science, that is, of technology derived from theoretical knowledge rather than from practical know-how. This was largely a Greek idea that was applied in the context of the rising Roman Empire, and the lecture describes selected Roman-era technologies that had an influence on the rise of modern science and engineering.

Bridging the ancient and early modern eras, Lectures Seven through Eleven explore the idea of the university and its role as a progenitor of modern science; medieval machinery and Europe's first "industrial revolution"; and the Renaissance ideas of progress, of the printed book, and of mathematics as the language of nature. All these ideas are obviously seminal for science as we know it, but they are also, if less obviously, seminal for the rise of modern engineering and the form of modern technological innovation.

Lecture Twelve discusses Copernicus's idea of a moving Earth, the cultural consequences of that idea, and its subsequent evolution as a modern scientific astronomical theory. This serves as a lead-in to Lectures Thirteen through Seventeen, which explore foundational ideas of modern science, among them, the idea of method; new mathematical ideas, such as algebra and the calculus; ideas of conservation and symmetry; and the invention of new instruments that extended the mind rather than the senses and forced a new conception of knowledge.

Lectures Eighteen through Twenty-Eight explore 19th-century scientific ideas that remain profound social, cultural, and intellectual, as well as scientific, influences. These include the idea of time as an active dimension of reality, not merely a passive measure of change; the chemical atom as an expression of a generic idea of fundamental units with fixed properties, out of which nature as we experience it is composed; the ideas of the cell theory of life, the germ theory of disease, and the gene theory of inheritance, all conceptually allied to the atom idea; the ideas of energy, immaterial force fields, and structure and, thus, of relationships as elementary features of reality; the idea of systematically coupling science to technology, of coupling knowing to doing, and of using knowledge to synthesize a new world; the idea of evolution and its extension from biology to scientific thinking generally; and the idea that natural phenomena have a fundamentally probable and statistical character.

Lectures Twenty-Nine through Thirty-Five discuss central 20th-century scientific ideas, including the gene, relativity and quantum theories, the expanding Universe, computer science, information theory,

molecular biology, and the idea of systems, especially self-organizing systems and the allied ideas of ecology and self-maintaining systems.

Appropriately, Lecture Thirty-Six concludes the course by reviewing the ideas that are distinctive of modern science and technology today and anticipating ideas likely to be drivers of change tomorrow, focusing in particular on cognitive neuroscience, biotechnology and nanotechnology, and physicists' search for a theory of everything.

Lecture Thirteen

The Birth of Modern Science

Scope:

One enduring mystery of modern science is why it happened where and when it did, in the Christian culture of 17th-century western Europe. Had modern science emerged in late Graeco-Roman antiquity, in 11th- or 12th-century Islam, or in China anytime after the Tang dynasty, there would be no mystery. One clearly crucial development was the idea that knowledge of nature can be developed only by applying a radically impersonal method to personal experience, a method that generates accounts of experience to be validated by observation, prediction, and control and replication by others. In truth, no one method was common to all the founders of modern science. Francis Bacon claimed that the only correct method was based on induction; René Descartes, that it was based on deduction; and Galileo Galilei, that it was based on a fusion of experimentation and deduction, following the model of Archimedes. All agreed, however, that method was central.

Outline

I. Modern science aspired to being a natural philosophy, which implied having knowledge of nature, not just opinions or beliefs.

- **A.** The Scientific Revolution was more evolutionary than revolutionary.
  1. Many of the ingredients that went into the making of modern science were at hand at the turn of the 17th century.
  2. These were supplemented by contributions from Islamic culture, the medieval university, and the 12th-century "renascence."
  3. The 15th and 16th centuries were extraordinarily dynamic.
- **B.** The level of scientific, mathematical, and technological activity and innovation reached or surpassed its Classical peak in the West.
  1. Practical concerns and the pursuit of "scientific" truths put a high premium on systematic experience and experimentation.
  2. The Humanists built an interconnected, international network of scholars sharing a common set of critical values and institutions.

II. Modern science can be new without any of its features being new.

- **A.** Modern science *was* new, and it *did* have a critical new feature.
  1. The new feature was method, the idea that achieving knowledge of nature was critically dependent on following a method.
  2. The discovery of "the" scientific method is said to have triggered the Scientific Revolution.
  3. The founders of modern science did share a concern with a problem posed by knowledge of nature that satisfied the Platonic-Aristotelian definition of *knowledge*: How can we have universal, necessary, and certain knowledge of nature if our only access to nature is experience—particular, concrete, continually changing?
  4. The founders of modern science used different methods to solve that problem.
  5. They also inherited a great deal from scientists of the 16th century.
- **B.** There seems to have been no such thing as "the" one scientific method, but method *was* a necessary condition of modern science.
  1. René Descartes and Francis Bacon proposed very different methods for discovering

knowledge of nature.

2. The most famous early modern scientists employed methods that were different from those of Descartes *and* of Bacon.
3. To this day, there is no single specifiable method that a student can be taught that guarantees success in discovering new knowledge.

C. Francis Bacon was an English lawyer, jurist, and educational reformer who is called the father of the experimental method.

1. Bacon's interest in science was as a generator of the knowledge of nature that would translate into technological control over nature.
2. In *The New Organon*, he argued that only a total reform of reason could lead to knowledge of nature.
3. He cited four "idols" of the mind that must be overcome in order to reason effectively about nature because the greatest obstacle to achieving useful knowledge of nature was the mind itself.
4. Bacon proposed a strictly "mechanical" approach to the study of nature based on experimentation and *inductive* reasoning.

D. Bacon's only application of his method to a scientific problem then current was to the nature of heat.

1. Heat was either motion of the small material particles of which large objects were composed, or an invisible fluid called *caloric*.
2. Neither caloric nor the microscopic motions claimed to be heat can be observed directly.
3. As with Copernicus, the object of scientific knowledge is an unexperienced reality that is the cause of experience.
4. This is fully consistent with the definition of knowledge as universal, necessary, and certain.
5. For Bacon, scientific knowledge accumulated over time and its ultimate test was the ability to predict and control experience.
6. The founders of the Royal Society of London looked to Bacon as the guiding spirit of the new experimental philosophy of nature.

E. René Descartes has a greater claim than Bacon to be a father of modern science but of a very different sort of science.

1. For Descartes, deductive reasoning was the only route to knowledge of nature, which he, too, claimed would give us useful power over nature.
2. In his *Discourse on Method* and *Rules for the Direction of the Mind*, Descartes outlined a deductive methodology for science.
3. Central to this were innate ideas and a mental faculty of intuition.
4. He proposed a strictly mechanical philosophy of nature that evolved into materialistic determinism and prohibited any forces other than direct contact.
5. Although this proved to be too limiting, it continued to be the metaphysical framework of modern science into the 19th century.

F. Descartes' deductive method had a strongly logical character, where Baconian induction had a strongly empirical character.

1. For Descartes, induction could never guarantee the truth of the universal generalizations that comprised knowledge.
2. Scientists needed to invent hypotheses that *could* be true and successfully deduce phenomena from them.
3. Isaac Newton opposed this methodology with its invention of hypotheses that "worked,"

arguing that the goal of science was to discover the “true causes” of natural phenomena.

4. Newton, like Galileo, practiced the brand of mathematical physics that Archimedes wrote about 1900 years earlier, in texts recovered and published by the Renaissance Humanists.
5. This is quite clear in Galileo’s *Discourses on Two New Sciences*, his last book and his most important scientific work, though his *Dialogue Concerning the Two Chief World Systems* is better known.

Essential Reading:

Francis Bacon, *The New Organon*.

Richard S. Westfall, *The Construction of Modern Science*.

Questions to Consider:

1. It seems impossible to bridge the logical gulf between induction and deduction; what confidence can we have, then, in the truth of universal scientific theories and “laws” of nature?
2. Did Galileo really “see” moons orbiting Jupiter through his telescope, or did he see moving dots that he interpreted to be moons, and what difference does it make if the latter is true?

Lecture Thirteen

The Birth of Modern Science

The subject of this lecture is the invention of modern science. So we've arrived at the 17^{th} century, which is the locus of what is usually called the scientific revolution, but I certainly hope that at this point we recognize that the emergence of modern science, the recognizable emergence of modern science in the 17^{th} century, was much more of an evolutionary phenomenon than a revolutionary phenomenon.

It was not necessary that the scientific revolution emerge in the 17^{th} century as far as anyone can tell. It was not inevitable and had not been predicted. It probably was not predictable, given the fact that we might have predicted it in the late Roman Empire or in the 14^{th} century. It was not predictable that it would happen just then or in Western Europe, but nevertheless, modern science clearly did not just drop down out of the sky like some deus ex machina in a Greek play. Modern science did not just suddenly appear out of nowhere.

Once it appeared we can see that it represents the integration, the synthesis, of a lot of pieces that had been around from the time of ancient Greece and Rome, through the medieval period and especially the university context that I described, and all of the dynamism of the Renaissance that we discussed in the previous lecture. So that the pieces were all there. What happened in the 17^{th} century is that a glue was added to hold all of those pieces together, and that glue seems to be the idea of method.

And so there is, in fact, this typical characterization of the rise of modern science that it is the result of the discovery or invention of the scientific method. And once people grasped the scientific method, then all of a sudden all of the available tools came together in a way that generated the theories characteristic of the rise of modern science, especially the work of people like Descartes and Galileo and Christiaan Huygens in Holland, and Isaac Newton and Gottfried Leibniz. And then we march into the 18^{th} century, the 19^{th}, 20^{th}, and here we are, the heirs of the riches generated by the scientific method.

Now I'm going to suggest that in fact method was a critical factor in pulling together all the pre-existing pieces that contribute to modern science: the Greek idea of knowledge; the Greek idea of knowledge of nature; the Greek idea of mathematics being the language of nature; the idea of techno-science as it arose in the Greco-Roman period; the medieval university with its sort of revival of Greek and Roman natural philosophy, with the focus on experimentation, on the use of mathematics to describe natural phenomena, and with its deep commitment to the idea that nature was a closed system, and that all natural phenomena had natural rather than supernatural explanations.

And then the Renaissance with its recovery of ancient learning, especially the great mathematical texts of classical antiquity, which allowed European mathematics not to have to reinvent the number, as it were, but by inheriting Greek mathematics and Islamic algebraic mathematics that 16^{th} century European mathematicians were able to start from already a pretty high level. Then that emerged in the 17^{th} century as an enormous flourishing of mathematics providing tools for people to apply mathematics to natural phenomena. All of these pieces, not to mention the technology of the Renaissance that I described two lectures ago, all of that represents the pieces that I'm talking about, and method is the glue.

However, I think that the crucial thing to recognize is that there is no such thing as "the" scientific method. Method was central to 17^{th} century nature philosophy that sort of morphed into what we recognize as modern science, but there was no one method that all of the founders of modern science used. What is interesting and important is that a sensitivity to methodological issues was the common denominator of the founders of modern science. That is very consistent with the focus that I've made since the beginning of this course on the idea of knowledge as being central to the idea of science and now to the idea of modern science.

What the founders of modern science, the people that all historians point to as the founding figures in modern science, what all of them were concerned about was this idea of knowledge of nature, and the problem that we saw that Aristotle recognized, that the medieval university recognized in the problem of universals: How can we have universal, necessary, and certain knowledge of nature if our only access to nature is experience, and experience is particular, concrete, and continually changing? So that becomes an explicit and self-conscious issue that the founders of modern science wrestled with even as they insisted that, as a matter of fact, it was possible to have knowledge of nature, understanding now that it was what was behind experience. And this could not have emerged without the recognition that what they were doing was building on what their predecessors had done.

It was not a fluke that Copernicus, for example, is perceived as one of the leading contributors to the origin of modern science. His idea of a moving earth was very important to the mindset of modern science—1543, that's 16th century; that's not the 17th century scientific revolution. Well, but you say, it's not very precise; there were, of course, some outliers. But it wasn't a matter of outliers.

The same year, 1543, Andreas Vesalius, at that time in Padua at the University of Padua, transformed the study of human anatomy by publishing the first what we would call "scientific" anatomy of the human body with beautiful illustrations and systematically disassembling the human body from the skin down to the skeleton, and revealing the entire structure of the human body.

Vesalius, who soon left the University of Padua because of the fame that he accrued, initiated a line of inquiry and research at the University of Padua that went on for at least a century or more, because William Harvey—the British physician who we give credit to for discovering the full circulation of the blood being pumped around by the heart, although he didn't use exactly that language in 1628, in his book then—he had studied at the University of Padua. He specifically went to the University of Padua because that was a place that was famous for what we would call "scientific medical research." Vesalius's students and their students made fundamental discoveries. In the period of 1543 on, there was an enormous growth in the body of biological and botanical, let's call it information, because I don't want to use the word "knowledge" loosely, having made such a fuss about it.

So the founders of modern science were inheriting a great deal. They were building on a great deal. To call it a revolution is fundamentally misleading because it makes light of—it's as if, well, we have to start all over again, and that's not the case—it was an evolution in which a sensitivity to method and the idea of knowledge played a key role in allowing people to integrate all of these pieces that were sort of ready—maybe ready is unfair—they were available. They were lying around, so to speak, and could be pulled together, and were pulled together by the people who founded modern science.

So who were these people and what were they doing? Well, one of the standard figures to point to is Francis Bacon. Francis Bacon is often called—especially by the British—the father of experimental science, or the father of the experimental method. Bacon was a lawyer by training and eventually rose to become the position that we would call in the United States Chief Justice of the Supreme Court in the court of King James. From political intrigue he was accused of corruption and was removed from office, although subsequently the penalty was abated—it was a very substantial financial penalty. And that was just, so to speak, his day job.

His real vocation was he was a social and educational reformer, as I mentioned before, and in the area of what made him famous in science was his tremendous emphasis, I would say his dedication to the idea, that knowledge of nature was the key to social reform. In order to get knowledge of nature you needed to disseminate knowledge of science and technology broadly in the British population, and that that would be the only reliable platform for prosperity and security for Britain in the future.

Now in order to do that, Bacon claimed we needed to reform the approach to the study of nature, that people had failed to generate the kind of knowledge of nature that could give us power over nature, that could give us control of natural phenomena that would allow us to generate wealth and military power, for example, because they were still mired in incorrect ways of thinking. So Bacon wrote a short book called *The New Organon*. Aristotle's logical texts focusing on deduction were called *The Organon*, which means something like “the instrument for reasoning.” So logic is an instrument for reasoning. Bacon wrote a book called *The New Organon*, the new instrument for reasoning, and in this book he argues very strongly that acquiring knowledge of nature is really not that difficult, or it would not be as difficult as it seems to be. You do not need geniuses to do it if only you could control the imaginative and speculative characteristics of the human mind. The human mind is the single greatest obstacle to acquiring knowledge of nature as well as, of course, the only means we have available to acquire knowledge of nature.

So what can we do? Well, Bacon did two things. On the one hand, he first identified what were the problems, the problems with the mind, and he identified what he called “four idols of the mind”: idols of the cave, idols of the tribe, idols of the marketplace, and idols of the theater. These are various kinds of prejudices that influence the way that we think, the way that we draw inferences from experience. So, for example, there are certain things that are built into human nature such as favoring positive outcomes over negative outcomes. So when you look at the results of experiments, we tend to overestimate the outcomes that confirm our hypotheses and we underestimate the negatives—well, there was something wrong with the equipment or it didn’t work quite right, or maybe we could drop that data out over there. There are prejudices that derive from the nature of language, which prejudice our thinking and the way that we reason. There are prejudices that derive from our social interactions—the idols of the marketplace. The society in which we grow up teaches us certain kinds of “truths” and we accept those as truths, especially the theories that we’re taught at the university or in the school at an earlier age, and those are idols of the theater. We’re taught philosophical systems that are really incorrect.

What we really need to do is wipe the slate clean. We need to recognize that we are loaded with misconceptions, that we are loaded with emotional and intellectual prejudices that get in the way of approaching nature objectively, as we would certainly say. Now that was the negative side of his book.

The positive side of his book is, now I’ll tell you how to get knowledge of nature. He offers an essentially mechanical procedure—not mechanical in the way of a machine, but a kind of conceptual machine; a conceptual machine for acquiring knowledge of nature. You look at some phenomenon that concerns you. He took, for example, heat. Now please note that Bacon was not a scientist, did not pretend to be a scientist. He was not a natural philosopher, and he had effectively no understanding of mathematics, so for him mathematics had nothing to do with nature. He didn’t know much in the way of mathematics, just what he had to learn in school. He thought that the focus on mathematics kept people away from nature because of the sort of mystical and abstract characteristics of Pythagorean and Platonic mathematical nature-philosophy that I’ve discussed in earlier lectures.

So Bacon said what we need here is a mechanical procedure. You have a problem that interests you. Let’s take heat, and that did interest him. Now you collect all the data that you can. You collect data with a completely neutral state of mind, without any prejudices whatsoever. You just collect all the data that are relevant to the issue of heat. What is heat? That’s the problem. What is heat? And there were really two candidates for the answer to that question. One was that heat was a thing, which was given the name caloric, a weightless fluid that was contained in everything, and when something got hot that was because the caloric was escaping from that thing. And the other possibility is that heat is motion, that heat is simply somehow the motion, what we would today call the kinetic energy, of the particles of which matter is made up.

Now of course, since caloric is invisible we can’t detect it. We can detect heat but we can’t detect this weightless fluid. Both of these solutions refer to things which we do not experience. And this is consistent with what I said right from the beginning, that one of the fundamental features of science once it has absorbed this Platonic-Aristotelian notion of knowledge as universal, necessary, and certain is that the object of scientific knowledge cannot be experienced. It must be something behind experience that is unexperienceable, but that causes experience, so that experience is the effect of reality, and that the object of scientific knowledge on this view is reality.

This is, by the way, completely reflected in Copernicus's theory of the moving earth. We do not experience that the earth is rotating on its axis. We do not experience that the earth is orbiting around the sun. We do not experience, for that matter, that the entire solar system is orbiting the center of the Milky Way, and that the Milky Way itself is moving in the direction of the constellation Virgo. We don't experience any of those things. We have to be shown or told by scientists that this is the truth of the matter. So this is and remains a fundamental feature of science.

So Bacon says collect all the data. Then you start analyzing the data. You look at the data, and you sort of steep yourself in the data. You go over the data and you make lists of the data. You put them in different categories until you start seeing certain relationships. You start seeing certain relationships among the data, certain patterns. Oh, look at that. This looks like a pattern. Now we form a hypothesis. The hypothesis suggests, well, if heat is caloric then such and such should be the case. And so you do an experiment to see if such and such is the case. If the experiment confirms the hypothesis, then you go back and you start collecting more data that's specifically relevant to that hypothesis, focused on that hypothesis, and you do more experiments. And at a certain point when you have gone through this cycle several times, and the experiments continue to confirm a continually refined hypothesis, you announce that you have discovered a law of nature.

So this is a strictly inductive method, and it is keyed to experiment. Nevertheless, Bacon believed and said that the goal of science is knowledge of natural phenomena. Truth, he said, adapting an old Roman line, "Truth is the daughter of time." You have to patient. Truth will emerge from the repeated application of this method, which even though it is based on induction, through the confirmation that comes from experiment we can be confident that we are going to converge over time—no one can expect to do it in their lifetime, but we can expect to converge in time—on a true account of nature. It's knowledge that we're after, not probability or opinion. However, in the short term we have to function on the basis of this induction-based approach, and what will validate it is that the knowledge that we get will give us power over nature, power to channel and transform natural phenomena, to control them in ways that we want.

The fact that we can use nature in ways that we desire will show that we are the masters of nature, although when he wanted to, he used the term steward—that man is also the steward of nature. We shouldn't, so to speak, rape nature; we should learn how to use nature to get what we want, but in a way that is consistent with, we would use the language today, respecting nature. But there's no doubt that the politics of his rhetoric—his books were dedicated to the English king—was that we needed to get power over nature because we wanted to become rich and powerful, and that the key to this is an induction-based experimental method for generating scientific knowledge.

Now this was enormously influential. The Royal Society, which was founded just 40 years approximately after Bacon published *The New Organon*, he was dead by that time, but they looked to him, they identified him as one of the conceptual founding fathers of the Royal Society in the 1660s. Now already the people are conscious that what we would call modern science has emerged, that they are the leading edge of the new wave of natural philosophers, who are fundamentally different from natural philosophers in the past, and are on a path that is going to achieve new and great things. And 20-some-odd years later, when Isaac Newton published *The Mathematical Principles of Natural Philosophy*, subsidized by the Royal Society of London, that vision was considered fully justified.

Now in parallel to Bacon you have the figure of René Descartes. Descartes was a somewhat younger philosopher than Bacon, and a *philosopher*. French by birth, but he spent a great deal of his adult life living in Holland, which at that time in the early 17th century was quite famous in Europe for its religious tolerance. Although Descartes considered himself a loyal Catholic, he was also very much aware of the fact that you could get into deep trouble with the Inquisition in a Catholic country if you published material that was perceived to be threatening or heretical. Of course the burning of Giordano Bruno, which Descartes referred to a number of times, in 1600 was evidence for that, and the subsequent punishment of Galileo some years before Descartes died was further reinforcement that you needed to be careful. So he was careful by living in a Protestant country that had implemented sort of religious toleration laws.

Descartes, especially in his books, *Discourse on Method* and *Rules for the Direction of the Mind*, emphasized that deductive reasoning is the only possible basis for science, for knowledge of nature, because nothing else gives you real knowledge. As far as he was concerned, this Baconian emphasis on induction was misguided. It was merely one phase of doing science. Scientific reasoning needed to be deductive. It needed to be logically based on deduction from first principles, and it is that that gives us knowledge. Everything else is mere probability and opinion. And Descartes offered, in the *Discourse on Method* and the *Rules for the Direction of the Mind*, a kind of a handbook for deductive reasoning about natural phenomena.

We get into the problems I mentioned in the time of Aristotle and again in the medieval problem of universals: How are we going to get these first principles? And Descartes talked about intuition and innate ideas and believed that we did have innate ideas that God had given us at birth, so to speak, that were built into us as human beings. Certain ways of thinking that were built into us as human beings, and certain specific ideas, especially mathematical objects. And that we had certain intuitions; that there was a power of seeing the truth of something that was even more believable than the conclusion of a deductive argument, that intuition was even more powerful than deductive reasoning. And I think one instance of this might be his famous, "I think therefore I am." Seeing the necessary truth of that statement is some kind of immediate intuition, and we have to measure other conclusions that we reach logically against the clarity of that intuition of seeing the truth of that, and deduction can do that for us, but we apparently do have some other faculty.

And so Descartes, who was an important scientist and who was the founder of this mechanical philosophy of nature—that all natural phenomena can be explained in terms of matter and motion and nothing else; that no other forces are required except the contact forces of matter and motion—failed by the end of the 17th century. It was perceived to be much too thin a philosophy. But conceptually it dominated science through the 19th century; that at some level, once you add appropriate forces, which Newton opened the way to, then a materialistic determinism is the only possible scientific version of natural phenomena; that science means materialistic determinism.

So Descartes launched that. Descartes argued for that, claimed it was the only possible approach, but the key was getting those first principles. We had innate ideas, we had intuition, but we also, according to Descartes, needed to use hypotheses. We needed to sort of create hypotheses from which we could deduce natural phenomena. So if you created a hypothesis that was consistent with the experience and allowed you to deduce experience, then we could say that those hypotheses have some probability of being true.

This is kind of a weird thing to say, because how can you mix probability and certainty? He, himself, recognized that this was a serious methodological issue, but there was no escaping the need to formulate some hypotheses. But he thought that the success of deduction verified, validated making those hypotheses, so in some sense they had to be true.

Newton reacted violently against this whole method of reasoning and in his *Principia* said, "*Hypotheses non fingo*," in the Latin version, of course. "I feign no hypotheses." Actually, "I make no hypotheses." Hypothesis is a dead end; it's sterile. He became radically anti-Cartesian the older and more famous that he got, and Newton had his own approach based on the Archimedean method that Galileo had made central to his approach to mathematical physics. Like Galileo, Newton thought that Archimedes showed that you could combine experimentation and deductive reasoning in a rigorous way, and that would reveal the true causes of natural phenomena. That means it would reveal the truth about the reality behind experience that is causing experience. When we talk about the true causes of natural phenomena, he's saying we have experience. Experience on its face is misleading. It says that the sun is moving across the sky, for example. It says that the earth is stable. But the truth is that there is a cause for all of this and that is the task of the scientist: to reveal the true cause of which experience is the effect.

Now in between Descartes and Newton, who are typically singled out as the great rival methodologists of the 17th century, of the scientific revolution, you have Galileo. The figure of Galileo, who is popularly identified most closely with the *Dialogue Concerning the Two Great World Systems*, his condemnation by the Inquisition, and a subsequent trial and conviction, and the last eight years of his life lived under house arrest. But in fact as a founding figure of modern science, Galileo's fame really rests on a book called *The Discourses Concerning Two New Sciences,* which was written while he was under house arrest, which was published illegally from the point of view of the deal that he made with the Inquisition when he was convicted. He was not supposed to publish any more on these subjects, and the book was published illegally in Holland shortly before Galileo died.

And I just want to read a brief passage at the beginning of this wonderful text, which contains in fact what you might consider Galileo's mature contributions to modern science. Not belittling the telescope and astronomy, but if he had never done that, this would have made him one of the founding figures of the scientific revolution. One of the two sciences that he writes about is what we would call engineering mechanics. He does mathematical theory of strength of materials.

Now I had referred in an earlier lecture to Domenico Fontana's wonderful exhibition of engineering skill by moving this 700,000 pound plus obelisk that was in the way of building St. Peter's Cathedral. There was a great deal of arithmetic calculation associated with designing the framework to be built around it, the size of the pieces of wood that would be necessary, the timber that would be necessary, and the ropes—how strong the ropes had to be, etc. Galileo made a science out of these rude engineering calculations, analogous to the way that Pythagoras made mathematics into the deductive body of knowledge that we identify it with out of the previous number know-how of the Babylonians and the Egyptians, for example. Galileo transformed a casual engineering calculation into a science of the strength of materials, and that became the basis for what developed over the next two hundred plus years right into the present as engineering mechanics. It only really got that name more recently. Anyway, that's one science.

The other science is the new science of motion that Galileo introduced and which really becomes the basis of the motion of material particles as treated by scientists from Galileo, let's say from 1640, all the way up to the present. So Galileo becomes the founder of mechanics through the second half of this book.

And what he says on the first day of these four days of dialogues among the same interlocutors that you see in *The Dialogue Concerning the Two Great World Systems*, Galileo says that (well, he's speaking through a mouthpiece), "Although some of my conclusions have been reached by others," (I'm rephrasing it slightly), "first of all by Aristotle, these are not the most beautiful, and what is more, they had not been proven in a rigid manner from fundamental principles. Now since I wish to convince you by demonstrative reasoning rather than to persuade you by mere probabilities, I shall suppose that you are familiar with present-day mechanics so far as it is needed in our discussion."

Now, when he gets to the second half of the book and he gives his new science of motion, the book begins with definitions and axioms à la geometry, and then he deduces from these definitions and axioms the laws of the motion of particles, including the famous equation for a freely falling body, $s=\frac{1}{2}gt^2$, that we consider one of the great achievements of early 17th century science. But as a matter of fact, as I'm going to be discussing in the next lecture, this equation appears nowhere in Galileo's text. The focus here, the idea of modern science, is the idea of method.

Lecture Fourteen
Algebra, Calculus, and Probability

Scope:

European mathematics was in a pitiful state prior to the 16th century. Renaissance scholars' recovery and careful study of Greek and Graeco-Roman mathematical texts, together with the growing use of mathematics, stimulated original mathematical research. The 16th century was marked by the adoption, by way of Islamic texts, of algebra and theory of equations on a par with geometry-centered Greek mathematics; the creation of a primitive probability theory; and the introduction of a symbolic notation for arithmetic and algebra. Progress was explosive from the 17th century on. Descartes and others showed how to use algebraic equations to solve even the most complex geometric problems. Isaac Newton and Gottfried Leibniz invented the calculus, which proved to be immensely fertile both in "pure" and applied mathematics. With the calculus, for the first time, scientists had a means of exploring change. Meanwhile, probability theory expanded to incorporate the application of statistics to political and commercial decision-making.

Outline

I. The shift of European mathematics from geometry to algebra was epochal for the rise of modern science and for its impact on society.

- **A.** There is an interesting connection between the 17th-century focus on method that was the subject of the preceding lecture and the shift from geometry to algebra.
  1. Bacon, Descartes, Galileo and Newton promoted different versions of "the" scientific method.
  2. Bacon's was inductive, Descartes' was deductive while Galileo and Newton adopted a broadly Archimedean methodology that was mathematical, experimental, and deductive.
  3. The common denominator was they were all radically impersonal and value neutral.
  4. All that matters in the modern-science style of reasoning is the methodology employed, the results, and the criteria for evaluating the results, for example, confirmatory experiments.
  5. This impersonalism, this objectivity, and the focus on logic in the study of nature are reminiscent of mathematics.
- **B.** The mathematics of the early 16th century was overwhelmingly Greek, but by the end of the century, it was very different.
  1. Greek mathematics was almost wholly geometric, including trigonometry introduced to deal with problems in astronomical theory.
  2. Especially during the Graeco-Roman period, Greek mathematicians explored number theory and equations, but overwhelmingly, the preference was for transforming all mathematical problems not obviously arithmetic into geometric terms.
  3. This preference seems related to the identification of geometric reasoning with deductive reasoning and its guarantee of (logical) truth.
  4. Islamic mathematicians mastered and extended Greek geometry and trigonometry, but they also cultivated "algebra." Al-Khwarizmi in the 9th century and abu-Kamil in the early 10th century became major influences when their books were translated into Latin during the Renaissance. The very term *algebra* derives from an Arabic word (*al-jabr*) used by al-Khwarizmi.
  5. Islamic mathematicians also transmitted to the West the Indian number symbols, including the use of zero, that became widely adopted only in the 16th century, finally displacing

Roman numerals.

C. This great legacy converged in the 16th century on a peculiarly receptive western Europe that responded enthusiastically and creatively.

1. The wholesale adoption of the new number symbols was of fundamental importance, especially when complemented by the invention of a symbolic language for algebraic expressions.

2. This symbolic language played an important role in the sudden increase in mathematical creativity, but it was a product of an antecedent "desire" to pursue mathematics.

3. Important new results were achieved, among them, a general solution of the cubic equation and the creation of probability theory, both by Italian mathematicians (though Omar Khayyam seems clearly to have anticipated Tartaglia's solution of cubic equations by about 400 years); advances in trigonometry crucial to astronomical theory; mapmaking and surveying; and the invention of complex numbers and logarithms.

4. Tartaglia, a nickname for Niccolò Fontana, and Ludovico Ferrari, a one-time servant to the physician-mathematician Jerome Cardan (Girolamo Cardano), solved the cubic and quartic equations, and Cardan introduced—among other innovations—probability theory, in a book not published for 150 years.

D. René Descartes was a father of modern philosophy and modern science—championing a deductive methodology, a mechanical philosophy of nature, and the mathematization of physics—and a major contributor to modern mathematics.

1. Descartes paved the way to analytic geometry, to equation-based geometry, by freely introducing *arithmetical terms* into the solution of geometric problems.

2. In his book titled *Geometry*, he states that every geometric problem can be solved algebraically, whether the problem is mathematical or "scientific."

3. Even as he equated matter and space in his theory of nature, Descartes reinforced the growing focus on algebra, not only in mathematics, but in physics, as well.

4. Descartes' *Geometry* is one of the earliest mathematical texts employing the full symbolic notation we use today, and thus, it is quite readable.

E. Algebra steadily displaced geometry in European mathematics (though geometry underwent a revival in the 19th and 20th centuries in a much more abstract, algebraic form), but it encountered strong resistance.

1. Galileo did not once use the term *algebra* in his *Two New Sciences*, and Newton employed only geometric proofs in his *Principia*!

2. The resistance seems to reflect a lack of confidence in the deductive character of algebraic solutions compared to the clearly deductive character of geometric proofs.

3. Using algebra solves the problem but not in a logically compelling way, almost as if a trick had been employed.

II. The calculus may have been the most creative and the most consequential mathematical invention of the 17th century, followed by the invention of probability theory.

A. The origins of the calculus lie in technical mathematical problems, but its consequence was to give unprecedented power to scientists modeling natural phenomena.

1. There are two "sides" to the calculus: the integral side, rooted in attempts to calculate areas and volumes, and the differential side, rooted in attempts to finding the tangent to a curve at any given point on the curve.

2. Newton and Gottfried Wilhelm Leibniz independently invented the calculus at very nearly the same time.

3. Subsequently, they engaged in one of the bitterest priority disputes in science, with Newton behaving particularly badly.
4. The "genius" of the differential calculus, and its power for science, lies in the ability it confers to measure change as it calculates the direction of the tangent to a curve at any point on the curve.
5. Geometry is static and timeless, but an algebra enriched by calculus is dynamic.
6. With the calculus, one can give a mathematical description of processes as they change in time, using the differential calculus to calculate the direction of change and the integral calculus to calculate the cumulative consequences of change.
7. Furthermore, the calculus was readily extended to all processes in the life and social sciences, as well as the physical sciences.

B. Plato and Aristotle recognized that "art"/technology involved a kind of near-knowledge, but they, and most Western intellectuals after them, were utterly dismissive of commerce.

1. If knowledge is universal, necessary, and certain, then a *science* of probabilities seems oxymoronic.
2. Probability theory, in this context, is an idea that had to be invented.
3. Though there were predecessors, perhaps the founding text of modern probability theory was Jacob Bernoulli's *The Art of Conjecturing*.
4. What distinguished Bernoulli's book was his claim that probability theory was the basis for rational, effective, real-world policy- and decision-making for governments and individuals.
5. His idea for a *science* of probabilities was applied in the 18th and 19th centuries, and it became a major feature of 20th-century social science.

Essential Reading:

Ivor Grattan-Guiness, *The Norton History of the Mathematical Sciences*.

Jacob Bernoulli, *The Art of Conjecturing*, translated by Edith Dudley Sylla.

Questions to Consider:

1. What is it about symbolic notations in mathematics that makes them so fertile?
2. Hindu-Arabic numerals first appeared in Europe in the 10th century; why were they not adopted until the 16th century?

Lecture Fourteen
Algebra, Calculus, and Probability

In this lecture I want to talk about three scientific ideas that are related, and the common denominator is mathematics, which is a nice thing to have a common denominator of, I guess. The first is going to be the idea of algebra, the second is going to be the idea of calculus, and the third is going to be the idea of probability theory, especially probability theory as applied to real world decision making.

All three of these ideas are 16th and 17th—especially 17th—century phenomena, and I understand that many people beginning immediately upon hearing words like algebra and calculus and probability theory think that it's time to bail out. But I will not be using any mathematics per se, and the ideas underlying these three developments in modern science are fascinating, and I believe quite beautiful, and very interesting from the point of view of the people involved.

In fact, some of the people involved, the people I'm going to be mentioning—Descartes and Newton are two central players here—have come up of course in the last lecture, having to do with method. So let me begin by picking up on the discussion of method in the previous lecture, in order to carry it forward in a way that I think blends nicely with the emergence of these three ideas: algebra, calculus, and probability theory in the 17th century.

I had highlighted in the previous lecture Francis Bacon, René Descartes, and Galileo and Newton as representing three different conceptions of the scientific method. This was just to give you some feeling for the fact that in the 17th century there was no such thing as one scientific method, one method that one can say, "This is the scientific method; this is the method that modern philosophers of nature, who we call scientists, use in order to get knowledge of nature."

Bacon, of course, championed a strictly inductive method, experimentally based, that required little or no mathematics. In fact, he thought the less mathematics the better, because mathematics led people into mystical and metaphysical speculations. Descartes's method was rigorously deductive, intensively mathematical, and very suspicious of experiment. Descartes's feeling was that experimental outcomes were ambiguous and needed to be interpreted, and that often led people astray; so that experiments should be very, very limited and carefully controlled.

Galileo and Newton used experiment intensively, and used a deductive mathematical form of reasoning intensively. Newton considered himself in the Baconian tradition, ironically, even though all of his work was intensively mathematical, and Galileo identified himself methodologically with Archimedes. And a lot of Galileo's experiments were thought experiments, including almost certainly the experiments that were associated with studying freely falling bodies; many of those were thought experiments. It is unlikely, I think, that Galileo actually climbed up the Tower of Pisa and dropped heavy weights off to see if they fell for the same time. We do know that a predecessor and a younger contemporary of his, Simon Stevin in Holland, a very important figure in late 16th and early 17th century early modern science, did do such an experiment, but of course not with the Tower of Pisa, because he lived in Holland.

Now, what is the common denominator of these approaches to what we call the scientific method? If you say, "Well, what is it that these people had in common?" What these people had in common was a total commitment to the idea that the right method for studying nature was a radically impersonal method. We would say a radically objective method, although the word "objective" was not used that way, even in English, in the 17th century. Whatever method you used had to be one in which the person of the student of nature, the natural philosopher, the person that we have come to call the scientist, the person of the scientist is irrelevant to the results.

Now this seems obvious to us, but it was not obvious in the 17th century because this is one of the pieces of the study of nature puzzle that was taken out, that was rejected by the founders of modern science. In Renaissance nature philosophy, especially the part associated with the dominant thread of magical nature philosophy, the person of the inquirer was relevant to their ability to acquire knowledge of nature. So that who you were and how you sort of cultivated your soul was a factor.

In the modern period, what we claim to be the case is that there is some method that you have to follow, and you have to present your results in a particular way in which you drop out, and who you are is utterly irrelevant. The conclusions have to be substantiated on the basis of logic and empirical confirmation, not on the basis of who you happen to be. We still have a considerable amount of influence on peers by knowing that somebody is a Nobel Prize winner. That’s why we’re supposed to have proposals and articles submitted in a blind or double-blind manner so that we don’t know who wrote the proposal, and we don’t know who submitted the article, and the merit has to flow from the argument that is presented. But in fact this is very often not honored. It can become quite awkward. And in fact, very often you see a proposal and you know immediately who must have done it based on your familiarity with the field. If you don’t have familiarity with the field, you can’t judge the proposal anyway.

So this is the common denominator of method, and it links up with the subject matter of this lecture, which is the way that mathematics became the language of modern science. And the first step towards creating a new mathematics that would become, in the 17th century and after, the language in which scientific theories were expressed, was the adoption of algebra in place of the Greek emphasis on geometry.

For whatever reason, the ancient Greek thinkers did not like algebra, or did not like the subject that we call algebra. That is actually a Latin and now English corruption of an Arabic word that only was formulated, that we found, after the 9th century. But in antiquity the study of equations was just not of interest to the Greeks. They believed in geometry, and their conception of deductive reasoning, as I’ve already mentioned many times, was considered to be exemplified by Euclid’s geometry. Not just that Euclid’s geometry embodied deductive reasoning; but *because* it embodied deductive reasoning, then geometry was the one descriptive language that you could use in explaining natural phenomena, that you could be sure led to truth, because it embodied deductive reasoning.

So, as a matter of fact, Greek mathematicians focused overwhelmingly on geometry, theory of proportions, which often was described in geometric language, and trigonometry, which also has a geometric character to it. So now the rise of algebra had to, so to speak, fight against this commitment to geometry as the only mathematical language that we could use confident that it would lead to truth, to demonstration. Remember what I read from Galileo; he wanted to not just tell you here are some interesting formulas for calculating the strength of material. I am going to show demonstrably; that means, give a deductive argument showing that the relative strength of two beams can be deduced from first principles.

So this replacement of geometry by algebra, which really took place in the 16th and 17th centuries, is as momentous as the transition from Ptolemaic astronomy to Copernican astronomy in terms of revealing the mindset, the ways of thinking that were essential to the founders of modern science and the practitioners of modern science. Remember I told you how bizarre it looks after the fact that for two thousand years effectively no one questioned Pythagoras’s notion that the planets surely were spheres moving at a uniform speed in circular orbits. And for two thousand years, astronomers wrestled with how you could have a theory of the motions of the planets that fulfilled those criteria and still displayed the appearances that we observe when we look at the night sky and keep track of the motions of the planets for some period of time. They don’t seem to be doing that.

And for two thousand years—I think I referred to this once as the Chicken Little syndrome in the history of science—well, here’s another one: that for over two thousand years, geometry had a stranglehold on the thinking of Western natural philosophers who used mathematics in their nature of philosophy.

So in the 16th century, Arabic language texts—from Egyptian and Persian authors primarily—came into the West and were translated into Latin. Especially al-Khwarizmi, a 9th century mathematician who used this term "*al-jabr*" to refer to solving problems where something is unknown and we want to solve it, and using what we recognize as algebraic equation. So algebra became an identified branch of mathematics in the 16th century in Western Europe, building initially on the work of al-Khwarizmi. His name survives in the word "algorithm," by the way, although it's obviously a bit of a stretch. You might not think from the word algorithm that it has an origin of a person's name, but it is a deliberate version of al-Khwarizmi. One of his successors and followers was a man who refers back to al-Khwarizmi's solutions and offers new and what he thinks are more interesting and better solutions, an Egyptian mathematician named abu-Kamil, who lived in the next century, the 10th century as opposed to al-Khwarizmi who lived in the 9th, but their lives overlapped.

So it was through this channel, so to speak, that apparently in the 16th century we see the beginnings of European mathematicians beginning to focus on algebra, and very quickly achieving new results, some of which had been said in antiquity could not be achieved. For example, solving the cubic equation. Now, I'm not going to give you a cubic equation, but we all know what a quadratic equation is from high school. A cubic equation is one that involves X^3, so we put it today something like $AX^3 + BX^2 + CX - D = 0$. So that would be a cubic equation in its most general form. And while the Greeks and Arabic mathematicians could solve the cubic equation for special cases, nobody had a general solution for that equation, and it was believed that such a solution did not exist. It was not possible to have a general solution; you could only solve specific cases.

There is now evidence, I must say, that Omar Khayyam, known to most Westerners I think because of the *Rubaiyat of Omar Khayyam* as a poet, based on Fitzgerald's creative translation of his poetry in the 19th century, the *Rubaiyat of Omar Khayyam*, "a book of verse beneath the bough," etc.; Khayyam was a lovely poet, but he was also a very good mathematician. He was a world-class mathematician, and manuscripts of his have been found now which show that he seems to have solved every specific case that's relevant—of the cubic equation—that's relevant to a general solution. But it does not look as though he sort of pulled it together and says, "And now that I've solved all these cases, I can say that I have a general solution to the cubic equation."

It turns out to be an important equation even in practical use. For example, Greek and Roman catapults were designed using the cubic equation in order to calculate the torsion necessary so that when you release the pressure the catapult threw the rock, or whatever it was throwing. So in designing those catapults, special solutions, specific solutions of a cubic equation are relevant. So it's not just an abstract piece of mathematics.

Well, what happened in the 16th century is that an Italian mathematician named Niccolò Tartaglia (that was his nickname, but that's the name he was known by, he even signed his own books that way), Tartaglia discovered a general solution to the cubic equation. And he used this general solution in order to win money at mathematics contests, which people did in those days because they didn't have television yet.

So they had tournaments for mathematics, and the way you did it was you set up a series of problems and you challenged other mathematicians to solve them. You, of course, already had the solutions to all of those problems. And then some king or prince who had nothing better to do with his money said, "Okay, I'll give a thousand ducats to whoever wins this competition." And everybody got together at that time and Tartaglia would always set problems that involved solutions to cubic equations, and he won all of the contests because nobody else could do it.

Finally, another Italian mathematician, and a man actually of extraordinarily eccentric character, but one of his geniuses was in mathematics—Jerome Cardan, Gerolamo Cardano—so Cardano eventually talked Tartaglia into telling him the secret of solving the cubic equation, and Tartaglia was stupid enough to tell him. Even though Cardano promised (maybe on his mother's name—I don't know) that he would not reveal the secret, he immediately published it—giving Tartaglia full credit, but he published it in a book that he wrote. Now of course this took away Tartaglia's bread and butter.

Interestingly, Cardano had a servant who subsequently became a professor of mathematics. Cardano tutored his servant in mathematics, he had a gift for it; a man by the name of Ferrari. And Ferrari improved on Tartaglia's solution and then showed that you could solve the quartic equation (equations in x to the 4th power) by reducing it to two quadratic equations. And these are major creative accomplishments in algebra, sort of showing that in fact European mathematicians had got it. They grasped algebra as a form of mathematics and were pursuing it aggressively and creatively.

Cardano himself also wrote a book that is perhaps the first book written on the subject of probability theory, but I'll come back to that. All of this is happening in the late-1500s. As you pursued algebra at the time, algebra problems were, and had been since antiquity, written in words. So, for example, reading from abu-Kamil —obviously an English translation—of abu-Kamil's 10th century Arabic textbook called *The Algebra*, he gives the following description of a problem. Here's a textbook problem:

> One says that ten be divided into two parts. Multiply one by the other. Multiply the larger part by itself. The part multiplied by itself equals the product of the one part by the other plus its half. [The half is also written in words, not in symbols.] The method for solving this problem is that we let the larger part be the thing. [We would call that *x*.] The other part is then ten minus the thing. Multiply the thing by ten minus the thing. It is ten things minus a square. Multiply the larger part, a thing by itself, to get a square. This square is equal to ten things minus the square plus a half of this. Multiply ten things minus a square by one and a half. It comes to fifteen things minus a square and a half square. The latter is equal to a square. Put the fifteen things with the one and a half squares. Then it is fifteen things. Add the one and a half squares to the square to get two and a half squares. This is equal to fifteen things. So the square is equal to six things. The thing [What we would call *x*, if you've been following all of this.] equals six. This is the larger part. The other part is four and is the remainder from ten.

Contrast posing mathematical problems and solutions in words, and using the symbolic notation that we're familiar with: in which you have x, y, and z standing for variables, a, b, and c standing for constants, the superscripts for square and the cube and 4th power and the square root sign for the square root of, and the equal sign, the plus and the minus and the signs for multiplication and division. None of that existed prior to the 16th century.

That symbolic notation was invented in Western Europe in response to the interest in algebra. And the symbolic notation then unleashed—this has something to do with the way we think and the way our minds work—once we had that symbolic notation, that unleashed an incredible exponential growth in mathematical knowledge in algebra over the next several hundred years. These notations had to be invented. People had to agree, "Okay, that's what an equal sign looks like." For a while people used different equal signs, but they had an equal sign. By the time you get to Descartes, writing in the 1620s and 1630s (and I'm going to be talking about that in a moment), he writes recognizable equations.

I want to do three things now. First of all, I had said earlier that the acceptance of algebra as the primary form of mathematical knowledge encountered resistance, because people didn't trust algebra. "Yeah, okay. These equations work, but show me a geometric version of solving this algebraic equation." How powerful was this stranglehold? I mentioned in the previous lecture that Galileo's most important book as a scientist was *The Discourse Concerning the Two Great Sciences*. The second part of that book founds the modern science of mechanics, which is the cornerstone of physics. There is not a single equation in the book. The word algebra does not occur in the book. Every single proposition, every single statement about the world, about motion, about moving particles, is demonstrated geometrically. "Oh, well, that was only the 1630s." But Newton's *Principia*—Newton, who invented the calculus, also only used geometry in order to prove the theorem in the *Principia*.

So even as algebra was becoming the dominant form of mathematical knowledge for Western science and in Western mathematics—geometry underwent a tremendous resurrection in the 19th and early 20th centuries, but one could call it an algebraized form of geometry—there was tremendous resistance to it.

And why was there resistance? Because the fear that an algebraic solution might not be deductively accurate; that somehow it pulls a rabbit out of a hat. When you give a geometric proof and you can step through the proof using lines and curves, then you really know that you've gotten the truth.

Descartes's major contribution here was that Descartes invented (well, this is a bit of an exaggeration—it's what the history books say, and it is largely true), Descartes invented analytic geometry, a forbidding phrase. In a book that ironically is called *La géométrie* in its French version—a book called *Geometry*—he says at the beginning, "Every problem in geometry can be solved algebraically, and therefore we don't need geometry anymore. All we need is algebra." And he shows the power of algebraic solutions to problems in geometry, in fact showing how easily he is able to solve problems that ancient geometers resolved were too complicated to do, that no one had even attempted to do. Yet he shows that algebraically you can find solutions very quickly. This book does have some residual echoes of falling back on geometry, but it really is in some sense a watershed, in that after this we can solve any problem in geometry algebraically. The fact that people didn't shows the strength that our ideas have on how we reason and what we reason about.

That is a little bit of the story of algebra as an idea, and I hope you see that it really is an idea, it's not a discovery. People didn't discover algebra in the 16th century. People were introduced to algebra in the 16th century, but that only opened the door that mathematicians ran through, and in the 17th century scientists tiptoed through, because they weren't sure that using this would lead to knowledge, demonstrative knowledge. Demonstration still was identified with geometry for a long time. But behind the scenes people like Christiaan Huygens, for example, were major contributors to the growth of algebra in the 17th century, as well as major contributors to the growing science of mechanics and science generally. Huygens wrote also on probability theory.

The second idea I want to talk about is the idea of the calculus. Newton, and independently, Gottfried Leibniz—in the 1660s Newton claimed he really got the idea, Leibniz in the 1670s, but Newton published later and then argued that, "Ah, but I was really first"—Newton and Leibniz invented the calculus. The calculus is an incredibly beautiful idea and an incredibly beautiful and powerful mathematical tool. For the first time we could, in an equation, capture motion and change.

Now you remember I said back in Aristotle's time the fundamental problem for a scientist, for a philosopher of nature, is explaining change. Change is the most fundamental phenomenon as far as responding to experiences. It is change that we need to explain. If things don't change, well, if they don't change long enough, then you might say, "Well, I have to explain that," but experiences always change. The problem of the scientist is explaining change, and the calculus, incredibly, gives us a tool for capturing change.

The calculus lets us take an equation that describes the motion of a particle or the changes in some physical system, whatever it is. Once you can describe motion and change in an equation, then the calculus lets you analyze that equation as if you were observing the moving particle or the changing system, and you can figure out in advance when the particle is moving up, when it's moving down, when it's at a point of inflection (I'm using up and down just as stand-ins here). You can analyze the details of changing patterns through the calculus, using calculus as a tool—that's the differential calculus.

The integral calculus—and the two are complementary, and Newton and Leibniz were involved in both—the integral calculus allows you to calculate the sum, the consequences, the accumulated change. So these two tools became extremely important. There is no way of exaggerating how important and powerful the idea of the calculus became, initially to physics and subsequently to any of the sciences that were able to capture in equations descriptions of the changes that they studied. Whether in sociology, in psychology, whether it's in biology, whether it's in chemistry, there is some scope for the application of calculus.

The third idea that I want to at least briefly refer to is the idea of probability theory. Now, in a culture dominated by a definition of knowledge that is universal, necessary, and certain, in which knowledge means certainty—well, you remember the thing I read about Galileo, but that's just the tip of the iceberg. The whole course I've been pointing out that this is just one of those intellectual fetishes of the Western intellectual tradition since the time of Plato and Aristotle, building on their predecessors, Parmenides and Pythagoras, although in Plato's time there was still a fight going on in which the Sophists and later the Skeptics rejected this definition. But, nevertheless, in a culture which has adopted this definition of knowledge, probability theory is a problem. It is an idea that needs to be invented, so to speak, because we dismiss probability. It's not really knowledge, that's just opinion.

I think that a founding text of probability theory, not because it was the first, but it is the first one that uses probability theory in the way that we do, and I believe it was the first text that explicitly linked probability theory to real-world decision making—that mathematical theory of probability was a tool for making wise decisions in the real world in the absence of the kind of knowledge that would allow you to deduce what to do—was the book called, in English, *The Art of Conjecturing*, by Jakob Bernoulli. Bernoulli wrote this book in the 1690s. He died in 1705, and it was published by a family member eight years later in 1713.

Now, it turns out that Cardano had written a book on probability theory in the late 1500s, but it was not published until the late 1600s. By that time two Frenchmen, Blaise Pascal and Pierre Fermat (famous from Fermat's last theorem) had written books on probability theory as applied to gambling games, and that unleashed a flurry of publications in the 1690s and early 1700s, most of which were triggered by responding to Pascal and Fermat on the probability applied to gambling games. But this four-part book by Jakob Bernoulli—who was a member of the great mathematical family that for generations produced world-class mathematicians, and he himself was one—part four is devoted to this idea that probability theory is a guide to decision making. It's not just a matter of gambling; that's not what it's all about. And he in fact was the first to use probability in this particular way. "We are said to know or understand those things that are certain and beyond doubt, but only to conjecture or have opinions about all other things." Right out of the first couple of lectures of this course. We are said to know or to understand those things that are certain and beyond doubt. Anything other than that is not knowledge. We can only conjecture or have opinions about anything else.

> To conjecture about something is to measure its probability. Therefore we define the art of conjecture, or stochastics, as the art of measuring the probabilities of things as exactly as possible to the end that in our judgment and actions we may always choose or follow that which has been found to be better, more satisfactory, safer, or more carefully considered. On this alone turns all the wisdom of the philosopher and all the practical judgment of the statesman.

He was already dead, but his book unleashed a whole new line of thinking in the 18th century that became associated with social reform, the idea that there was a rational basis for making decisions that were not deductive. That is a very important complement to the rigidity of a definition of knowledge that doesn't allow you to act on the basis of knowledge, to deduce action from knowledge. So you can't act rationally if you mean by rationality only deductive reasoning, certainty. Here was a claim that it is possible to loosen up that definition of rationality, to still be scientific, mathematical; less than certainty, but you can proceed rationally by being confident that your mathematical analysis of a situation has identified the most reasonable course of action. And this has become very important in contemporary science.

Lecture Fifteen
Conservation and Symmetry

Scope:

The purpose of science is to give us knowledge of nature derived from, and validated by, experience. The feature of experience that above all demands explanation is change, but knowledge purports to be changeless. How can we have a changeless account of the continually changing? This problem had been raised by the first Greek philosophers, who offered two responses that have survived to the present. One, which evolved into modern atomic theory, supposed that the ultimately real was composed of changeless, elementary substances whose properties in various combinations generated the rich diversity of experience. The other supposed that change was elementary, that reality was a web of processes, but all change expressed changeless patterns of change. This line evolved into modern field theories of matter and energy. Common to both lines are assumed principles of conservation and symmetry that underlie change and make scientific explanation possible.

Outline

I. *The* fundamental fact of experience is change, which we experience as relentless and universal—everything in experience changes all the time—thus, *the* fundamental task of natural science is to explain change.

- **A.** At the very beginning of Western philosophy, the problematic character of change was identified as a core issue.
  - **1.** Parmenides wrote a book-length poem arguing that change could not possibly be real because being and not-being are mutually exclusive categories, yet change implies that something that is, is not and that something that is not, is.
  - **2.** Parmenides went so far as to argue that it was not even possible to think about not-being, let alone reason logically about it.
  - **3.** Though flatly contradicting everyday experience, Parmenides's critique of change provoked a refined materialism as a response.
  - **4.** On this view, changeless elementary forms of matter are the ultimate constituents of reality.
  - **5.** One version of this materialism was Empedocles's theory of four elementary forms of matter: earth, air, fire, and water.
  - **6.** Another was atomism, especially as developed by Epicurus and Lucretius.
- **B.** It was easy to mock or dismiss Parmenides's conclusions but not the point he raised about the at least apparent non-rationality of change.
  - **1.** Heraclitus made the reality of change the cornerstone of his philosophy and the philosophy of nature: "Everything changes; no *thing* remains [the same]."
  - **2.** But if everything changes all the time, then how can we make sense of experience, let alone have *knowledge* of it?
  - **3.** Heraclitus's answer was that although change is real, it is rule-governed: Nature is a collection of processes, each of which has a distinctive *logos*, or rule/law, that endures over time and gives that process its identity.
  - **4.** For Heraclitus, the goal of knowledge of nature, of what we mean by *science*, is to discover lawful patterns of change, and this makes the calculus a particularly powerful analytical tool.

II. As modern science took shape in the 17th century, two ideas emerged as fundamental to its practice: conservation and symmetry.

A. Symmetry functioned implicitly until the 19th century, but conservation was explicit from the start.

   1. Change is a fact of experience and so is orderliness.

   2. Science is not needed for people to recognize patterns in everyday natural phenomena.

   3. Seasons change in regular ways; stars and planets move in recurring patterns; plants and animals reproduce predictably.

B. What experience does not reveal is a necessary order to natural phenomena, an absolute order to nature.

   1. Science enters with the proposition that there is a necessary order to experience and that it is the task of science to expose this order.

   2. Science explains changing natural phenomena by invoking something that is unchanging.

   3. If everything changes all the time, patternlessly, then explanation is not possible.

   4. Either some explanatorily fundamental things do not change or some patterns do not change.

C. Determinism is inescapable if explanation has to satisfy an idea of knowledge based on deductive reasoning.

   1. The introduction of the falling-weight–driven mechanical clock quickly was followed by the metaphor that the Universe was a clockwork mechanism.

   2. The clock measures time, of course, which is always changing, yet the clock has a deterministic structure to its design and operation.

   3. Every gear-train mechanism, of which the mechanical clock is one type, has a deterministic character by design.

   4. To say that the Universe is a clockwork mechanism is to say that nature, the Universe, is deterministic.

D. We noted earlier the idea that nature is a closed system; this idea contains the seed of the idea of conservation.

   1. Given deterministic change within a closed system, one of two things must happen.

   2. Either the system steadily “winds down,” as mechanical clocks do, or it is stable, in spite of continual change.

   3. Natural patterns seem very stable, with no sign of winding down; thus, there must be *something* invariant *within* change, some aspect of change must be conserved that keeps the Universe from winding down.

E. In the late medieval and Renaissance periods, this *something* was motion.

   1. The conservation of motion was, until the mid-17th century, the first and the bedrock law of conservation in science.

   2. Mechanics, that branch of physics that describes the laws of motion of material objects, began to be practiced in the 16th century.

   3. Galileo was trained in an Italian school of mechanics that succeeded in identifying laws of motion for moving objects.

   4. The conservation of motion was a necessary condition of the very possibility of these laws.

III. The second great conservation law in modern science was the conservation of matter.

A. The conservation of matter and the conservation of motion play complementary roles, and both turned out to be wrongly conceived.

   1. Like the conservation of motion, the conservation of matter is implicit in the late-medieval naturalistic determinism of the closed-system clockwork-mechanism metaphor.

   2. Although it was recognized by the 16th century, the conservation of matter did not become an explicit principle of nature until the late 18th century and, in particular, in the work of Antoine Lavoisier.

3. Lavoisier's oxygen-based theory of combustion inaugurated modern scientific chemistry and the atomic theory of matter as built up out of elementary forms of matter.

B. Descartes' mechanical philosophy of nature, influential from the mid-17th through the 19th centuries, is based on these two conservation laws.

1. Nature, for Descartes, is matter in motion, and that's it!
2. All natural phenomena, with only one exception, are to be explained in terms of the distinctive motions of distinctive complexes of matter.
3. The exception for Descartes, but not for later materialists, was the human mind and its free will.
4. Descartes' materialism stands in a tradition of those ancient Greek philosophers called *materialistic monists*, who believed that there was one generic type of "stuff" out of which all material objects were composed.

C. Descartes' explanation of free will revealed flaws in his conception of the conservation of motion.

1. Descartes' anatomical studies led him to propose that the pineal gland was a kind of switchboard directing nervous fluid throughout the body.
2. Descartes defined motion as mass multiplied by speed, arguing that the direction of the nervous fluid could change without violating the conservation of its motion.
3. Around 1650, Christiaan Huygens showed that a force is required to change the direction of a moving object, even if the speed and mass are constant.
4. This implied that the "correct" definition of the motion that was conserved was mass multiplied by velocity, a quantity we call *momentum*.
5. The conservation of momentum, linear and angular, became an inviolable principle of nature/reality, and it remains so to the present day.

D. As modern science evolved, the "thing" or quantity conserved was not obvious.

1. What remained obvious and inescapable was that some fundamental things must be conserved in order for scientific explanation to be possible.
2. As we will see, the creation of thermodynamics in the 19th century created energy as a new elementary feature of reality and a new law: that energy was conserved.
3. At the end of the 17th century, Newton and Leibniz argued over the significance of the quantity mass times velocity squared.
4. Newton dismissed it as a mere number, but Leibniz claimed that he had discovered a new conserved feature of nature that he called *vis viva*, or "living force."
5. In the 19th century, *vis viva* became *kinetic energy*, which is indeed conserved, but this dispute reflected a much deeper dispute over how deterministic the Universe was and what role this left for God.
6. In 1905, just 50 years after the law of the conservation of energy was proclaimed as a great triumph of science, Einstein overturned it with his discovery that matter and energy were interconvertible.

E. In the 19th and 20th centuries, the idea of conservation as an elementary feature of nature was joined by the ideas of invariance and symmetry.

1. In effect, invariance and symmetry are mathematical versions of conservation of physical quantities.
2. Both ideas reflect the intensification of the connection between mathematics and descriptions

of natural phenomena.

3. By the end of the 19th century, for many physicists, the mathematics *was* the phenomenon, such that a mathematical invariance or symmetry implied the conservation of a physical quantity.

Essential Reading:

Mary Hesse, *Forces and Fields*.

Peter Pesic, *Abel's Proof*.

Questions to Consider:

1. Are the Parmenidean and Heraclitean accounts of reality exclusive of each other, as they have been taken to be historically, or could they be complementary?
2. How do scientists know that constants are truly constant "forever"?

Lecture Fifteen
Conservation and Symmetry

In the last lecture I emphasized that the genius of the calculus is that it gives us the power to capture change in an unchanging equation. You have the equation and the equation somehow contains within it the facts about the changes that a physical system undergoes, a physical system described by that equation, instead of, so to speak, running the experiment and watching the system change.

If you've got the equation, then you can analyze the equation and you can deduce from the equation changes that you have never observed, changes that would be observed if you ran the experiment, let's say, for a longer period of time. If you change different parameters in the equation, if you added more weight, if you added more energy, if you speeded things up, then you can see what will be the effect, and you can analyze that from the equation using the tool that we call the differential calculus, and the complementary integral calculus. So the calculus is a powerful tool for dealing with change, and I also reminded you that change is the foundational problem for science of nature.

Change is also the fundamental fact of experience. And it is a fact that change as a fundamental fact of experience, together with a definition of knowledge which denies the ultimate reality of change at some level, created a historic problem for science that has repeatedly forced scientists and philosophers to deal with the question of how human beings can have such knowledge.

This denial of the ultimate reality of change takes a number of forms, the most extreme form in the surviving fragmentary writings of Parmenides, who I've referred to a number of times. It is also the basis for the materialistic and atomistic theories of nature that we are familiar with from ancient Greek natural philosophers, the ones who preceded Plato and Aristotle. I've referred to these before, but the whole idea is that there is an ultimate reality that is matter, and that in some form, in its elemental form, matter does not change. It is the different combinations of matter, and changing configurations of these combinations of matter, that generate the world of appearances, which does change.

So, for example, the early atomism of the form taught by Democritus was made famous through the writings of Epicurus and his Roman follower Lucretius, who wrote a very influential poem on the nature of things that promoted the atomic theory of matter. When you have configurations, atoms come together quite coincidentally in various ways that form plants, trees, animals, us, and then since atoms are constantly in motion, at some point they dissociate and they form other combinations. The animal dies and the atoms that made up the body of the animal become parts of other configurations of animals, which could be flowers, grass, and various forms of dirt. This idea is that the atoms are ultimately changeless, so again the line of thinking here is that we can only explain change if we reduce the appearance of change, if we explain the appearance of change by means of a changeless thing.

It seems as though Heraclitus represents the counterpoint to this. I referred to him as the philosopher who said, "No, no. These materialistic theories of nature are ultimately misconceived; that change is a fundamental reality. Change cannot be reduced. There is no thing that is changeless." There is no thing that is changeless, and that stands behind change in the way that Parmenides said, or the atomist said, or the materialist like Empedocles, whose theory was that there were four fundamental forms of matter—earth, air, fire, and water—and that these were changeless, but combined in various ways to make up all the different things that the world is made of. That was the theory that actually survived right through the 18^{th} century, much more than the atomic theory, which only really became a scientific theory in the 19^{th} century, as we will be discussing.

Heraclitus says, "No, all of these are misconceived. Change is fundamental. It cannot be reduced. However, there are changeless laws of change." So he, too, had to say that there is something changeless, but it's within change; that change is guided by rules. It's not anarchic; it's not chaotic—and we will eventually be talking about what we used to call chaos theory, and that arose and became particularly powerful in the 1970s and 1980s. So Heraclitus's view is that what we need to identify are the patterns of change, and the calculus relates to that. The calculus is a tool for discovering and identifying and analyzing processes of, patterns of change.

What we need to appreciate here, and in this lecture what I want to focus on, are two very powerful scientific ideas: the idea of conservation and the idea of symmetry. There is a bridging idea of invariance that I'm going to raise, but the two focal ideas are conservation and symmetry. These ideas have played and continue to play fundamental roles in scientific reasoning and in scientific theories, but what they really go back to is the recognition that you can believe that nature is orderly—and experience suggests that it is orderly. What experience doesn't tell us is that there are absolute, rigid, eternal, universal orders of nature, but certainly our experience is that nature is orderly. The planets move in predictable ways, the seasons follow in predictable patterns, we see predictability in creatures and plants and trees being born, so to speak, and going through different phases and eventually dying. There is no experience of anyone coming into existence fully grown and working backwards to a seedling. So there is a basis for the idea that nature is orderly, but if you take the view that there is an absolute order, and that we're trying to get at it, then you have to say, "Well, what is required in order for us to make good on this, I'm calling it *belief*, that there is an absolute order to nature?"

And one of the criteria, one of the things that you have to suppose is that something is conserved; because if everything is changing all the time, then you can't explain anything. The whole idea of an explanation, let alone a scientific explanation, presumes that something is changeless, because if everything is changing, you can't have an explanation (to repeat myself). I pointed out that in the Middle Ages in the context of the medieval university and the study of natural philosophy, the invention of the clock stimulated the metaphor that the universe is a clockwork mechanism. Now, this metaphor is already found in the 14th century, just a few decades after the first weight-driven mechanical clock was installed in Europe in the late 13th century. So within 50–60 years, people were already using the clock as a metaphor, and using it as a metaphor for the cosmos, for the universe.

This reflects the idea that gear-train mechanisms, the hidden secret of gear-train mechanisms is that they are deterministic. When you have a collection of gears that are interconnected, then by moving any one gear (assuming that they are not sloppily machined), then by moving any one gear you can predict precisely the motion of every other gear. If that were not the case, you wouldn't be able to build a water mill or a wind-powered machine that worked in the way that you anticipated. One of the things that's implicit in gear-train mechanisms is determinism. If you say that the universe is a clockwork mechanism, meaning by that it is a mechanism analogous to a gear-driven clock, then you're already committed to the view that the universe is deterministic, that all natural phenomena are determined in the same way, and are analogous to a clock.

Now put that together with the contemporary commitment to the view that nature is a closed system and you have to say, if you're religious—and everybody at the time was—that in the beginning, God created the universe as this clockwork mechanism, and imparted a certain amount of motion—we would say *energy*, but in those days motion—to the inhabitants of the universe. And one of two things was going to happen: either the clock winds down, motion is lost, and eventually everything comes to a stop, or God designed it in such a way, a way that a human clockmaker cannot do, in such a way that motion is conserved and therefore the universe will go on indefinitely. The clock never needs to be rewound.

The winning view is that motion is conserved. So the first explicit conservation law in Western nature of philosophy is that the total amount of motion in the universe and in specific closed subsets of it is conserved. It is conserved when you are analyzing a particular system, in principle if you are going to write equations of motion, which in the 16th and 17th centuries nature philosophers started doing in the way, for example, I've described with Galileo, but he is already in a tradition of Italian mechanics, meaning a physicist doing analyses trying to give mathematical descriptions of the motion of material objects, then that goes back perhaps 50–60 years before Galileo, and then of course from him continues on to the present. When you start writing these equations of motion, the assumption is, which becomes quite explicit in the 17th century, that the amount of motion in a system is conserved. If this is not the case, then you can't predict the behavior of the system.

You say, well, that's not a good reason for believing it. Well, it's a pretty good reason for scientists. Then by writing these equations you in fact can predict the behavior of the system, and then you must assume that your assumption was correct, that motion is conserved. I'm going to qualify that in a moment.

You all know that there is such a thing as the conservation of matter. So that is another conservation rule, but that also is an idea that begins to become explicit in the 16th century and strangely enough is only considered to have been proven in the late 18th century, in part through the experimental work of Lavoisier—Antoine Lavoisier, who was credited as the discoverer of oxygen, but who certainly initiated the transformation of chemistry from know-how to a modern science; but that's jumping ahead. The conservation of matter, as a conservational principle, was a background idea, and was there and sort of taken for granted from the 16th century through the 18th century. It was really only at the end of the 18th century that it was expressly used in the quantitative analysis of chemical processes, and transformations explicitly stated that since matter is conserved, we must be able to draw the following inferences from the experimental data that we have.

I'm focusing now on this conservation of motion because that is, in a certain sense, a more abstract thing to be conserved. Descartes, for example, already builds it into his mechanics, builds it into his theory of nature—which for him, remember, was matter and motion; there was nothing else for Descartes in nature but matter and motion. All natural phenomena had to be explained in terms of the complex combinations and collisions of bits and pieces of different kinds of matter and motion. Although for him, ultimately, all matter was generically the same, but it came in different forms.

Actually it seems to echo ancient Greek materialistic monas of the sort, for example, like Thales, who thought that there was only one ultimate form of matter, which he called water, but I think he really meant fluid, but there's some kind of universal fluid that can be compressed and forms a solid the way water forms ice. It can be rarified to form a gas the way water does when it turns into steam. He thought that from one fundamental stuff that had a lot of flexibility to it, and could be either a gas, a solid, or a liquid, and that these properties could be combined in various ways, that you could generate all natural phenomena.

They taught geometric physics in which space is identified with matter. There are no vacua and there's only matter, but it takes different forms, comes in different styles—the same stuff comes in different forms—that you could generate all the natural phenomena. Descartes assumes conservation of motion. And, for example, in his philosophy where he has to defend free will, because otherwise he will really be in trouble with the Catholic Church, he decides that it's quite scientific to believe in free will. Given his anatomical studies he came to the conclusion—he did very creative and intelligent anatomical studies, some of which, like discovering the reflex arc, we still have today—he decided that the nervous system was made out of hollow tubes. And the way that the body worked was that there was a fluid inside the nervous system that circulated and selectively stimulated different muscles to cause the body to do all the things that the body does.

Now, in a creature like us where we exercise free will, we selectively energize the nervous fluid. How do we do that? Well, as a scientist, the motion of the fluid in the nervous system must be conserved. However, without violating the conservation of motion, Descartes—which is the product of mass and speed for Descartes, the amount of motion in an object is the product of its mass and its speed—he thought that he had identified a gland (it is a gland) called the pineal gland in the brain, and he thought that was like the central switchboard of the nervous system. The nervous fluid flowed through the pineal gland, and in the pineal gland the mind could direct the nervous fluid to this nerve, to that nerve, and then that would lead to raising this arm, raising that arm, and that this didn't violate anything because motion is conserved. All you're doing is changing the direction. The mass stays the same, the mass of the nervous fluid. The speed of the nervous fluid stays the same, but the direction is changed, and that's perfectly okay. That doesn't violate the conservation of motion.

Now, whether he really meant this—I think he did mean it—people in the 17th century did seem to take him seriously in this. But one of the things that Christiaan Huygens, who started life as a Cartesian, in part because Descartes was a familiar of his father and a frequent guest in their home in Holland, Huygens quickly saw when he became a mature young scientist that Descartes's physics doesn't work. And one of Huygens's greatest contributions to modern science was the discovery that it takes a force in order to get an object to change its direction. Even if the mass doesn't change, even if the speed doesn't change, the velocity changes, because velocity and speed are not identical.

Descartes didn't make a distinction between speed and velocity. Velocity is speed in a direction, and Descartes just assumed that the direction didn't matter. But Huygens showed that it did, that any change of direction requires a force, and so it is not motion that is conserved. But if motion is not conserved, what is going to replace it? Ah, we call it conservation of momentum. Momentum looks superficially just like motion; it's mass times velocity. But the difference between velocity and speed is profound.

So, for example, it was only in Huygens's work, published in the mid-17th century, that people finally got away from the Greek notion that circular motion is natural and doesn't require a force. It was Huygens who showed that circular motion is unnatural. You need a force to keep the planets in their position. If the planets are moving in a circular path or in an elliptical path, anything other than a straight line, a force is necessary in order to keep that going.

So it is Huygens's work that opened the way to Newton's laws of motion, which became the foundation for mechanics right through the 19th century. The laws of motion are that an object in motion, in the absence of any forces, an object in motion remains in uniform straight-line motion forever, and an object at rest stays at rest forever. How could you write equations of motion for billiard balls if they could jump all over the table depending on the way they felt—I don't want to move now—or they start moving all by themselves before you pick up your cue stick.

So it is necessary to assume something like this, from the specific form of the law of motion that an object in motion remains in uniform straight-line motion in the absence of any force, once forces are available, then either the path is not straight or the object is either accelerating or decelerating. So the conservation of momentum—but notice, this is not immediately obvious, this is an idea; we must find something that is conserved and that becomes a basis for the ability to do science—so the idea of conservation is very central here.

Conservation of momentum actually turns out, based on Huygens's work, to take two forms: conservation of linear momentum and the conservation of angular momentum—that means circular motion, or, it's really curvilinear motion, it doesn't have to be circular; any kind of curved motion. So, for example, the earth and moon are gravitationally coupled together. We see the evidence of this, of course, in the role that the moon plays in the tides. Now, the distance between the earth and the moon has been changing ever since the moon first was formed or captured by the earth—billions of years, or, well, whenever you decide that the moon became part of the earth's destiny. So it was only about 140,000 miles away from the earth; now it's 190–220,000 depending on its orbit's elliptical. The distance between the earth and the moon, the mean distance between the earth and the moon, is slowly increasing; has been slowly increasing for hundreds of millions of years.

In order for the angular momentum of the earth–moon system to be conserved, the earth is slowing down and the day is getting longer. The earth's day is measurably increasing in length as the moon, so to speak, drifts away. Now this is a very, very small quantity, but it is measurable over decades and centuries, and now of course that we have laser rangefinders planted on the moon, we can actually measure this phenomena. But all I'm interested in here is that the conservation of angular momentum is not merely some abstract idea that we have to assume in order to do science. It is built into the doing of science, as the conservation of matter was in science in the 17th and 18th centuries; formalized, so to speak, by Lavoisier, and made an explicit principle in the 19th century.

We will be discussing in a future lecture the rise of the science of thermodynamics and the invention of the idea of energy. In thermodynamics in the 1850s, it was decided that energy is conserved. Given how important we suddenly realized energy was, then, like motion, it must be the case that energy is conserved. Because if energy can be created or destroyed, then again, the ability to write equations of motion, the ability to describe change in physical systems becomes impossible if energy can appear and disappear, so to speak, at will.

There was an interesting personal episode that bridges the conservation of momentum and the conservation of energy. In the late 17th century, Leibniz, through his work as a mathematical physicist in mechanics, had identified a quantity that he called *vis viva*, sort of living force that was measured by the mathematical quantity mv^2. Some of you may remember from high school physics or college physics that that sounds like kinetic energy. That word didn't exist at the time, but mv^2, which he thought was an important quantity, that it was a conserved quantity, and that it was an insight into the structure of nature, that nature conserves mv^2. Nature conserves momentum, nature conserves matter, and nature conserves mv^2. This is another fundamental principle of nature.

Newton, who by that time was already at loggerheads with Leibniz over this question of who invented the calculus first, Newton decided, "Nonsense, mv^2 is just a number. There are all kinds of numbers you make up in the course of equations. It doesn't have any physical significance whatsoever." They also had a very bitter dispute over the whole business I raised about the clockwork universe. According to Leibniz, God wound up the clock in the beginning and He's such a good clockmaker that God doesn't have to do anything afterwards forever. The world will last forever, conserving all of the mv^2 and the *vis viva* and momentum and the matter, etc. It's all conserved.

Newton, who was deeply religious in a different way from Leibniz, Newton claimed that, no, in spite of being a perfect being, the universe in fact will run down and these conservation laws are a sign that God episodically intervenes in nature to restore the amount of motion, the amount of what we would call energy. He wasn't saying that the universe is running down, but what he's saying is that, "Look, there is conservation of momentum, there is conservation of matter, and those are signs of God's continuing providential involvement with the universe that God created." And Leibniz's response is, "Oh, come on. There's religion and then there's physics, and that can't be part of physics." This debate took place in the context of a series of five letters—four and a half letters—exchanged between Leibniz and Newton through an intermediary, because Newton did not take criticism lightly, and did not like to engage in controversy, but he wanted to make sure that his views were defended, so he had a mouthpiece, a man by the name of Samuel Clark.

Now in the middle of the 19th century, as I said, we get the concept of energy, and energy is conserved. And now all of a sudden at the end of the 19th, beginning of the 20th century, there are three great principles of conservation that enable scientific explanations to take place: the conservation of momentum, the conservation of matter, the conservation of energy.

In 1905, Einstein's paper that we call the *Special Relativity Theory Paper*, the one that is on the electrodynamics of moving bodies but it was the founding paper of special relativity theory, it comes out of Einstein's reformulation of Newtonian mechanics that $E=mc^2$. Not an equation Einstein was looking for, but it pops out of his reformulation of Newtonian mechanics, which means that energy and matter are interconvertible. Energy can be destroyed, so to speak: It can be transformed into matter. Matter can be destroyed, and you can create matter—you can create matter out of energy. You can annihilate matter, as we do in the atomic and hydrogen bombs, for example, or you can make matter out of photons. Now, this is not easy to do, but we have done it.

So subsequently Einstein turned out to be correct, but notice the implication here. We used to be very proud, there was conservation of matter, conservation of energy, and now, now all of a sudden we have to say that only one thing is conserved; namely, there is a lawful relationship between energy and matter. When energy disappears, a certain amount of matter must appear. When matter disappears, a certain amount of energy must appear. So there is still a conservation.

Okay, I want to get off that for a moment and talk about another form of conservation that was forced by the form of scientific theories, especially the increasingly intensively mathematical theory of physics in the 19th and early 20th centuries, and that is the idea of invariance. What happened in the 19th century, and it's related to the power of techno-science, is that scientific theories finally in the 19th century became powerful enough to describe nature in ways that we could actually apply technologically.

Until then, it was mathematics. We saw that in the Renaissance, for example (I won't review that), that mathematics was a powerful source of knowledge for technology. But in the 19th century, scientific theories and especially these mathematical theories in electricity and in electromagnetic theory, for example, but the core of 19th century physics was something called aether physics—and we'll be talking about this in a future lecture—and the mathematics of aether physics, the idea increasingly scientists came to, the Pythagorean-like idea, that it's the mathematics that has the reality to it. That mathematical equations had to be invariant under certain kinds of transformations; that the equations—they are is an abstract version of a conservation of matter.

Now all of a sudden certain equations that describe what we believe reality to be like, those equations must be invariant under certain kinds of transformations, because if they weren't, then reality would be chaotic. The idea of invariance becomes especially important in the special and general theories of relativity, so we'll talk in more detail about it, but I just wanted to get that on the record. The idea of invariance is related to a comparably abstract idea that has become very powerful in mid-20th century and subsequent physics, and that's the idea of symmetries.

Now we will also talk a little bit more about this in a subsequent lecture, but just again to get on the record, this is a very strange thing. Nature observes certain symmetries, and we build our theories around the idea that certain natural phenomena—fundamental natural phenomena—are symmetrical. For example (and we might not use the word symmetry in this particular way), they're symmetrical in the sense that, for example, there was a time in the history of the universe, shortly after it emerged, when the electromagnetic force and the force that's called the weak force that is associated with the decay of radioactive nuclei, they were both one force; and then something happened and they split into two different forces. This is described as analogous to when water freezes and it undergoes a phase change, so its properties after it freezes are different than its properties before it froze, when it had liquid properties.

So analogously, there is a certain symmetry that is observed in nature. Symmetry is a fundamental fact about nature, but it's really an abstract fact about certain kinds of mathematical theories of nature that would not work unless you assumed symmetry. Together with this idea of symmetry comes an idea that came from a Japanese physicist named Yoichiro Nambu of spontaneous symmetry breaking. That it is a fact about nature that under certain circumstances fundamental symmetries break, and so all of a sudden you get the electromagnetic force and the weak force, even though earlier there was no such distinction. There was just one previous kind of force that was homogeneous.

So this idea that the most fundamental natural phenomena observe symmetry and there is, like, a force at work, so to speak, that makes them be symmetrical—they can't not be symmetrical unless a certain situation changes—we'll be talking about the inflation theory of the universe, in which the symmetry spontaneously breaks. And to a considerable extent these ideas of symmetry breaking, and symmetry, are very fundamental to physics over the last 30 years, and especially to what is called string theory and which in another name is called supersymmetry theory—finding the ultimate symmetry. So these ideas become fundamental to the way we think about nature.

Lecture Sixteen

Instruments as Extensions of the Mind

Scope:

Ordinarily, we think of instruments as extending the senses, analogous to machinery extending the muscles, but this is misleading. It is a fundamental premise of modern science that the reality it seeks to describe as the *cause* of sense experience is fundamentally *different* from sense experience. The microscope and the telescope, among the earliest instruments associated with modern science, seem to be extensions of our visual sense, but again, this is misleading. Typically, we cannot verify independently, for example, by visual inspection, what the microscope and the telescope show us. This is also true of such simple instruments as the air pump, barometer, and thermometer and, of course, of such complex instruments as electron and scanning tunneling microscopes, DNA sequencing machines, high-energy particle accelerators, and neutrino and gravity telescopes. Modern science is a web of concepts, and the instruments it employs are conceptual: What they tell us about nature is a matter of interpretation, not observation.

Outline

I. Scientific instruments have not received nearly as much attention from scholars as scientific ideas, perhaps because they are associated with know-how rather than with knowledge.

- **A.** It is a commonplace to refer to instruments as extensions of the senses, but in the overwhelming majority of cases, they are extensions of the mind.
  - **1.** Some simple instruments, for example, magnifying lenses and spectacles, *are* extensions of our senses, as basic machines are extensions of our physical strength/power.
  - **2.** We tend to assume that this is true for instruments generally, but this is not correct.
  - **3.** Even relatively simple instruments, such as telescopes and microscopes, are really extensions of the mind, of how we conceptualize and explain experience.
  - **4.** When the results obtained by using an instrument cannot be verified independently by the senses, then the instrument is the embodiment of ideas.
- **B.** The first modern scientific instruments are, not surprisingly, 17th-century phenomena, and they are clearly extensions of the mind, if not projections of the mind.
  - **1.** As extensions/projections of the mind, the telescope, microscope, air pump, and barometer tell us at least as much about how people conceptualize nature as they do about nature.
  - **2.** Consider Galileo's shift from using the telescope to see distant objects on Earth and in the sky. The former can be verified by inspection but not the latter: for example, his claim that there are moons orbiting Jupiter.
  - **3.** The same is true of the microscope and its "revelation" that there are tiny, invisible "animals" in our drinking water.
- **C.** As extensions of the mind rather than the senses, what instruments "reveal" about nature cannot be verified by direct inspection: We need to "trust" the instrument and the ideas/theory on which its construction is based.
  - **1.** Trusting instruments means trusting the ideas/theories in accordance with which the instrument is constructed.
  - **2.** How do we know whether an instrument whose results we cannot verify independently is revealing truths about nature or "truths" about the (mal)functioning of the instrument?
  - **3.** In fact, in the 17th and 18th centuries, both microscopes and telescopes suffered from optical aberrations that produced misleading, blurry, false-colored images.

4. **4.** These aberrations became worse as magnification increased, and everyone wanted higher magnification, especially for the microscope.
5. **5.** Techniques for making color-corrected microscopes were invented in the late 18th century but didn't become available until the 1820s.
6. **6.** Simple microscopes of the late 17th century had allowed Anton van Leeuwenhoek and Robert Hooke to make wonderful "simple" discoveries, but 19th-century microscopes allowed biologists to study the internal structure of cells and their nuclei.

II. The telescope and microscope are the best known of the instruments used by the 17th-century founders of modern science, but they are not the only ones.

- **A.** The air pump, barometer, and thermometer are also important 17th-century instruments and also embody ideas.
  1. **1.** The barometer was invented for the explicit purpose of testing an idea: Was there a vacuum?
  2. **2.** The prevailing view, inherited from Aristotle and defended by Descartes, among many others, was that a vacuum was impossible.
  3. **3.** Atomists, among them Galileo, defended the existence of "local" vacua between atoms, and some accepted Epicurus's version of atomism, in which atoms and "the void" are the ultimate reality.
- **B.** For both religious and scientific reasons, the reality of the vacuum was a controversial issue in early modern science.
  1. **1.** The Catholic Church was hostile to Epicurus's atomic philosophy because it was explicitly anticlerical and denied the soul or life after death.
  2. **2.** Blaise Pascal, a brilliant, young French natural philosopher and mathematician, made early barometers and believed that the empty space at the closed end of the column of water or mercury was a vacuum.
  3. **3.** One of the experiments he proposed and arranged to be carried out was to carry a barometer up a mountain, observing any changes in the height of the supported column of mercury.
  4. **4.** His conclusion was that the atmosphere, air, possessed weight and exerted a mechanical pressure, just as a liquid does.
  5. **5.** He also claimed that this proved that the empty space in the barometer tube was a true vacuum, but many others disagreed, interpreting the results of this experiment in a way that was consistent with the denial of a vacuum.
- **C.** How do we know what an instrument, especially a new kind of instrument, is telling us about nature?
  1. **1.** If a thermometer gives us a temperature reading that is not manifestly ridiculous, we assume that it is operating correctly.
  2. **2.** The air pump, developed into a research instrument by Robert Boyle and his then-assistant Robert Hooke, was particularly problematic in this regard.
  3. **3.** Boyle and Hooke used their pump, which was fragile, finicky, and malfunctioned often, to proclaim new laws of nature relating to the pressure, volume, and temperature of air.
  4. **4.** Thomas Hobbes, a Cartesian-style rationalist philosopher, famous for his social and political philosophy rather than his attempts at natural philosophy and mathematics, criticized Boyle's results.
- **D.** Following Descartes, Hobbes was deeply suspicious of complicated experiments.
  1. **1.** Hobbes was not prepared to trust that a newfangled machine could reveal nature's secrets, and he argued forcefully that experiments were open to multiple interpretations: Experience with the barometer showed that.

2. This illustrates very well that instruments are extensions of the mind.
3. Hobbes attacked the air pump as producing the results obtained by Boyle and Hooke, not simply revealing facts about nature.
4. We need to keep this in mind with respect to complex instruments of today, such as DNA sequencing machines and computer simulations.
5. Even a simple electronic calculator is almost invariably accepted on trust, but complex simulations involving programs produced by a large team of researchers are especially problematic.
6. Particle accelerators produce "real" physical events, typically, millions of collisions between subatomic particles, but those events are recorded and analyzed by extremely complicated instruments and computer programs.
7. The "discovery" of the sixth quark, called *top*, in 1995, involved identifying half a dozen "sightings" of the top quark among 15 million events!
8. Consider neutrino telescopes, buried deep underground, "observing" a minute fraction of a fraction of neutrinos passing through the Earth or, perhaps, just randomly "firing."
9. Only the theories used to build a device and interpret its output—ideas, in short—can distinguish between static and meaningful signals.

III. There would seem to be a logical circularity in claiming that instruments that embody ideas and theories reveal a reality that is independent of experience.

A. The study of scientific instruments with respect to their role in theories and explanations raises questions about the nature of scientific knowledge.

1. The Sophists, recall, argued that knowledge was about experience and was a form of what we would call high-probability belief about experience validated by experience.
2. It was Plato and Aristotle who championed the rival view that knowledge was universal, necessary, and certain truth about a reality independent of experience.
3. The role of instruments in the logic of theory formation and explanation seems closer to the Sophist view than the Platonic-Aristotelian.

B. It is also true that instruments designed for one purpose sometimes give completely unintended results, leading to new theories or revisions of existing ones.

1. Instruments invented to detect the *aether* in late-19th-century physics gave results that led to the conclusion that the aether did not exist.
2. Radio frequency radiation from outer space was discovered by telephone company engineers studying static on long-distance lines.
3. The discovery, dating, and analysis of fossils, for example, using radioactive dating and DNA testing, has led to multiple theories and changes in theories.

C. The relationship between physical instruments and theories and ideas is complex and reciprocal.

1. It is simplistic to say that instruments are ideas only, incapable of telling us something we were not already committed to.
2. It is also simplistic to dismiss scientific explanation as logically circular because of this reciprocity.
3. It is important to realize that instruments are extensions of the mind, not the senses, and as such, the relationship between instruments and theories demands much more attention than has been given to it.
4. This has become increasingly important as the most sophisticated instruments require our most sophisticated theories for their design and for the interpretation of their results.

Essential Reading:

Steven Shapin and Simon Schaffer, *Leviathan and the Air Pump*.

Davis Baird, *Thing Knowledge: A Philosophy of Scientific Instruments*.

Questions to Consider:

1. If instruments embody ideas, can observation be independent of the theories that observation is supposed to confirm or disconfirm?

2. As instruments become more complex and experiments more expensive, what happens to replication by others as the traditional test of the validity of scientific knowledge claims?

Lecture Sixteen

Instruments as Extensions of the Mind

The subject of this lecture is scientific instruments. And perhaps there would be a collective sigh of relief—if I could hear such a collective sigh—based on sort of getting away from the abstractness of the last couple of lectures, of dealing with scientific ideas of such abstractness as conservation, invariance, and symmetry, and before that of algebra, calculus, and probability theory.

In fact, however, I don't want to talk about scientific instruments as bits of hardware. They are, of course, and I will be talking about them at that level, but what I want to focus the lecture on is scientific instruments as ideas. Now, that is an idea all by itself that I think we need to build up to.

It is self-evident that instruments are central to the conduct of what we mean by science and scientific research. It is as inconceivable to do hard science without instruments today as it is to do science without writing. So science is, critically, not just dependent on them—instruments are woven into the fabric of the practice of science. And yet instruments are almost never treated for purposes of understanding the nature of science and scientific practice, are never given the status of theory and ideas.

Philosophers of science, historians of science, sociologists of science have spent a lot of time trying to understand the development and the dissemination of scientific ideas and theories, but there is very little literature on the history of scientific instruments. Obviously in the last 20 years—I shouldn't say obviously, but it is the case that in the last 20 years this has become obvious to more and more historians and philosophers and sociologists, and we are beginning to see an increasing focus on instruments. But primarily these are on, so to speak, the hardware, the technology of the instruments; but some attention is now being given to the obvious dynamic interaction between scientific ideas and instruments.

It is not just that scientists use instruments in order to validate ideas, but that the invention of new instruments often drives scientific ideas and scientific theories in ways that we'll be discussing very shortly. So I want to talk in particular about a view of instruments that may seem odd on the face of it, but that is especially why it needs to be discussed in a course like this.

We ordinarily, perhaps, think of instruments as extensions of our senses, and that therefore they allow us to have experiences that we would not otherwise have. And we think of such instruments, for example, as hearing aids and prescription eyeglasses and magnifying lenses as clear extensions of the senses. And sort of by extension we assume that things like telescopes and microscopes and special devices that let us hear sounds that we cannot hear, that can detect sounds that we cannot respond to (let's say sounds above somewhere in the 20,000 hertz and up range—certainly above 30 or 40,000 hertz I don't believe anybody claims the ability to have an auditory response to) as also extensions of our senses.

But this is not correct, I believe. These are extensions of our mind. The crucial point is that scientific instruments, the instruments that scientists beginning in the 17th century used in order to formulate and justify and defend their ideas about nature, their theories of nature, their explanations of natural phenomena, these instruments gave results that could not be verified by the senses, either in fact or in principle.

Nowadays, of course, it's in principle. You cannot verify the results that you get from an electron microscope or from an X-ray crystallography machine or from a DNA sequencing machine by looking at the natural phenomena very carefully close up. Well you say, "I don't want to bother. It's very painstaking." You can't do it. But that was just as true in the 17th century. That is to say, Galileo's claim that using the telescope he had identified four moons that were circling Jupiter is not something that could have been verified at that time. So we could have said it could not be verified until, let's say, nowadays.

We could, in principle, send a spaceship up, and we have sent spaceships up into space, and then they have sent satellites out to probe Jupiter and Saturn, and we can now take pictures. We have beautiful close-up pictures of many of the moons of Jupiter and now of Saturn, but in Galileo's time there was no way to verify that. Just as nowadays we have no way of verifying what X-ray telescopes, what gamma ray telescopes, what neutrino telescopes tell us by direct observation using our senses. You could not go up to Jupiter to say, "Yep, those are moons all right."

Now, what happens is we get seduced into this because initially when the telescope was invented (not by Galileo), and when Galileo first built the telescope, the way he sort of tested it was by looking at things that were not visible. Let's suppose that there was a big billboard in Florence (although at the time Galileo was not in Florence), but let's suppose there was a big billboard in Florence, and you moved far enough away that you can't read what it says on the billboard. And then you look through the telescope and you can read it. So you say now, "Is the telescope really showing what's written on the billboard?" So you go closer and you see that yep, it told me. People used the telescope to look for ships at sea as they were coming to the port, and they could see them before they came into the port, and so they could see that, yes, the telescope showed me that this particular ship, long before I could see it with the naked eye, that that was coming into port; and so the telescope tells me the truth. But that's because I can check the results of the telescope.

Once you use the telescope to make inferences about what the surface of the moon is like, whether Jupiter has moons or not, then you can't verify that by going there to check to see if the telescope has really shown you moons around Jupiter. Or are there funny little air bubbles in the lens that somehow are moving, and that simulate—or that I am confusedly interpreting as—moons circling around Jupiter?

And so the results of using the telescope, and this of course is true for the microscope as well—initially the microscope is a magnifying lens, but once it becomes a compound microscope with a power exceeding the magnifying lens capability, so that you now can look closely enough at a drop of water and see that there are tiny little creatures swimming around in the water. Under the microscope you look at a drop of water, as Leeuwenhoek did in the 17th century, and you see creatures squirming around in there that you have been drinking. But you can't see them, so how do you know that they're really there? Maybe somehow, for some weird reason, they're in the microscope, or that they are artifacts of the microscope. Now, again, this situation only becomes "worse" with time; that is, the sense with which instruments are an extension of our mind, not of our senses, only becomes more intensified as instruments become more complicated.

Once you get to the 19th century, where microscopes become extremely powerful because techniques were developed for correcting for chromatic aberration from the fact that, as Newton already knew, different (what we would call) frequencies of light come to a different focal point. Because they have different frequencies, and therefore different wavelengths, the different colors that make up light (unless you're using a laser, which can be as narrow as one frequency), then the different colors come to a focus at different points. And the more curved the lens is, the more magnification it's capable of giving you, the more there's going to be a blurring of the focus of those different frequencies that make up the light, whether it's sunlight or whether it's the light that you're using to illuminate the slide stage of the microscope.

In the 18th century a technique was developed to overcome this, but it only became a commercial product in the 19th century, and between the 1830s and the 1870s much more powerful microscopes were developed. And now all of a sudden, as we'll be discussing when we talk about the cell theory of life, we could look inside the cell and discover the nucleus of the cell; look inside the nucleus and discover things like the chromosomes in the cell. But you can't verify that. You have to trust the instrument. And this was true even in the 17th century. And it was explicitly understood as a challenge that experimental science needed to address.

For example, just think of what were the core instruments that were used by scientists in the 17th century. There was, of course, the telescope and the microscope, not invented in the 17th century, invented in the 16th century, but developed into a scientific research instrument in part by Anton van Leeuwenhoek in

Holland, and by others, including very notably Robert Hooke in England. Hooke wrote a very beautiful book called *Micrographia* in which he made drawings of the kinds of things that he saw in the microscope. One of which, looking at a piece of cork, was the cellular structure of the cork, from which he speculated that this cellular structure was fundamental to living things, an idea that sort of dropped out of sight and then was recovered in the 19th century. Those are two instruments that we recognize as identified with the early modern scientific research. The transition to modern science, using instruments like the telescope and the microscope, overturned earlier conceptions of nature.

Three other instruments that we don't often think about as scientific research instruments, but which were in the 17th century, are the barometer, the thermometer, and the air pump. Now these are much simpler instruments in a certain sense than we normally identify with scientific instruments. Everybody has got a thermometer, for example, and lots of people have barometers—some of them are built into alarm clocks and watches. But the barometer was invented specifically to explore a particular scientific idea and question: Is there such a thing as a vacuum in nature? The Greek prejudice was that "nature abhors a vacuum," and this prejudice was disseminated and transmitted into the 17th century. It was a very lively argument in early modern science as to whether there was such a thing as a vacuum.

Descartes, for example, clearly a brilliant individual—science, mathematics, and philosophy—Descartes rejected the possibility of a vacuum, that there is no such thing as a region of space that is empty of matter. That cannot be. Galileo cautiously defended an atomic view of matter, and believed that while there was no large-scale vacuum in nature, that there was a vacuum at the atomic level in between the atoms that made up matter. But this was cautious because in his own lifetime, and as he understood very well when he was brought before the Inquisition, atomism was identified with Epicureanism, which is from the Catholic Church's point of view a fundamental heresy.

And although the travesty of Epicures's philosophy, that "eat, drink, and be merry, for tomorrow we die" was not something that he either said or could possibly have said, that was identified with Epicureanism from an early Christian period. And it is a fact, however, that if you look deeply into Epicures's theory, Epicures's atomism—atomic theory of matter—was motivated by his anti-religious attitude. In ancient Greece, his atomism was an attempt to show people that they should not be afraid of death, and they should not have anything to do with priests, because death is the dissolution of the particular atomic configuration of atoms that is you. And there's nothing left of you when the atoms dissociate, so you don't have to worry about that. You will not be punished after death for anything that you do. Death is really the end of that particular configuration.

Now, of course, from the Catholic Church's point of view this is heretical. We now have very good evidence that the pope, who initially encouraged Galileo to write his book about Copernican astronomy, became embroiled in a serious political battle within the Catholic hierarchy that involved being, so to speak, soft on heretics at a time when the Church was fighting for its life against the Protestants. Remember, Galileo's trial came out in almost the middle of the Thirty Years' War between the Catholics and the Protestants, 1618–1648. And so the pope decided that he could not defend Galileo. He had to let the Inquisition run with what they were doing, in part because of this atomism.

Anyway, the vacuum was a major issue in the first half of the 17th century, and together with the then-recent invention of the air pump, the question was connected with the question of whether air has weight. So Blaise Pascal, a brilliant French scientist of the early 17th century, a man who as a teenager invented the first (as we think) mechanical calculator for multiplication and addition, and contributed to early probability theory and to geometry and algebra—generally before he got religion in a serious way and decided that all of this was frivolous and he needed to save his soul—Pascal suggested to his brother-in-law that he build essentially this first device, the barometer, and carry it up a mountain and see if the height of the column of mercury that was supported in the barometer changed as a function of height. It was an early and very important experiment and in fact, son of a gun, it did. As you climbed, the size of the column of mercury that was supported by a barometer shrank, and that showed that air pressure was lower. The weight of the atmosphere pressing down on the open tube of the barometer was less than at sea level, and so the pressure went down. At least that was Pascal's interpretation of what was happening in the barometer, and that required believing that in the closed section of the barometer, the empty space between the top of the level of mercury and the top of the barometer tube, was a vacuum, and therefore did not exert any force on the column of mercury. The only force was coming from the open tube, which was exposed to the atmosphere.

And that then became a source of controversy: how to interpret the results of the experiment—which reinforces Descartes's view that experiments are equivocal. They're always equivocal. They need to be interpreted, so you have to use them very carefully. But the barometer tells us about air pressure, and we cannot independently verify that, just as if a thermometer tells you that the temperature of something is 413 degrees or even 186 degrees, you can't verify that. You have to assume that it's 186 degrees because the thermometer says so. Now that can matter if you are, for example, monitoring a chemical process in which the ingredients have to be kept above 186 degrees or below 186 degrees. So then it matters. And if the thing works, then you say, "Well, if the thermometer told me 186, then that's good enough for me. It's telling me the truth."

And the third instrument, which was actually related to the barometer, was the invention of the air pump, which Robert Boyle and his then-assistant but subsequent peer collaborator, Robert Hooke, used to discover the first laws of the behavior of gasses: the relationships among pressure, volume, and temperature. Mathematical, algebraic equations relating pressure, volume, and temperature of a gas—these were formulated by Boyle and Hooke by using this air pump, which created a partial vacuum and then could allow you to see what happens to the pressure of a gas when you change the volume and, conversely, the same thing with temperature.

Now at the time Thomas Hobbes, a rationalistic, deterministic philosopher of Cartesian type, Hobbes severely criticized what Boyle and Hooke were doing. He severely criticized the air pump on grounds that actually are not so much right, but very relevant to the issue that I'm trying to raise here. How do you know that what you are observing is not being produced by the machine? How do you know that the machine is operating correctly? Once you get below a certain level of sophistication, and in fact even telescopes and microscopes are at that level, you have to be trained in order to make sense of what the instrument is showing you. The instrument has to be tuned. It has to be calibrated. You have to know that the instrument is working right.

But when you're inventing a new instrument, how do you know it's working right? How are you supposed to confirm that? When your DNA sequencing machine gives you a sequence, then you have to assume that the machine is working right if those sequences make sense to you. So you're interpreting them and you're relating the sequence that comes out to the results that you have read in the journals, that, yes, this laboratory here identified that sequence, and so I assume that the bits and pieces in between are correct also.

At a very simple level we use electronic calculators all the time, for example, to do your tax returns. Nobody checks to see if the calculator is working correctly. How come? Even Lexuses have flaws. How come nobody wonders whether the calculator is giving the right multiplications, the right additions or not? But in fact we don't do that. We could do it for arithmetic calculations. It might be very tedious, but we could do it.

When it comes to using the computer for very complex simulations—for example, weather simulations, for simulations of what's going on inside the earth reconstructed from picking up seismic waves from earthquakes or from detonating explosives—then the computer is doing something that we can't check. It might take hundreds or thousands of scientists, engineers, and mathematicians years to reproduce that particular set of results, so it's not going to happen.

When you're talking about particle accelerators, as we have a picture of here, the particle accelerator generates a mountain of numerical data which needs to be interpreted. When the top quark was discovered in 1995, it was after several years of analyzing data that had been taken in the earlier 1990s—some 15 million events within the particle accelerator—and it turned out that six of them were interpreted as signs that the top quark was created momentarily inside the particle accelerator at Fermilab. This seems to me a quite clear example that instruments are extensions of our mind. They are not extensions of our senses.

A neutrino telescope is buried deep under the ground in which thousands of photomultiplier tubes float in super pure water and every now and then they go off, and we interpret this as "Uh-oh, neutrinos are passing through here." The instrument is designed in accordance with ideas and theories, and then the instrument tells us something which we interpret by means of ideas and theories. So it's an interesting question.

Is there a circularity here? Is there a sense in which the Sophists were really right? That while we pay lip service in science to a definition of knowledge as universal, necessary, and certain, while we insist that the presentation of scientific results be in this deductive format, that we say that a theory is only correct if we can deduce from it consequences that match empirical experience, that really the reasoning that goes on in the laboratory is very, very different, and it's really about experience? That it reflects ideas that we have derived from experience that we then formalize and say they are True with a capital T, as proven by the fact that we can deduce from the assumptions of the theories, from the principles that the theory employs, from the premises of the theory, we can deduce specific phenomena that are confirmed in the laboratory?

If that's the case, then I think that the study of instruments raises some very interesting questions about the idea of science and the nature of scientific knowledge. It is the case, of course, and that's what makes life complicated and in some respects beautiful. It is the case that sometimes instruments designed for a totally different purpose reveal outcomes, give results that force new ideas and new theories.

It was experiments done in the 19th century in support of this aether physics that dominated European physics in the second half of the 19th century that suggested to Einstein that maybe the absoluteness of the speed of light in a vacuum for all observers that were in uniform motion with respect to one another, there were some experimental outcomes that supported his inventing that axiom of special relativity theory. Nothing could be said to have proven it, but it was suggestive, and certainly that was not intended.

When Karl Jansky built a device in order to study static on long distance transmission lines and inadvertently discovered that the sun is a source of radio waves, electromagnetic energy—that had not been anticipated. That founded the discipline of radio astronomy, and radio astronomy and the subsequently building of much more complicated and sophisticated instruments, has caused us to rethink what the universe is made up of and what stars and galaxies and intergalactic space are really like. We used to think of intergalactic space as basically empty with gas clouds and some dust, but we had no idea what was really going on. Through radio telescopes we have been able to identify the atoms and molecules floating around in space and quite a complicated inventory of molecules which has forced us to revise our conception of the universe in ways that we'll be talking about.

So sometimes scientific instruments, even though they may be built with one particular set of ideas, give outcomes which force us to change our ideas. Sometimes an instrument that's not a scientific instrument, strictly speaking (Jansky was not building a scientific instrument, he was building an engineering device, studying static on long distance telephone lines and trying to find sources of interference with the telephone cables), can also force us to change our ideas, just as archaeologists can discover objects in the ground. Objects in the ground are not ideas. It may be that ideas led you to dig in a particular place, but once you discover an object, then that object could force a reconsideration, and in fact it can force whole new theories.

When we started finding human fossils in East Africa, for example, especially since World War II; then repeatedly, new discoveries have changed our theories about the evolution of human beings. Then when DNA was applied to the study of these fossils, then it also has led to complete changes. So it's not that instruments are merely ideas; or that instruments are neutral, that are objective means by which scientists study nature, and so they're not tainted, so to speak, by theories and ideas, and there's no logical circularity; it's a more complex situation than that. Scientific instruments and scientific theories have a complicated relationship, a relationship of reciprocal influence.

And I think that a crucial insight, the one that I'm focusing on in this lecture, the point that I want to make sure that I get across to you in this lecture, is the idea that for instruments, as a matter of fact, it is misleading—at least misleading and I think it is an error—to think of instruments as extensions of our senses. We must appreciate the role that ideas and theories play in the design and construction of instruments, but also in the interpretation of the results, of what it is that the instruments have revealed to us. Instruments do not simply reveal what is out there. You have to make sense of what they reveal.

When you look through an atomic force microscope and the computer paints a picture on the computer monitor screen of one type of atom, gold atom, sitting on top of silicon atoms, spelling out IBM in a very famous illustration recently, then that is a computer reconstruction. You're not seeing atoms. You're seeing a computer reconstruction. The computer program is based on quantum theory and it's based on very complex mathematical algorithms that interpret minute fluctuations in the electromagnetic energy at the tip of the probe of the atomic force microscope and the surface of the material that you're trying to create an image of.

This is even true for observational astronomy. I think, well, nevertheless, I'm exaggerating; when you talk about a telescope we still look through the telescope and we see what's out there—at least optical astronomy. But that hasn't been true for decades. Astronomers really don't look through telescopes any more because the latest generation of telescopes are computer controlled, not just computer controlled in terms of their direction, but they're computer controlled because they have multiple mirrors that are flexed in real time by computers to keep them in focus as temperature changes, as humidity changes, and because they have what's called *adaptive optics* to compensate for the turbulence in the atmosphere. Computers now collect light not through lenses that give you an image on the human eye; they collect light using charge-coupled devices like the things in your digital camera, so that the observational astronomer sits in a room and looks at a computer screen and observes the images constructed by the computer software based on the light coming in.

So even for observational astronomy, let alone cosmic ray astronomy, gamma ray astronomy, X-ray astronomy, neutrino astronomy, those are more obviously cases in which the instruments are extensions of the mind, but even optical astronomy. And so the idea of scientific instruments which became identified with science in the 17th century, so that the invention of such instruments that are extensions of our mind is a pivotal development in modern science.

If you're talking about scientific ideas that have changed the world, it is through instruments that scientists have developed theories that have changed the world, and those instruments did not drop down out of the sky. Those instruments themselves are extensions of the minds of the scientists who were trying to understand the world.

Lecture Seventeen
Time, Change, and Novelty

Scope:

Time is not a fundamental feature of reality, either for modern science or for the philosophical tradition whose definition of *knowledge* science assimilated. If the ultimately real—whether God, elementary substances, or laws of change—is changeless, it is also timeless. This timelessness of the real appears in modern science as the reversibility of time in the equations of mathematical physics. The irreversibility of time *as experienced by us* is merely a fact about us, reflecting the limitations of our ability to experience reality. Although the 19th century began with a declaration of the ultimate insignificance of time, developments in the course of the century challenged this. The concept of energy, the new science of thermodynamics, and the theory of evolution implied that time truly was irreversible and that it was the dimension in which unpredictable novelty emerged. The debate over the nature of time continues to rage even today.

Outline

I. How to explain change has been the fundamental challenge for knowledge of nature since Parmenides and Heraclitus, and because time is the measure of change, it is pivotal to scientific explanation.

- **A.** That instruments are extensions of the mind makes an issue out of the relationships among instruments, ideas, and tools.
  - **1.** As physical devices, scientific instruments seem very different from what we commonly mean by *tools*.
  - **2.** Consider the obvious difference between the Hubble Space Telescope and a screwdriver.
  - **3.** Conceptually, however, even a tool as simple as a screwdriver or a hammer has a great deal in common with complex instruments: Both embody systemic ideas.
- **B.** Although it seems odd to say so, scientific ideas and concepts—ideas become concepts when defined in more specific ways—are tools.
  - **1.** It is by means of concepts that scientists analyze phenomena and construct explanations.
  - **2.** How the concepts scientists use are defined is central to doing science, and for physics, the most fundamental concepts include space and time.
  - **3.** Keep in mind that we are talking about ideas as they function in scientific explanations and that *all* scientific ideas change over time—even the idea of time itself!
- **C.** Perhaps the most famous philosophical analysis of the idea of time is in Augustine's *Confessions*.
  - **1.** Augustine concluded that *time* was a name for a mental phenomenon, not a feature of reality.
  - **2.** Time is coordinate with, and the measure of, change; the changeless is timeless.
  - **3.** But if we want to know what time is, we are puzzled because time's manifestation in consciousness lacks being!
  - **4.** The past no longer is; the future is not yet; and the present is a timeless instant (so Augustine claimed) between past and future.
  - **5.** Augustine concludes that time is a feature of the mind, not reality.
- **D.** Newton's masterwork, the *Mathematical Principles of Natural Philosophy*, founded the modern science of mechanics; he begins with definitions of space, time, and motion.
  - **1.** Newton notes that these ideas are familiar to everyone, but this simply means that, as Francis Bacon warned, we have preconceptions that need to be clarified.
  - **2.** Before he can write equations describing the motions of material objects under various forces, he needs precise definitions of these ideas.

3. It is especially important for Newton to distinguish relative and absolute time, space, and motion.
4. Newton defined time, as well as space and motion, as having an absolute character.
5. Time exists independently of anything that happens *in* time.

E. Newton defined time as an absolute clock, “ticking” away at an absolute, uniform rate.

1. This idea of time, and Newton’s definition of space, as well, remained the cornerstone of mechanics and, hence, of physics for 200 years.
2. There was an implicit problem in how these definitions can be correlated with the actual measurement of time and space.
3. This problem became explicit in the late 19th century, and in the early 20th century, Einstein’s relativity theories forced redefinitions of time and space that abandoned their absolute character and made them into relationships.

II. There is a philosophical aspect to the idea of time that underlies and even haunts its scientific definition.

A. Those Greek philosophers for whom knowledge was universal, necessary, and certain valued the timeless over the temporal.

1. The centrality of deductive reasoning to the idea of knowledge as formulated by Parmenides, Plato, and others implies that knowledge, truth, and reality are timeless.
2. The conclusion of a deductive argument is already *contained* in the premises: It is only “accidental” that we human thinkers have to draw it out for examination in an explicit conclusion.
3. Transposing this deduction-based philosophical idea of knowledge to knowledge of nature implies that effects already exist *in* their causes; thus, natural time, too, is a mere “accident.”

B. In fact, modern science assimilated just this set of ideas.

1. The mathematico-deductive methodology of Archimedes was, as we have seen, adopted by Galileo and Newton, and it became the “gold standard” of scientific theory construction.
2. Scientific theories take exactly the form of deductive arguments, from which phenomena to be explained are deduced.
3. But that means, ultimately, that time is not real, as Augustine concluded on philosophical grounds.
4. *We* need to draw conclusions because our minds are limited in power, but an unlimited mind would see everything in an instant.
5. In the early 17th century, Galileo said this in his *Dialogue*, and later in that century, Leibniz wrote that the present is “pregnant’ with the future, as the past had been “pregnant” with the present.

C. This is the essence of determinism, which is timeless.

1. Leibniz’s dictum found literal expression in contemporary 18th-century embryological theories of *preformationism*.
2. Embryos were fully preformed neonates, minutely folded inside the egg or the sperm, and unfolded only during gestation.
3. In physics, the ultimate timelessness of reality was reflected in the *reversibility* of equations in mechanics: Time can go either way.
4. At the turn of the 19th century, Pierre-Simon Laplace proclaimed the indifference of the material world to time in the context of his proclamation of the exhaustive character (in principle) of the materialistic determinism of mathematical physics.

III. The prevailing cultural and scientific conception of time changed in the 19th century, even as Laplace’s formulation became canonical.

A. The idea of progress entails an asymmetric conception of time, as does the idea of historicity.

1. The future orientation of Renaissance believers in progress makes time not just the dimension of change but change for the better.
2. History, as an account of change over time in human affairs, achieves a new stature.
3. The Renaissance Humanists, contra Aristotle, made history a "science," that is, a body of true knowledge and even the model for knowledge, in spite of its particularity and contingency.
4. Through their studies of the past, the Humanists made intellectuals in the early modern period aware of the historicity of language, law, and institutions, that these changed *irreversibly* over time.
5. The idea of progress makes time into the dimension of human hope and even salvation.

B. In the 18th century, the Humanist sensitivity to history and to historicity expanded its scope.

1. Giambattista Vico's *New Science* proposed that human consciousness evolved, that *how* we thought changed over time.
2. Eighteenth-century theories of the origin of the Solar System and the Earth attributed change to them, contrary to Aristotle's claim that they had eternally been the same.
3. At the turn of the 19th century, Gottfried Herder argued for the historicity of human culture in all its forms.
4. Early in the 19th century, Hegel attempted a new form of deductive logic in which time played a significant role—a dynamic determinism as opposed to simple preformationism—which became the "inspiration" for Karl Marx's *scientific materialism*.

C. Time, as defined explicitly by Newton and implicitly in the idea of scientific knowledge, became an issue in science in the 19th century.

1. The idea of energy that blossomed into the new theory of heat called *thermodynamics* led to a new "law" of nature that implied that time was *irreversible*, that it could flow in only one direction.
2. This flatly contradicted the *reversibility* of time in mechanics.
3. The Darwin-Wallace theory of evolution, contemporary with the invention of thermodynamics, also implies that time is a dimension of the emergence of novelty, not simply the unfolding of what is already there in germ.
4. Such developments created a tension in science between those committed to a deductive-deterministic conception of knowledge and reality and those for whom new theories implied that knowledge and reality both had a statistical-probabilistic character.

Essential Reading:

Ilya Prigogine, *Order Out of Chaos*.

Martin J. S. Rudwick, *The Meaning of Fossils*.

Questions to Consider:

1. What is revealed about Western intellectualism by the fact that so many of our greatest philosophical and scientific thinkers believed that time was an illusion?
2. Is a deterministic account of nature compatible with a conception of time as irreversible?

Lecture Seventeen
Time, Change, and Novelty

The last lecture on instruments as extensions of the mind contained an implicit problem that's worth getting back to and making explicit as a way of a lead-in to the subject of this lecture, which is the idea of time.

The implicit problem is the distinction between an instrument and a tool. What is the difference between a scientific instrument like the Hubble Space Telescope, for example, and a tool like a screwdriver? It would seem as though there is a clear distinction between something as complex as the Hubble Space Telescope—and maybe that's exemplary of a scientific instrument—and something as simple as a screwdriver—well, surely that's not an instrument. And yet it turns out to be the case that the difference between an instrument and a tool is much less clear than may at first seem to be the case.

For example, the tool, like a screwdriver, already shapes the kinds of problems that it is capable of solving and the kind of solution that it offers to that problem. For example, if the problem is fastening two objects together, then the screw is one solution to that problem, but the screw and the screwdriver are complementary. You can't have screws without a screwdriver; you can't have a screwdriver without the screw. Is the screwdriver going to have a plain head, for example, or is it going to have a Phillips head, just to pick two examples? The screwdriver does not exist separately from the screw, and from a problem context that the screw and the screwdriver are both part of, let's call it a simple system, that solves that problem, that offers a solution to that problem.

Obviously the nail and the hammer and glue would be other solutions to the problem of fastening objects together, and there have been historically many solutions to the problem of fastening objects together. It depends on what the context of the fastening is. The point here is that instruments and tools both define a problem space, so to speak. Metaphorically speaking, the space of defining a problem in a particular way and then offering a particular kind of solution rather than a different kind of solution. We must think of a scientific instrument as an element in a broader context of posing problems, defining problems, and then suggesting ways of solving or addressing that problem.

An instrument or a tool can take a number of different forms. It can be an artifact like the Hubble Space Telescope or a tool can be a concept or an idea. For example, two lectures back we talked about the ideas of conservation and symmetry. Conservation and symmetry are ideas. They become scientific concepts when they are defined in specific ways, and they serve the way tools do in defining a problem area and addressing, proposing a solution to that problem area. So although it sounds odd, metaphorically at least, concepts can be—and in general it is good to say that concepts are—tools.

In particular, we are going to look now at the concept of time, at the idea of time as a scientific idea, and use it as a way of illustrating the difference between an idea and a scientific idea. This is a very important distinction to keep in mind generically, and we've been making it throughout this course: An idea is a scientific idea when it functions in the context of a scientific explanation, which includes defining a problem in a specific way and suggesting that X will be a solution to that problem as opposed to Y or Z, for example.

So a scientific idea is not just an idea; it contains within it an implicit and explicit set of definitions that allow us to shrink the problem space to one that has a very specific form, and then to address solutions to that problem, and to see whether in fact we consider that problem solved. This is what you might call, in a very broad sense, the underlying logic of scientific inquiry.

So if we look at the idea of time and of how time became a scientific idea and how time became an issue for science, especially in the 19th century, then I think we'll get a good idea of how scientific ideas generally evolve from a casual notion or from a commonsense ordinary-language notion of an idea to a precise scientific idea.

The fact that they are precise does not necessarily mean that now they are clear and unambiguous; because they can be given a precise definition, but the definition itself is contingent. It could take a number of different forms, and it could well be the case that you have multiple precise definitions of time that are conflicting. And although this is very bad technique in comedy as it is in prize-fighting, I will telegraph that our conclusion is going to be to show that the idea of time in 19th and 20th century physics was, in fact, deeply conflicted. That contrary definitions of time as ultimately real and ultimately unreal somehow are both being carried along within the framework of scientific theorizing.

I want to begin by reading a passage from Augustine's *Confessions*, Book 11 of Augustine's *Confessions*. This is one of the classic expressions of inquiry into time, which is of course a universal aspect of human experience. So when philosophers look for a philosophical idea of time they must do the same thing that scientists do when they take the ordinary sense of time and convert it into a scientific idea. Let's begin with Augustine, who writes in Book 11:

> What, then, is time? I know well enough what it is provided that nobody asks me, but if I am asked what it is and try to explain, I am baffled. All the same, I can confidently say that I know that if nothing passed there would be no past time. If nothing were going to happen, there would be no future time. And if nothing were, there would be no present time. Of these three divisions of time, then (past, present, and future), how can two—the past and the future—be, when the past no longer is and the future is not yet? As for the present, if it were always present and never moved on to become the past, it would not be time, but eternity. If, therefore, the present is time only by reason of the fact that it moves on to become the past, how can we say that even the present is, when the reason why it is, is that it is not to be? The whole point of the present is that it slides into the past and becomes the past. So we can never grasp the present. The future doesn't exist yet, and when it does exist it's the present, which is sliding into the past, which no longer exists.

And so Augustine leaves us with this puzzle of what can time be. How can we clarify the idea of time given the commonsense perception that time falls into one of three categories—past, present, and future—and yet none of these fully is, in a way that allows us to give any reality to time? Well, Augustine later on in Book 11 (or we would call it Chapter 11) of his philosophical autobiography called the *Confessions* gives a philosophical theory of time.

But what I'd like to do now is turn to Isaac Newton, his *Mathematical Principles of Natural Philosophy*, his great work of 1687, in the translation by I. Bernard Cohen and Ann Whitman, a superb recent English translation with extensive commentary. At the very beginning Newton, who is going to offer us a theory of mechanics—that is to say, a theory of how one can reduce the motion of material particles to scientific law, to universal laws—must define space and time in ways that are adequate to the problem of describing motion, because motion is change of space over change of time—change of position in time. So without definitions of space and time, we can't even begin to write an equation of motion. Newton wants to make these definitions explicit.

Now getting back to what I started with—the screwdriver—Newton is going to define space precisely, define time precisely (at least philosophically speaking) and for purposes of contracting the problem, the problem here being how to describe the motion of material particles in a way that gives us universal laws of motion. He is going to define them in very specific ways. But it will turn out in 1915, when Einstein formulates the general theory of relativity, that Newton's ideas of space and time are by no means obvious, and in fact have to be given up in order to do justice to 20th century physical theories about space, time, matter, motion, and energy. But listen to what Newton wrote, and this becomes foundational for modern science from the end of the 17th century, from Newton's *Principia*, right up to the general theory of relativity.

> Although time, space, place, and motion are very familiar to everyone [sounds a lot like Augustine] it must be noted that these quantities are popularly conceived solely with reference to

> the objects of sense perception, and this is the source of certain preconceptions. Ordinarily we have various preconceptions about space, time, place, and motion, and these have to be clarified if we're going to do anything as precise as write equations of motion that are universally valid. To eliminate these preconceptions it is useful to distinguish these quantities—space, time, place, and motion—into absolute and relative, true and apparent, mathematical and common. Absolute true and mathematical time in and of itself and of its own nature, without reference to anything external, flows uniformly, and by another name is called duration. Relative, apparent, and common time is any sensible and external measure of duration by means of motion. Such a measure, for example, as an hour, a day, a month, a year is commonly used instead of true time.

Which for Newton, again, is an absolute entity which exists independently of anything happening in time, as if there were an absolute clock slowly ticking away at the center of the universe, and that becomes the absolute metronome, so to speak, of all of the affairs of the natural world. All of the processes of the natural world, from the smallest to the largest, are measured; change in any of these processes is measured, ideally in accordance with this absolute clock.

Now this definition, when you harp on it to this extent, is clearly highly problematic, because then you can ask the question, "How do you measure it?" And it's interesting that people did not until the early 20th century, until Einstein challenged this definition. Einstein was not the first, but Einstein was the first to build it into a systematic theory of the universe. He challenged this definition and claimed that the fact is, the definition cannot be sustained—this notion of absolute time. And Newton gives a definition of space as absolute as well.

So now we have the foundational definition of time for science, which is absolute in this particular way. Nevertheless, time as Newton describes it, is still flowing. It has an absolute character, and it flows uniformly. How we know that this next second is just as long as the preceding second is a thorny problem, and once you start thinking about it, it's liable to make you dizzy.

But there's another aspect of time that was brought into science from the very beginning. That is the timelessness of knowledge, truth, and reality, the timelessness of reason that was brought into modern science when it incorporated the Greek philosophical definition of knowledge that we've talked about in earlier lectures right at the beginning of this course, defining knowledge in a way that is universal, necessary, and certain, and epitomized by deductive reasoning. Deductive reasoning gives us access to truth, and that implies that ultimately knowledge, truth, and reality are timeless because deduction is timeless. What makes deduction work, so to speak, the reason why the conclusion of a deductive argument is a necessary consequence of the truth of its premises, is because the conclusion is already implicit in the premises. It is merely an accident that we have to draw the conclusion. The conclusion was always in the premises. And this notion of deduction—deductive reasoning as the sole means to truth, knowledge, and the exposure of reality—means that, in physics, the effect is deducible from the cause.

All scientific theories present themselves in this way. This is the Archimedean method that Galileo and Newton made the centerpiece of their own scientific methodology. The effect is deducible from the cause. That means that the effect was always in the cause, and therefore time is an illusion. Ultimately the future is already contained in the present, which was, of course, the future of a past. And so from the very beginning of the existence of the universe, every subsequent moment of time, everything that happened and everything that will be was already implicit in the beginning and is deducible from it, and therefore is, so to speak, superficial. It ultimately doesn't matter.

It matters to us, of course, but in the ultimate scheme of things, time is an illusion of that limited consciousness that human beings possess that requires that they draw the conclusion of deductive arguments instead of seeing the conclusion in the argument instantaneously. So, in fact, this was part of Augustine's solution to the problem of time, and it is referred to explicitly by Galileo that God does not need to draw conclusions. God sees all future time in the instant of creation.

And in fact this is fundamental to science and, as we will see, even into the 20th century this notion—that if we had a clear understanding of the nature of the universe the instant it sprang into existence, we would be able to predict the existence of stars, galaxies, planets, the possibility of life, and the emergence of an intelligence such as ours capable of figuring out the nature of the universe—all of this is implicit in the premises, logically speaking, the premises of the universe, and physically speaking, the initial moment of the physical existence of the universe is pregnant with the whole future of the universe. And in fact Leibniz, one of the founders of modern philosophy and of modern science, used that expression that “the present is pregnant with the future.” The future is already in the present, and it is only, so to speak, accidental that it takes time to emerge.

Concurrently, from the late 17th and throughout the 18th century, while Leibniz was saying this, he was saying this in the context in which embryological theory had taken the form that we call preformationism. That is what they called it as well. Preformationism is the theory that the embryo is in fact fully formed within the—well, there were two different preformationists—some held that the embryo was fully formed in the egg of the female; some that it was in the sperm of the male—and if you had a powerful enough microscope, you could look inside a sperm cell or inside an egg cell (although that language is anachronistic for 1700), you could look inside and you would see the infant with all of its organs fully formed.

But the implication of that is that embryological development is simply an unfolding of what is already there. The implication is that if you went back to Adam, in Adam’s sperm you would see Seth. But then if you looked in Seth’s sperm then you would see the sperm of his children forever, which does seem a bit implausible. And the same thing for those who believed that preformationism was centered in the egg. If you looked in one of Eve’s eggs you would be able to see folded inside each other an egg, an egg, an egg, for all future human beings. The idea here, of course, is it really reduces the flow of time to something incidental.

The form that this took in physics, for example, was the reversibility of the equations of motion of matter. Now this vision of time comes to a head in Pierre Simon de Laplace’s statement in the early 1800s that if we knew a complete description of the motions of the material particles that made up the physical universe at any given moment in time (call that T-0), if we knew the position and the momentum of every particular particle of matter in the universe (finite; in principle such a thing could be done, although obviously we can’t do it, and maybe nobody else other than God could do it as well), if you had such an intelligence, then that intelligence would be able to predict the future with unlimited accuracy, and retrodict the past with unlimited accuracy.

Again, the implication of this is that time really doesn’t matter, and that is a fundamental feature of modern science centered on the physical account of matter. I have to be careful now, because this conception of time underwent a transformation, and ultimately a radical alternative was offered by the 19th century. Here again we see something that I’ve referred to a number of times in these lectures, that the history of ideas is pretty fuzzy. Even people who claim to be dealing with precise ideas, like philosophers and scientists, they have a tremendous capacity for keeping ideas and inconsistent alternative ideas together when it suits their particular intellectual agendas.

But the challenge to this notion of time as ultimately irrelevant, because at the deepest level reality does not change, began innocuously enough with the Renaissance humanists, who I’ve referred to before, who erected history, contrary to Aristotle, into a science. Aristotle had said that history could not be a science precisely because it is contingent. It does not have this deductive character. It is particular and contingent. Whereas, the humanists claimed that that’s exactly what makes it the real science, not this philosophical notion of knowledge that Plato and Aristotle argued for in which knowledge is universal, necessary, and certain. The humanists argued that history was a science because history captured a fundamental truth about reality, which is that it is contingent, that it is merely probable, that it is highly particular and context-specific.

And in the course of the 16th, 17th, and18th centuries, this idea of the historicity of reality, that reality develops in time and that it makes a difference, becomes increasingly important. We devoted a lecture to the idea of progress, and clearly the idea of progress is a temporal idea. It is the secular version of the religious idea in the Judeo-Christian tradition that history is the dimension of hope and salvation. The secular version of that, which again the Renaissance humanists were instrumental in making central to European consciousness, is the idea of progress.

Time is the dimension in which hope for an improvement in the human condition is contained. It is in time, and history is the story of time, which becomes the dimension of opportunity. Now the future is the dimension of opportunity. It is not mechanically implicit in the past and inevitable. The future can be one of hope because of opportunities that we can exploit, that we can shape, in order to improve the human condition.

In the course of the 18th century especially, we see more and more theories that make reality in many different forms historical. So the Italian (I would still call him a humanist thinker) Giambattista Vico published a book early in the 18th century called *The New Science* that argued for the historicity of human consciousness, that we didn't always think the same way. Human beings did not always think the same way. We did not mean by *reasoning* what the Greek philosophers meant by reasoning in the time that was antique, when the ancient Greeks lived. So in the beginnings of the human race we experienced the world differently, we spoke differently about the world, we thought and felt and reasoned differently about this world. In this book he gives an argument for what we would now call the evolution of human consciousness and human reasoning.

We see this notion of historicity applied to the development of the universe, the development of the solar system, and the development of the earth as a planet. Aristotle had said that on balance the earth has always been the way it is—an earthquake here, a volcanic eruption there, a tidal wave there, but those are simply local phenomena. Whereas, in the 18th century, we began to understand that the earth had a history. There was a time when it was fundamentally different from what it is now, and that it is changing in ways that make it irreversibly different from what it had been.

At the end of the 18th century, Gottfried Herder argued for the historicity of human cultures; that cultures go through historical development and change over time. This concept of changing, that time is a dimension in which fundamental change manifests itself, has made time an issue for philosophy. Hegel at the beginning of the 19th century, perhaps the most influential philosopher of the 19th century, Hegel tried to develop a new theory of deduction, a new logic of deduction which incorporated time, but it was a time which was deterministic in its character so that the future did unfold deductively, but time manifested itself. It was a dynamic logic, but it still retained this deductive developmental character. We see this in the maverick Hegelian, Karl Marx, whose materialistic determinism was one in which the future is an inevitable product of the past and the present.

In science, too, in the 19th century, time became an issue, and we're going to explore this in a future lecture on the idea of energy. But telegraphing that in advance, in the middle of the 19th century within physics and chemistry, the idea of force in the second law of thermodynamics—the science of energy that emerged in the 1850s and 1860s—that the second law of thermodynamics is that heat can only flow from a hotter body to a colder body, to a less hot body, and that implied that there was an arrow to time, that time could only go in one direction. It was not reversible. It was irreversible, and the Darwin–Wallace theory of evolution, which we will again be exploring in another lecture, that theory, too, implies that there are irreversible and unpredictable dimensions to time, that time is the dimension of unpredictability of the contingent, and that in fact time is the dimension in which true novelty appears. Something is truly novel if it is not a deductive consequence of the present.

Now this notion of time as having an arrow, as having a direction so that it is not reversible, poses a serious challenge to the prevailing notion of time in physics, where the equations are all reversible in time. Given any equation of motion, if you plug in a plus value for time, then the particles that the equation described evolved, so to speak, in one direction, into what we call the future. If you replaced it with a minus value, a negative value for time, then it flows into the past. Prediction and retrodiction are perfectly symmetrical.

The emergence of thermodynamics and evolutionary theory in biology forced, so to speak, many physicists to develop statistical interpretations of thermodynamics, and ultimately statistical interpretations of mechanics that preserved the reversibility of time. There was a positive need, so to speak, intellectually, for time to be reversible, which means that ultimately time is not real. And this led, even as late as the middle of the 20th century, Einstein, for example, to insist that quantum theory, because of its probabilistic character, cannot be the ultimate theory in physics. Because Einstein, among many others, continued to believe that time in the end was an illusion of the limited nature of human consciousness. It was not ultimately real.

Meanwhile from the middle of the 19th century on throughout the 20th century, as we will be exploring in subsequent lectures, there was a continual growth in this challenge to this notion of time. A growth in the characterization of time as irreversible and therefore ultimately real. So we have within science, I would call it an ambivalence at best or a serious conflict about time. On the one hand, a feeling that if time is not reducible to ultimately being merely an accident, or incidental to the way human beings experience the world, then we lose the power of scientific explanation because we cannot use deduction and predictability, and law cannot mean what it has meant.

But, on the other hand, a more and more powerful case continued to be made for the view that time is not reversible, that it is fundamentally irreversible, and that probability must come into our description of the world.

We are going in the next lecture to begin exploring a series of ideas in which the concept of time and this ambivalence are very real features that shape the development of those ideas, and we'll begin with the concept of the timeless atom.

Lecture Eighteen
The Atomic Theory of Matter

Scope:

The Parmenidean view that the ultimately real was changeless found expression even in antiquity in atomic theories of matter, which became prominent again in the late Renaissance. Newton's atomism explicitly proclaimed the timeless permanence of atoms and their properties, but atomism became a functional scientific theory only in the early 19th century, when John Dalton argued that an atomic theory of matter explained chemical reactions and some puzzling physical phenomena. Chemists quickly took up the theory and used it with great success, though many physicists rejected the reality of physical atoms until the early 20th century. While this debate raged, the generic approach of explaining phenomena by postulating fundamental entities, "atoms" broadly speaking, whose properties cause the phenomenon to be explained, flourished. Instances of this way of thinking include the cell theory of life, the germ theory of disease, the gene theory of inheritance, and the quantum theory of electromagnetic energy.

Outline

I. That matter is atomic in nature was an idea, hence an invention, not a discovery.

- **A.** As we saw with time, there is an important difference between an idea and a scientific idea.
  - **1.** Augustine's philosophical idea of time is far more sophisticated than common usage, but it is not a scientific idea.
  - **2.** In Newton's *Principia*, we saw that a scientific idea is one whose definition is adapted to the context of a scientific explanation or theory.
  - **3.** The fact that scientific ideas change, as did the idea of time in the 19th and 20th centuries, reveals the contingency of scientific definitions and, hence, ideas.
- **B.** The atomic idea began in antiquity and, until 1806, was a metaphysical speculation.
  - **1.** Greek atomism was a response to Parmenides's logic-based critique of the reality of change.
  - **2.** Atoms explain change as a rearrangement of things that are themselves changeless.
  - **3.** Anaxagoras postulated a variety of atoms as broad as the variety of things in nature.
  - **4.** Epicurus's atomism claimed that natural objects were combinations of atoms that possessed only size, shape, weight, and motion.
- **C.** Epicurus's atomic theory was explicitly proposed to support a moral philosophy hostile to organized religion.
  - **1.** Epicurus taught that life was an irreducibly material phenomenon that ended with death and should be lived as such.
  - **2.** Reality was a vast but finite "rain" of atoms falling eternally in infinite space, randomly swerving, colliding, and forming more-or-less stable agglomerations and hierarchies of agglomerations that dissolve and form new agglomerations.
  - **3.** Epicurus's theory was disseminated in the Roman era by Skeptical philosophers and Lucretius, among others, and was anathema to Christian authorities.
- **D.** Atomism entered modern science through Humanist texts and in spite of Church opposition to the dissemination of Epicurean ideas.
  - **1.** In the 16th and early 17th centuries, natural philosophers concerned with explaining and describing the motion of matter saw the atomic theory of matter and the idea of empty space as useful.
  - **2.** Galileo defended atomism.

3. Robert Boyle, whose (Protestant) religious orthodoxy was beyond question, used an atomic theory to explain chemical reactions, emphasizing size, shape, and motion as the elementary characteristics of atoms.
4. Pierre Gassendi was a prominent contemporary atomist and a probabilist, opposing both to Descartes' necessitarian nature philosophy.
5. Descartes rejected both atomism and the possibility of empty space, making nature a matter-filled plenum: For anything to move, everything must move!

E. Newton wove the atomic idea of matter into his theories of nature.

1. In his *Opticks*, Newton speculated that God had created matter in the form of minute spheres, indestructible and possessing innate properties, especially forces of selective attraction and repulsion.
2. His theory of light was a "corpuscular," or atomic theory, and although the *Principia* is not explicitly atomic, the spread of Newtonian mechanics in the 18^{th} century came at the expense of Cartesian anti-atomism and disseminated at least the idea of atomism.
3. Leibniz elaborated a complex metaphysical system in which the ultimate reality is a vast array of immaterial "atoms" called *monads*, each the center of a unique set of forces expressive of a unique manifestation of being.
4. Leibniz's physics and mathematics were fundamental to Continental science in the 18^{th} century, as were Newton's, and both Newtonian and Leibnizian metaphysics were widely disseminated.
5. Roger Boscovich's 1758 *Theory of Natural Philosophy* offered a Newtonian-Leibnizian theory in which matter is composed of "atomic" point particles that are the centers of innate forces acting at a distance.

II. At the start of the 19^{th} century, then, the atomic idea was familiar in philosophical and scientific circles, but scientific atomism is said to have begun with John Dalton.

A. Dalton's *New System of Chemical Philosophy* first appeared in 1807, though he started developing his atomic theory of matter by 1803.

1. Dalton was a natural philosopher with a wide range of interests, but he had a special interest in meteorology and atmospheric pressure.
2. Under the influence especially of Lavoisier's chemical revolution of the 1780s, Dalton built his explanation around the new definition of an element and an unshakable conviction that elements combine only in fixed proportions to form compounds.

B. While the bulk of Dalton's research lay in what we would call physics, his atomic theory of matter was of immediate, direct relevance to chemistry.

1. Many of the leading chemists rejected Dalton's fixation on laws of fixed proportions for chemical reactions, but Dalton persevered.
2. Making the "weight" of hydrogen 1, he calculated the relative weights of many other elements, assuming that atoms differed only in weight, size, and innate properties, à la Newton.
3. Throughout the 19^{th} century, chemists and physicists were comfortable with using the atomic theory of matter, but most physicists did not accept that matter really was atomic.

C. Acceptance of the reality of atoms grew steadily in chemistry from the mid-century but in physics only in the decade after 1900.

1. Chemical research, leading to a growing power to control increasingly complex reactions, reinforced the idea that elements combine in fixed, though multiple, proportions.
2. Concurrently, chemists discovered the significance of molecular structure in giving compounds with the same number of the same atoms different physical properties.

3. The ability to solve practical chemical problems with the atomic theory was reinforced by the kinetic theory of gases.
4. The combination of these developments should have clinched the reality of atoms even for physicists, but this was not the case; Ernst Mach remained a violent opponent of real atoms into the 20th century.
5. Boltzmann became convinced of the reality of atoms, but Maxwell waffled, although the statistical interpretation of thermodynamics and the kinetic theory of gases strongly suggested their reality.

III. Historically, the idea of the atom is of a simple, indivisible, and indestructible unit, but atoms became complex, divisible, and destructible.

A. The new understanding of the atom and its technological exploitation began with the discovery that atoms have parts and are mutable.

1. In 1897, J. J. Thompson announced the existence of lightweight, negatively charged particles *within* the body of the atom.
2. This required a radical redefinition of *atom*, which from the Greeks through Newton and Dalton to 1896, had been an irreducible, solid unit.
3. In 1911, Ernest Rutherford announced that the atom was overwhelmingly empty space!
4. In the 1930s, the nucleus was determined to have an internal structure and also to be largely empty.

B. By WWII, the atom was composed of protons, neutrons and electrons, with hints of other particles.

1. By the 1960s, physicists had identified over two hundred “elementary” subatomic particles, leading to a new theory of matter in which protons and neutrons are composed of quarks bound together by gluons.
2. At every stage in the development of modern physical science, the atom, purportedly *the* fundamental building block of reality, was redefined to fit the prevailing context of theory and explanation.
3. In the context of quantum theory, atoms even acquired qualities of waves, as we will discuss in a later lecture.

Essential Reading:

Bernard Pullman, *The Atom in the History of Human Thought*.

Carlo Cercignani, *Ludwig Boltzmann: The Man Who Trusted Atoms*.

Questions to Consider:

1. What are we to make of the fact that the more the atom was accepted as physically real, the emptier it became of anything solid?
2. Must atoms be ultimate units of solidity with fixed properties, or can they be relatively stable processes?

Lecture Eighteen
The Atomic Theory of Matter

The subject of this lecture is the atomic theory of matter, and the story of the atomic theory of matter is an outstanding illustration of a number of themes that run through this course. One of them, starting from the very first lecture, was that the story of science, the history of science, is a history of ideas, not discoveries. Because discoveries, I said then, are sort of latent with ideas, are enabled by ideas that create the framework within which a discovery is interpreted to be a discovery. So no ideas; no discovery. And the atomic theory of matter is a good illustration of that point.

It is also an excellent illustration of the difference between an idea and a scientific idea, between an idea even in philosophy where philosophers attempt to give precision to ordinary language ideas, and the difference between a scientific idea and a philosophic idea has a distinctive character which is as different from a philosophical idea as a philosophical idea is from an ordinary language sort of commonsense idea. We played with that a bit in the case of time, and what I want to emphasize here is the role that definition plays.

Remember I discussed Augustine's definition of time, Newton's definition of time; eventually we will get to Einstein's redefinition of time. But in the case of the story of the atomic theory of matter, we will see how contingent the scientific definitions are, that they change over time; that scientists will simply redefine what an atom is, what space is, what time is, what matter is, what energy is, in order to fit new explanatory contexts.

So the idea of the atom is illustrative of the role that ideas play to enable us to make sense of experience in ways that allow us to say we have discovered X, and it is also illustrative of the role that definitions play in scientific ideas. Now the atom is a good illustration of an idea rather than a discovery because the atomic theory of matter was not discovered. The atomic theory of matter was an idea that was applied, especially in the 19th century, to first chemistry and then physics, with increasing success.

It may come as a surprise to people that into the early 20th century it was highly controversial among physicists that atoms were real. The claims that atoms were real was a highly controversial claim to make in physics into the early 20th century, and we will come to understand why, but to appreciate that we need to look at the pre-history, so to speak, of the atomic theory of matter.

The idea of the atom was in fact invented in ancient Greece as a response to good old Parmenides, who, on strictly logical, deductive grounds, had argued that the ultimately real must be changeless. The real must be changeless—that means atemporal.

And one response to this, since experience shows us that things change all the time, change is the fundamental problem of science, as I referred to it in an earlier lecture, a number of Greek philosophers came up with the idea that okay, Parmenides has a point: change is apparent and superficial. The ultimate elements of reality are themselves changeless. They are atoms. They are units of physical beings, so to speak, and that all of the things that we experience as changing are merely different configurations of these atoms, and when those atoms reconfigure themselves, then our experience changes. The different configurations have different properties, and so in a certain sense, yes, there is change, and we can explain it, but what we use to explain it is something changeless.

And so the concept of the atom was specifically invented. It was not discovered by carefully observing natural phenomena. It was invented in response to a philosophical problem posed by Parmenides. I've been using Parmenides's name as a synonym for a style of thinking, this substance style of thinking, that experience is built up out of hidden elements of reality which are themselves changeless. They are substances with fixed properties, and everything that we experience is built up, Lego-like, out of these fundamental particles—in the case of atoms, that's what they were supposed to be. They were, in a sense, Lego building blocks.

In ancient Greece there were really two versions of this atomism, one by Anaxagoras, which was that atoms came in many different forms. There were blood atoms and bone atoms, for example, and hair atoms and fingernail atoms, and every natural object contained some atoms of almost every different type. So, for example, when you ate bread, your body abstracted from the bread the bone atoms that were in the bread, the blood atoms that were in the bread, and that's the way you nourished yourself.

Anaxagoras's version of atomism—and these atoms were changeless over time; they could never change into anything else; they were permanent—was replaced really by Epicures, who adopted a different theory of atomism out of Democritus (who also had a teacher who taught him this), which was that at one level all atoms are the same. They only differ in size and shape, and they form different configurations which have all of the different what we would call physical and chemical properties that we associate with nature.

Epicures's writings, especially as developed by the Roman poet Lucretius in a poem called *On the Nature of Things*, which was translated by the Renaissance humanists during the Renaissance and became popular again because Epicures, as I've mentioned before, was anathema to the Church, since he developed his atomic theory of nature explicitly to teach people not to be afraid of death since death is this kind of non-being. Nothing survives the dissolution of the atoms that make up our body and which will now become configured as grass and dirt. That was considered, obviously, a deep threat to the whole concept of spirituality as interpreted in Christianity.

The Renaissance humanists brought atomism into the Renaissance by translating Lucretius's texts as well as other atomistic texts from antiquity, including some writings of Epicures. We find that by the 16th and certainly the 17th century a growing number of thinkers are adopting this atomic idea, they find that atomism is a very plausible theory of material nature. In particular, Galileo was an atomist. Robert Boyle, the father of modern chemistry, as he is often described in history books, thought that atomism made for an excellent conceptual framework within which to explain the behavior of gasses, and he was a pioneer in the study of the relationships among pressure, volume and temperature, and chemical combination.

And a man who is today virtually unknown, but in the 17th century was extremely well known, Pierre Gassendi, was a rival to Descartes in that Descartes was an anti-atomist; he believed that matter was continuously distributed through space, was infinitely divisible, so there was no such thing as a smallest bit of matter. Gassendi developed a physics in which matter was atomic. It was also a physics in which probability played a significant part. He denied the notion of knowledge as universal, necessary, and certain, which was fundamental to Descartes's philosophy of nature.

And Isaac Newton was an atomist, and a very important atomist. In one sense one can say that he was the first scientist who began to use atomism as a scientific idea functioning within the context of a scientific explanation. Well, Galileo had done something like that too, but much more so in the case of Newton. And I want to read from one of the queries at the end of Isaac Newton's 1704 work, *Optics*, to give you a flavor of the notion of atomism in its pre-modern sense which we will see really begins with John Dalton in the early 1800s.

> All things being considered, [Newton writes] it seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles of such sizes and figures and with such other properties and in such proportion to space as most conduced to the end for which he formed them. And that these primitive particles, being solids, are incomparably harder than any porous bodies compounded of them, even so very hard as never to wear or break in pieces, no ordinary power being able to divide what God himself made one in the first creation.

And Newton writes in Question 31:

> Have not the small particles of bodies certain powers, virtues, or forces by which they act at a distance not only upon the rays of light but also upon one another for producing a great part of the phenomena of nature? For it's well known that bodies act on one another by the attractions of

> gravity, magnetism, and electricity, and these instances show the tenor and course of nature, and make it not improbable but that there may be more attractive powers than these.

And Newton goes on to describe how chemical combination can be understood in terms of certain selective powers that atoms have, to be attracted to or not attracted to, or positively repulsed by, other atoms, in order to form what we would call molecules. Now Newton also developed an atomic theory of light, not just an atomic theory of matter. "Are not the rays of light very small bodies emitted from shining substances?" So that for Newton—Newton was a thoroughgoing atomist at the physical level—applying this atomic hypothesis (although he would have hated the term "hypothesis" in this context) to matter, matter is made up of tiny, impenetrable, ultimately hard solid objects with fixed properties. Every atom is created by God and cannot be destroyed in any natural process, only supernaturally if God chose to do so; but nature cannot change any atoms.

And that becomes a fundamental precept of 19th century atomic theory, that atoms have this ultimate character. They cannot be reduced any further, and they have no parts to them. They are solid. They are units, which was what the Greek word *atom* was supposed to convey, that they are units of reality; but they have, according to Newton, in addition to size and shape and motion, they have innate properties.

And he goes on later on in this same text to justify, using this language, even though it sounds like Renaissance magical nature philosophy, that atoms have the power to act on other atoms across empty space, at a distance. Electricity and magnetism and gravity are instances of this, he believes. All attempts by the Cartesians to come up with mechanical theories of electricity, magnetism, and gravity, that denied acting at a distance through empty space, failed ultimately.

And so what we see in the 18th century is a growing interest in Newton's theory of atomism—atomic theory of matter—and acceptance of Newton's atomic theory of light, that light is like tiny little bullets, and together with Newton's great rival, Gottfried Leibniz, who developed a metaphysical theory called the Monadology in which reality is made up of ultimate units that act from the inside out. They do not truly interact with any other unit, and so every unit of reality, every monad, is a kind of a dynamic atom. It's a force center.

And while Leibniz's metaphysics, his Monadism, is not appropriately a scientific idea for our purposes in this course, it exercised great influence on 18th century philosophy and science, and in 1758 a Jesuit physicist named Roger Boscovich published a book that was a theory of natural philosophy that blended Leibniz and Newton and offered a theory of atoms as point centers of force. He dropped the materiality of the atom, à la Newton, let them be point particles, so to speak, à la Leibniz, and made them the centers of forces that dropped off as a function of distance. And depending on the atom, different forces were associated with it, so you could explain electricity, magnetism, and chemical combination, Boscovich thought. And Boscovich's book was well known and was quite influential over the next 50 years of so.

The pivotal figure in the story of the atomic theory of matter is John Dalton. He was an English scientist that we would call a physicist, and yet his most famous book is a new theory of chemical philosophy. He was analogous to Antoine Lavoisier, who 25 years earlier had precipitated a revolution in chemistry, and Lavoisier, too, was a physicist. And there's a connection between Lavoisier and Dalton in that Dalton's work was, so to speak, built on the studies of Lavoisier and Joseph Priestley, especially the studies of gasses, and that there are different kinds of gasses, what we would call oxygen, and carbon dioxide.

And as these studies were extended by Henry Cavendish at the end of the 18th and the beginning of the 19th century in England, the recognition that the atmosphere, the air that we breathe, is not an element, it's a compound—and it's made up of primarily oxygen, nitrogen, and carbon dioxide. And Dalton was interested in how these three gasses with different (as we would call them) molecular weights, how they mix, how it comes to be the case that they are thoroughly mixed in any breath of air that we inhale, mixed throughout the lower atmosphere.

And in the course of these studies Dalton decided that the atomic theory of matter, which he knew of through, obviously, knowing Newton and knowing of Boscovich and Lavoisier's own work in chemistry, led him to the idea that matter came in the form of atoms and that all chemical reactions could be explained in terms of atom's elements, by supposing that matter had an elemental atomic character. There were oxygen atoms, carbon atoms, nitrogen atoms, iron atoms, etc., and each atom had a specific set of properties that were associated with their chemical combination, so that oxygen combined with hydrogen, with carbon, with nitrogen in very specific ways.

This is called the theory of fixed proportions—that the atoms of elements combined with one another in fixed proportions. It was highly controversial for the first half of the 19th century among chemists because there were great chemists in the early 19th century who held that this was not true and that, depending on the circumstances of the reaction, the volumes of the different reactants, the temperature, and the pressure, that atoms would combine in different proportions. So you could be an atomist and not agree that chemical reactions were fixed on the basis of fixed properties of the individual atoms. But in time, Dalton's view prevailed—that the atom had fixed properties.

Now it turns out chemists had to acknowledge that the same element could combine in different proportions with different other elements, and that there was not one single combining proportion. Sulfur is polyvalent, for example, and in combination with different other elements it will display a different combining proportion than it does in other cases. So it's not as simple as Dalton hoped that it would be.

But Dalton's book, *New System of Chemical Philosophy*, in 1806, 1807 (he had worked on it over a period of years and it was published over a period of years, but let's use 1807), becomes sort of the founding document of modern atomic theory. And in the course of, especially the middle of, the 19th century, more and more chemists working with the atomic theory became convinced that atoms were real. But most physicists, including very prominent physicists, like Michael Faraday throughout his life and Maxwell, the great founder of electromagnetic theory in its modern form, waffled on the whole question of the reality of atoms.

And some physicists of prominence, Ernst Mach most notably, right into the early 20th century, violently opposed the idea of the reality of atoms, claiming that that was a very wonderful idea but they were not physically real. It was an idea that we used to bind together many different experiences and to give plausible explanations to use these ideas to make predictions and to explain, but they did not correspond to anything out there. He took very strong exception to that, and he was very articulate, and he defended this view for decades.

What made chemists believe that atoms were real were, of course their continuing study of reactions and realizing that in fact elements did combine typically in very strict proportions. But, as we will see in a subsequent lecture, starting especially in the 1830s and 1840s, there was a growing recognition that the structural arrangement of atoms within a molecule determined the properties of the molecule. The same atoms arranged differently had different properties. Now that suggests that these atoms are not just a convenient way of referring to bits of matter, but they are actually real. So the discovery that the structural arrangement of atoms makes a difference, lends reality to atoms.

In the middle of the century, really we can date it to 1860 at an international chemists conference in Karlsruhe in Germany, where this notion that you've all encountered in high school chemistry or college chemistry if you took it, Avogadro's number, which is an estimate of the number of atoms in a particular volume of a gas or a liquid, that this number, that atoms are countable, also of course lends them substantial reality.

From the 1860s on, the development of the kinetic theory of gasses, especially by James Clark Maxwell and Ludwig Boltzmann, said, let's assume that gasses are made up of atoms the way Dalton said (and he got started studying gasses, you remember) and that Avogadro has given us a clue as to how to count these so we know how many we're dealing with; we can explain pressure and temperature (Maxwell and

Boltzmann claimed) by assuming that matter actually is atomic. And Boltzmann himself was as vigorous a defender of the reality of atoms as Ernst Mach, his nemesis in this regard, argued that this didn't prove that atoms were real, only assuming that atoms were real made for very powerful scientific explanations. So the development of the kinetic theory of gasses lent reality to the atom, especially for chemists.

I mentioned at the end of the last lecture that physicists were driven to a statistical interpretation of thermodynamics in order to undo the arrow of time, and Maxwell and Boltzmann were associated with that—and in order to give the statistical interpretation they needed to argue that matter was atomic. If you assumed that matter was atomic then the statistical interpretation of thermodynamics allowed you to say that the flow of heat from a hotter body to a colder body (which is the second law of thermodynamics) is merely statistical. It is not an absolute law of nature and therefore the arrow of time is a statistical law, it is not an absolute law. Time is, in principle, reversible. It's just highly unlikely.

The atom became increasingly real for physicists not specifically because of the kinetic theory of gasses. It convinced Boltzmann, but Maxwell waffled, and he was one of the co-founders of the theory. But in the last decade or so of the 19th century, with the study of cathode rays, which had been discovered in the 1880s when people started doing experiments with evacuated tubes like incandescent light bulbs of Edison's invention, and discovered that the cathode—the heated element in such an evacuated tube (William Crookes in England became associated with one style of these tubes in which you had two plates—you had a plate that was connected to one side of the battery that got heated, and then there was a plate connected to the other side of the battery, the anode as we call it)—that there were funny rays that moved from one to the other. The study of these rays in the 1890s led to the recognition that these rays were in fact streams of electrically charged particles.

A French physicist named Jean Perrin identified these rays as being made up of a huge number of particles with negative charge, and in 1896, 1897, J.J. Thompson, who was the head of the Cavendish Laboratory at Cambridge University at the time, announced the discovery, which is epical given our discussion of the atom, that in fact the atom contains within it these tiny little particles with a fixed negative electric charge that were identified as electrons. The electron is much, much, much lighter than any atom (it's approximately 1/1828 of the weight of a hydrogen atom, which is the lightest of all atoms). And this is a shocking discovery.

Remember what I said about Newton and the solidity of atoms. Atoms were ultimate units; they didn't have parts. And now Thompson is telling us at the very close of the 19th century that atoms have an internal structure. They contain negatively charged bits, but they also contain positively charged bits, because overall they're neutral. So that raises the question, well, if atoms have an internal structure, first of all we have to redefine what we mean by an atom, but then we ask how are these bits arranged? What is the internal structure of the atom?

I 1904, Thompson proposed what has been referred to as the pudding model of the atom, in which there is a solid sphere of positively charged stuff and embedded in it like raisins in a pudding are these tiny little electrons which are arranged in orbits based on the electrostatic forces between the positively charged stuff and the negatively charged electrons, which repel one another, but are attracted to the positively charged stuff. And the question was, how are these electrons arranged inside the different atoms?

Perrin came back with the explanation in terms of a primitive version of what we now call the solar system model of the atom. Perrin also picked up on work that Einstein did in 1905 on Brownian motion, the motion of tiny little particles suspended in a fluid which moved jerkily, and which Einstein used to estimate the size of molecules which began to convince physicists that atoms were real, because now we could not only count them, but we could also identify how big they are in a way that physicists responded to. Perrin extended that work and in 1926 was given a Nobel Prize for what even in the Nobel Prize was called "reinforcing the discontinuous theory of matter." Atomism is a discontinuous theory of matter contrary to Descartes's. So even in 1926, the atomic theory of matter was in a certain sense something that was worth giving a Nobel Prize for, because it needed to be established for physicists that these atoms were real. That prize award, by the way, mentioned that Perrin had in fact extended Einstein's work, which in a certain sense first started convincing most physicists that these atoms were real, because you could calculate what their size was.

It was in 1909, 1910 that Ernest Rutherford, a former student of J.J. Thompson, that Rutherford with his graduate students, Geiger and Marsden, formulated the so to speak modern version of the solar system model of the atom, in which we have the nucleus that is positively charged, the electrons rotate around it, and the atom is about 98-plus percent empty space. What started with Dalton as a solid atom, 103 years later is now suddenly discovered to be 98-plus percent empty space (and that turns out to be an underestimate of how empty the atom actually is) having a nucleus made up of protons and orbital electrons around it.

In 1932 the neutron was identified as a particle that needed to be in the nucleus in order to explain a number of increasingly puzzling phenomena. So we now had a picture of the atom in which the nucleus was solidly packed with neutrons and protons, and these orbital electrons surrounding it.

In 1935 it was discovered that the nucleus had an internal structure (it was actually mostly empty space), and that the protons and neutrons were arranged in shells, and nuclear physics began in earnest. Between 1935 and 1964 increasingly powerful atom-smashing instruments, particle accelerators, revealed that there were over two hundred elementary particles in nature. That became quite ridiculous, and the resolution of that situation, which restored the underlying concept of the atom as a fundamental unit of physical reality, took the form of what is called quantum chromodynamics, or quark theory, in which all ordinary matter is made up of either electrons which are not reducible (they are a kind of atom; they cannot be broken down into anything smaller) and three different kinds of quarks. There are altogether six, but only three are required to make protons and neutrons, and so the new atomic theory, so to speak, is that protons and neutrons are not truly atomic. They are built up. They are compounds of quarks which cannot be broken down any further. Protons and neutrons turn out to be mostly empty space because quarks are much, much smaller than the protons and neutrons that they compose. And now we have a new atomic theory, so to speak, but notice how the atom has been systematically redefined at every stage in order to serve scientific explanation.

Now the context is quantum theory. The context of quantum chromodynamics (you get that from the name), and quantum theory exacts a price, which is that the atom also has a wavelike character, which seems to be an echo of Descartes's continuum theory. And we'll be exploring this further in the next lectures.

Lecture Nineteen
The Cell Theory of Life

Scope:

What is life? This became a scientific question—to be resolved within a theory of nature—in the 18th century. The Cartesian school held that all life processes in their various manifestations were purely mechanical phenomena, consistent with an exhaustive materialistic determinism. Against this, it was argued that life phenomena were not reducible to matter in motion only: They were governed by forces and laws unique to the domain of living things. With the advent of microscopes with high-power lenses corrected for distortion, it was argued that there was a common building block to all forms of life: the cell. From about 1835 to the end of the century, progressively more sophisticated observational studies advanced the cell theory of life, which together with the germ theory of disease and the gene theory of inheritance, evolved into a mutually reinforcing web of correlated ideas.

Outline

I. The atomic theory of matter is an instance of a particular style of thinking in science, a "Parmenidean" approach to explaining natural phenomena.

- **A.** Other scientific theories exhibit this same style of thinking.
  1. The cell theory of life, the germ theory of disease, and the gene theory of inheritance are examples.
  2. What all have in common is the postulation of some elementary unit with fixed properties that produces the phenomena to be explained.
  3. The cell, with its internal structures and processes, is the basis for explaining all life phenomena, which we cluster under the rubric *biology*.
  4. This style of thinking is deeply ingrained in Western culture and at every level of social, political, and scientific thinking.
  5. It contrasts sharply with the process style of thinking characteristic of science since the mid-19th century.
- **B.** Biology, as a unified science of life, is a product of the turn of the 19th century.
  1. Botany, zoology, and medicine were all clearly "scientific" by the 18th century.
  2. Throughout that century, rival interpretations of life were pursued, one mechanistic and the other vitalistic.
  3. Around 1800, Jean-Baptiste Lamarck coined the term *biology*, consistent with his evolutionary theory of life in which all life forms shared a common origin.
  4. In the mechanistic view, articulated by Descartes and many successors to the present day, life is no more than the result of very complex configurations of matter.
  5. Analogously, many artificial intelligence researchers have thought that once computer chips achieve a density of interconnection comparable to the neurons in the human nervous system, consciousness will emerge.
  6. In the vitalist view, life is special, marked by the action of forces that are not reducible to physics or chemistry and certainly not to mechanical action.
- **C.** Lamarck was an early proponent of the unity of life but not the first or the only one.
  1. George Buffon was an important predecessor a generation earlier.
  2. Erasmus Darwin, Charles's grandfather, was Lamarck's contemporary.
  3. Lamarck's evolutionary theory of life was a dynamic one that was highly influential in the 19th century, though reviled in the 20th.

II. The introduction of the microscope in the 17th century opened up the scientific study of life.

A. For one thing, the microscope revealed unseen and unseeable "worlds."

1. The researches of Anton Leeuwenhoek, Robert Hooke, and Marcello Malpighi expanded our conception of the realm of life forms.

2. The drive to see more by increasing magnification caused blurrier images and some researchers abandoned the use of the microscope as hopelessly misleading.

B. Correcting chromatic aberration allowed much greater magnification and much deeper glimpses of the secret of life.

1. John Dolland discovered how to combine different types of glass to correct aberration and took out a patent in 1758.

2. Contemporaneously, the great mathematician Leonhard Euler developed a mathematical theory for correcting aberration.

3. Euler's theory was not used to design commercial lenses for 100 years but then became the basis of the famous Carl Zeiss Company line of state-of-the-art microscopes.

C. Although the problem of chromatic aberration was solved by the late 1700s, it was not until the 1820s that a new generation of research microscopes became available.

1. Giovanni Battista Amici developed a complete microscope "package" incorporating the new lenses, and this, along with rival designs, inaugurated a new phase in biological research.

2. In effect, the cell theory of life "popped out" almost at once.

3. There is an important lesson here about scientific instruments: The technical capabilities of their components are much less important than the usability of their integration into a functional design.

III. The microscope is inextricably involved with the cell theory of life and is a powerful case study in the relationship between instruments and theories.

A. The origins of the cell theory go back to the 17th century.

1. Robert Hooke coined the term *cell* to describe the microscopic structure of slices of cork.

2. In the 18th century, botanists speculatively generalized Hooke's observation to all plants.

3. With color-corrected microscopes in the 1820s and 1830s, observers identified not only cells in plants and animals but even the nucleus within the cell (at that time, just a dark spot).

B. Cells were proclaimed the building blocks of all living things in the late 1830s.

1. In 1838, Mathew Schleiden proclaimed the universal cellular structure of all plant tissue, and in 1839, Theodor Schwann did the same for animals.

2. Both held mechanistic views of life but were associated with the fertile laboratory of Johannes Müller, who was a stout vitalist.

3. For no logically compelling reason, the cell theory of life was effectively universally adopted as true immediately.

4. By contrast, the atomic theory of matter was not accepted as true by many chemists for decades and by most physicists for 100 years after Dalton.

C. Given the cell theory of life, the leading research subject must be to discover what is going on inside the cell.

1. Fortunately, microscopes kept improving, especially from 1870 with the new Carl Zeiss models, as did specimen preparation techniques.

2. One crucial question is: Where do cells come from?

3. In the 1850s, Rudolf Virchow emerged as a champion of the cell as the building block of life and of the view that all cells come exclusively from other cells.

D. This highlights the process of cell division going back to the fertilized egg as the "starter" cell of all sexually reproducing organisms.

1. During 1850 to 1875, it was established that the fertilized egg is a single cell formed by the fusion of a sperm cell and an egg cell.
2. In the 1880s, microscopes allowed observation of new details of the process of cell division, named *mitosis* by Walther Flemming, and the stages of this process were identified by the end of the century.
3. Note two points for future reference in the lecture on gene theory: First, in the 1870s, Friedrich Miescher suggested that an acid molecule in the nucleus might play an important role in cell division. Second, the question of how organisms inherit characteristics from their parents now focused on the formation of the "starter" cell.

IV. The overarching question for biology, of course, is: What is life? The cell theory must be understood as a response to that question.

A. That cells are the universal building blocks of life still does not tell us what life *is*.

1. In the mid-19th century, it was proposed that the essence of life was *protoplasm*, a term coined by Hugo Mohl, collaborator of the very influential mechanist chemist Justus Liebig.
2. By the end of the century, with the growing understanding of the complex structures and molecular processes internal to the cell, the colloid theory replaced the protoplasm theory.
3. Early in the 20th century, enzymes replaced colloids as the key to life, that which controls the cellular processes that confer life on a mass of chemicals.
4. With the discovery that enzymes are proteins, enzymes became the essence of life; this view endured into the 1950s.

B. The great German chemist Emil Fischer put enzyme theory on the research map.

1. Fischer discovered that enzymes are composed of amino acids, which could readily be synthesized.
2. He was able to synthesize proteins out of amino acid combinations, including proteins occurring in the human body.
3. This strongly reinforced the mechanical/biochemical view of life, and vitalism disappeared as a scientifically respectable theory.
4. In the 1950s, DNA was proclaimed the essence of life because it contained the "instruction set" for protein manufacture.
5. DNA theory perfectly illustrates the atomistic style of thinking, at least in its initial development, but we'll return to this in the lectures on gene theory and molecular biology.

Essential Reading:

William Coleman, *Biology in the Nineteenth Century*.

Ernst Mayr, *The Growth of Biological Thought*.

Questions to Consider:

1. Is life ultimately "just" a matter of physics and chemistry?
2. Can the nature and behavior of organisms be explained at the cellular level?

Lecture Nineteen
The Cell Theory of Life

In the last lecture we discussed the atomic theory of matter, but the atomic theory of matter is just one instance of what I will call an atomistic style of thinking ultimately rooted in this Parmenidean approach to explaining reality. The atomistic style of thinking includes the atomic theory of matter, but I believe that it is also correct to characterize the cell theory of life, the germ theory of disease, and the gene theory of inheritance, which we will be exploring in the next two lectures, as further instances of this same style of thinking in which we attribute phenomena to the manifestation of different configurations of underlying elementary building blocks. These building blocks have fixed properties and they combine in various ways with one another in order to produce all of the phenomena that we are interested in.

In each case the idea is that we can isolate an elementary cause that is itself fundamental in some functional sense, and functional within the context of scientific explanations, and that fundamental element, that cell, that germ, that gene with its particular distinctive properties allows us to explain life processes, in the case of the cell theory of life; disease, in the case of the germ theory of disease; what we call genetics or inheritance in the case of the gene theory.

In this lecture we're going to focus on the cell theory of life, the idea being that all living things are made up of cells. Right from the beginning they are understood to have certain internal structures and properties, and that they combined with other cells in various ways to give you tissues. The tissues then built up into organs. The organs then built up into an organism. So that the cell is, again, a building block; not identical to an atom, but it has that same explanatory and conceptual flavor as the atom in the theory of matter.

This style of thinking is very characteristic of the West. Just think in terms of our attitude towards society, in which we think that the individual is the basic unit of society. Individuals form families, families form clans, clans form communities, communities form societies, and societies form the so-called family of nations, although that's a relatively recent concept. So that same idea, that the ultimate building block is the individual—at least, of course, in the Western social atomic—we even call Western social theory, or one aspect of Western social theory, social atomism—that the individual is the basic building block of society.

An alternative view would be that society has a holistic character that supersedes the reality of the individual. The individual is in a sense created to and beholden to society; whereas, we believe that the individual has inalienable rights, and that society cannot legitimately take a form which violates those rights.

So this style of thinking is very familiar to us. Even in sports we tend to think that there are stars, superstars that deserve especial praise and attention, and we have a lot of difficulty dealing with teamwork. We praise teamwork at one level, but in fact we then undercut it by highlighting somebody as the hero, somebody else as the goat, and giving extraordinary praise to superstars—sports superstars—but also intellectual superstars. The whole theory that geniuses are what propel intellectual history, associated with the 19th century British historian Thomas Carlyle, is another instance of that.

Anyway, what we're going to deal with in this lecture is to focus more narrowly now on the cell theory of life. What prompts the cell theory of life, of course, is the emergence in the 18th century especially of the scientific response to the question: *What is life?* Which is in some sense the most fundamental of all questions for us to answer, not necessarily the first question that we want to address or be capable of addressing, but certainly it seems to be the most fundamental of all questions—what is life?

So a typical response, prior to the rise of modern science, is that life is a divine gift; but within science that response does not wash. We need to explain life in terms of natural phenomena, natural forces, and that really becomes possible, or at least it emerged, in the 18th century within the framework of modern science. The scientific term that we use to describe the study of life is biology. That word was invented around 1800 by Jean-Baptiste Lamarck, a very, very important French biologist—zoologist, in fact—who developed an evolutionary theory of his own that we'll be talking about more when we talk about the theory of evolution and the Darwin–Wallace version of that theory.

But Lamarck was an extraordinarily important thinker at the end of the 18th and the beginning of the 19th century, and he coined the term biology from the Greek word *bios*, from "life," as an umbrella term to refer to the spectrum of increasingly scientific studies. In ways that we now understand when we say that a study is scientific because the ideas have been framed in terms that fit within the context of what the community of scientists recognize as a scientific explanation; studies in, for example, botany, zoology, anatomy, medicine of course, and the study of respiration, the study of digestion, the study of reproduction, especially reproduction as we will see is of special significance, to understand these as natural phenomena, to understand the processes and what causes them.

And in the 18th century there were, broadly speaking, two underlying theories. One was a Cartesian-influenced mechanistic theory of life, that life happens to be no more than a very complex manifestation of strictly mechanical physical forces. Therefore all biological phenomena (the term was anachronistic until roughly 1800), all living phenomena are reducible to physics on this view. They're mechanistic. It is that their matter can be configured in ways so complex that we call those ways "living creatures."

And analogously today, for example, there are some people working in artificial intelligence research who believe that once we can make computers, once we can make chips that have billions of transistors that are interconnected in the dense way that the human nervous system is, that somehow consciousness and intelligence would emerge out of the complexity of those interconnections. And so there is really nothing special. If you have a sufficiently complex nervous system where the cells are connected in a sufficiently complex arrangement, then consciousness simply emerges. There is nothing wonderful in that sense except the improbability of it all.

So we have this mechanistic view, but then there was a rival view, broadly called vitalist, which held—from the word *vitality* for life—that there were irreducible forces at work in biology that were necessary to be added to physical and chemical forces in order for those physical and chemical forces to be selectively utilized to construct living things. And in the course of the 19th century this vitalist view came under increasing pressure from the growing materialism of 19th century science, where more and more biological processes could be explained in terms of physics and chemistry without any need for a special vital force.

Lamarck himself was an early proponent; but not the first. One can argue that perhaps Georges Buffon, great mid-18th century French naturalist in his book *Natural History*—a multi-volume work that appeared over a period of many years, and was an international sort of coffee table bestseller (if they had coffee tables then), the *Natural History,* one volume of which had to do with the ages of the earth—Buffon argued for something like the common origin of all life forms. But it's not clear that there was a single life form in Buffon that then radiated into all the different life forms that we see in nature.

But Lamarck explicitly argued that in the beginning there was one extraordinarily primitive, very simple life form and that all subsequent life forms, including human beings, evolved out of that life form under various kinds of pressures—environmental pressures—acting on the complex character of a living organism (we'll come back to that in a moment). What's interesting is that in the 1790s, when Lamarck was formulating and publishing these ideas, Charles Darwin's grandfather, Erasmus Darwin, who was a physician with a wide range of interests and quite an eccentric character, published several epic poems. His writings in biology and naturalism were in the form of very long poems, which actually sold pretty well, although what I call "real poets" thought he was comical.

But Darwin argued, like Lamarck, that in the beginning there was one single life form and that all of the others radiated out under something like natural selection. Eventually, Charles Darwin admitted that as a teenager he had actually read his grandfather's poem, although he claimed it didn't influence him very much.

Lamarck's theory was a dynamic theory, that through the use of its organs in response to environmental challenges, organisms evolved, and developed new capabilities through striving to survive under continually changing environmental circumstances, which implied the inheritance of acquired characteristics. We will see how controversial that became when we talk about the gene theory of inheritance.

The study of life in the 18th century had been aided tremendously in the 17th century by the development of the microscope, especially the use of the microscope by Leeuwenhoek in Holland, and by Robert Hooke in England, and by Marcello Malpighi in Italy. They revealed that there was a whole world within ordinary experience, especially by looking in fluids of various kinds to reveal that there were these tiny little creatures swimming around. The temptation in the 18th century was to keep pushing the magnification of these microscopes in order to look more and more carefully at these creatures in order to discover the secret of life.

But the more you magnified the original simple microscopes of the 18th century, which were not corrected for what's called color aberration, chromatic aberration—which is because light has a wave-like character which even Newton recognized in his atomic theory of light; he recognized that these light atoms had something like what we would call a wave-like character, although he called it "different fits of transmission and reflection," that because different colors of light have different frequencies they are brought to a focus at different points by a lens—if the lens is not very curved and the magnification is low it's not a big deal. But the more you curve the lens in order to get higher magnification, then the blurrier the image becomes.

And so 18th century microscopy became a kind of a Rorschach test in which you saw pretty much what you were looking for, because everything you saw was extraordinarily blurry. This led a number of 18th century biologists to give up the use of the microscope; most notably a French biologist contemporary with Lamarck named Bichat, who developed a tissue theory of life which was an early rival to the cell theory of life before the cell theory of life was formulated in its scientific form. The tissue theory of life postulated that the fundamental unit of biological explanation was tissues. And he identified, for example in the human body, 21 different types of tissues that combine to form all of the organs in the body, and then the total system that made up the human organism; and so with all other living things.

The problem with the microscope was solved in two ways that were not unrelated, and were kind of interesting. One was a very interesting character named John Dollond, who was a silk weaver who became self-educated in mathematics and physics and chemistry to the point where he was clearly a serious scientist, and he figured out how to combine crown and flint glass—two different kinds of glass—in a three-piece sandwich that solved, within limits, the problem of chromatic aberration. In 1758 took out a patent on this, and founded together with one of his sons a business that flourished for about 100 years, making optics.

Concurrently, the great mathematician Leonhard Euler addressed this problem of chromatic aberration and came up with a mathematical theory that sort of solved the problem mathematically, and also predicted that by combining a glass lens and a fluid—water for example—you could use a combination of a single lens and fluid rather than these compound lenses. And interestingly, Dollond originally did his experiments to prove that Euler was wrong, and discovered in the course of his experiments that Euler was quite right; but he nevertheless made up a three-piece sandwich lens rather than a lens made up of glass and a fluid.

It was a hundred years almost before a superior kind of microscope (in the 1870s) was designed by Ernst Abbe for Carl Zeiss (everybody has heard of Carl Zeiss Optics, I assume), They started marketing an oil immersion lens in which oil and a glass lens are combined to solve this problem of chromatic aberration.

So the problem was in a certain sense solved in the last third of the 18th century. But it wasn't until the 1820s that we have the whole microscope set, not just the lens but how you package the lens. Here we have an achromatic lens. The blurring problem is solved, but not until you package it in a microscope with an appropriate focusing mechanism with a stage for the preparation and presentation of the specimens you're studying, with appropriate lighting. Packaging matters, as the Apple II and the IBM PC remind us. Packaging the same technology that other people may be using can have a powerful influence on how that technology is used, and sort of unleashes a torrent of innovation.

And in the 1820s, especially a design by the Italian Amici, who put together a package that you just buy and use, we start seeing from the 1820s on a tremendous explosion in biological research and a revival of the cell theory which had first been suggested by Robert Hooke in the late 1600s when he published his work *Micrographia*. He included in it a picture of a slice of cork that he had observed under the microscope, and you can see the beautiful little "cells" (as he called them), and wondered if maybe this is the way plants are, that they have a cellular structure. But he didn't go any further than that.

In the 18th century it was kind of casually assumed that plants, at least some plants, had the same kind of cellular structure that cork had. But it was really in the 1830s that the idea began to grow that all plants, and then separately all animals, have a cellular structure, that all of them are built up out of cells. And in fact not only are they built up out of cells, but cells have what Robert Brown (who we know of from Brownian motion) named, he was the person who named the nucleus. He saw this dark spot within the cell.

And so in 1838 and 1839, Theodor Schwann and Matthew Schleiden (Schleiden in 1838; Schwann in 1839) formulated the cell theory as the universal theory of life. That all plants (in the case of Schwann), all animals (in the case of Schleiden) have a cellular structure and that the cell has a nucleus, and that this nucleus seems to play some role in cell reproduction. Now let me just say at the outset that Schwann and Schleiden—both of whom were directly or indirectly students of Johannes Müller, whose laboratory at the university was a seedbed for mechanistic theories of life, physical and chemical theories of life, while he himself personally was a vitalist; but his students advanced the mechanical theory or the materialistic theories of life—they were not the first to come up with the idea that plants and animals have a cellular structure. There were predecessors in the early 1830s—a Frenchman by the name of Rene Dutrochet and a Czech by the name of Johannes Purkinje—who also claimed that they saw in all plant and all animal tissues that they examined a cellular structure. But it was Schwann and Schleiden who are considered to be the ones who formulated a universal theory of life based on the cell.

And what is interesting is that in the course of the 1840s and 1850s, this theory was universally accepted. That is very interesting, that the theory was universally accepted on the basis of relatively modest experimentation, when you consider how broadly sweeping the claim is. How could you empirically justify the claim that all living things have a cellular structure when you haven't examined all living things? What percentage of the different kinds of living things on the planet were examined at the time that that claim was made and essentially universally accepted? Minute. And yet that is a very interesting fact about science, that sometimes theories are accepted on the basis of relatively modest empirical evidence, strictly speaking, by looking at what percentage of the possible pool of evidence there is. And others, like the atomic theory of matter in the preceding lecture, can have a growing body of evidence and function within scientific explanation for decades and still be controversial.

So the cell theory of life is now, in the 1840s and 1850s, essentially universally adopted by biologists. And the question is, what are cells? What is going on inside these cells? One of the questions, of course, has to do with identifying the internal structure of the cell. Unlike the atom, the cell clearly has an internal structure. And in the course of the 19th century, and especially after the 1870s when the improved Abbe-Zeiss microscopes came out—the Dollond microscope had a resolution of one micron, which is a millionth of a meter; it could resolve two objects that were only a micron apart, a millionth of a meter apart—but after 1870, the Abbe-Zeiss microscopes (Zeiss had actually died by that time, but the company remained the Carl Zeiss company) were much better, and so we see a tremendous increase again in the sophistication of microscopic observation of the cell, identifying structures within the cell. Because after the 1870s, for example, we already are seeing not only chromosomes, but seeing that during reproduction of the cell chromosomes split longitudinally, and even making out structures within the chromosomes.

So one line of research is to identify what the composition of the cell is, because the secret of life is now believed to be contained within the cell. To understand the secret of life you must know what is going on in the cell, and one facet of research into the cell that captured more and more attention was, how do cells reproduce? Where do cells come from? Initially Schwann and Schleiden thought that the cells were somehow formed out of some mucous substance that was in the embryo sac, and that they were manufactured within the growing embryo.

But in the 1850s, and this is associated especially with Rudolf Virchow—a very powerful figure in the mid-19th century biology and especially the biology of the cell, that the cell is the key to life—and Robert Remak and Rudolph Kölliker, who argued and came up with a principle that all cells only come from the division of other cells. You can't manufacture cells out of raw materials. Cells reproduce by division. Cells come from other cells only. Of course that leaves open the whole question of where did that first cell come from? That is the spontaneous generation of life question which is quite complex for science, and obviously still not resolved. But given a cell, the cell produces other cells by a process of division.

It was Remak who, in the early 1850s, first recognized that a frog egg is a cell, but it was another 25 years before Oskar Hertwig was able to show that the fertilized egg is a single cell that comes from the fusion of sperm and egg cells. That the sperm is a cell, the egg is a cell, that the fusion of the two produces a single fertilized embryonic cell from which all the other cells of the body then develop. This is a major discovery within the framework of the cell theory of life: the idea that the cell is the basis of life.

As I said, in the 1870s, there was an increasing recognition that there are structures internal to the cell that are fundamental to the process of cell division, which is the same as cell reproduction. And in the 1880s this process was given a name by Walther Flemming. It was called mitosis, and all of the different steps of mitosis began to be worked out between the 1880s and the end of the 19th century.

What is especially interesting, I think, that we will note in the lecture on the gene theory of inheritance, is that as early as the 1870s a German chemist named Friedrich Miescher—chemist, biologist, biochemist—suggested that within the nucleus there was a particular substance, an acid by nature, that seemed to be important for the purpose of cell division. That played some particularly important role in cell division, and that idea sort of lay dormant for quite a while. But that acid, of course, in the 20th century was identified as DNA. And DNA is another version of atomistic style of thinking within genetics, but we'll come to that.

Let me pull together a number of ideas here that are relevant to the cell theory of life. We are still concerned with answering the question, *What is life?* The cell theory by itself is valuable to us because it seems as though the cell theory of life is our best scientific answer to the question, *What is life?* But we need to understand, well, what is it about the cell that is the essence of life? What within the cell is the essence of life?

The first version of a response to this question was based on what was called protoplasm, a term invented by the German, Hugo Mohl, again a biochemist, associated with Justus Liebig, who we'll run into again. Liebig was a kind of a radical mechanist, and attempted to reduce all biological phenomena to chemical phenomena. So Mohl introduced this term "protoplasm." Protoplasm was conceived to be the essence of life. In fact, we still hear that word, or read that word, being used as if somehow the secret of life is contained within protoplasm. But by the end of the 19th century that was much too vague a term and in the 1890s especially it had morphed into a colloid theory of life; namely that colloids are tiny little particles that are suspended within some solid. So within the cell it was believed that there were tiny little particles that were the key to controlling cell metabolism.

This colloid theory rather quickly gave way to an enzyme theory of life at the turn of the 20th century. That is, that enzymes were the secret of life, that every cell manufactured enzymes, and that it was the enzymes that were responsible for controlling all the processes going on within the cell. So if you wanted to have a really satisfactory theory of life, you had to understand how enzymes worked—identify them and discover how they worked. Clearly this is moving us increasingly towards a biochemical theory of life, in which life is reduced from being something that can only be explained in living terms to being explained in terms of complex processes that are physical, chemical, mechanical, and electrical, but the processes themselves are not specifically alive. So life becomes a kind of a derivative property.

In the early 20th century enzymes were soon discovered to be a particular kind of protein. Enzymes are those proteins which act as catalysts. So now it becomes a protein theory of life. Proteins were discovered by Emil Fischer early in the 20th century—we are still in the first 15 years of the 20th century—and were discovered to be chains of amino acids, or made up of amino acids. Amino acids are chemicals that you can make in the laboratory, and you can then link them together and you can make proteins, and Fischer made several proteins in the laboratory, including some proteins that actually exist within living bodies, including within the human body. This again reduced the idea of life to essentially a chemical phenomena, although as quantum theory developed, chemistry itself was believed by physicists to have been reduced to quantum theory.

So, ultimately, life becomes a strictly physical phenomenon within this context. But proteins now become the key to life, until in 1953, when Watson and Crick discover the structure of DNA, it precipitates a consensus that DNA is the secret to life.

But again, in each one of these stages, what we're doing is we're identifying an "atom," a conceptual atom that is responsible, that ultimately it's the properties of that atom that are going to explain everything else. Everything else concatenates out of that particular definition of that particular atom. And that's why I say that the cell theory of life is an instance of the atomistic style of thinking. And we'll see this very clearly when we talk about DNA and molecular biology.

In the next lecture we're going to see how the germ theory of disease is another instance of this atomistic style of thinking.

Lecture Twenty
The Germ Theory of Disease

Scope:

The germ theory of disease is the cornerstone of modern scientific medicine, yet it was quite controversial initially. From antiquity, the dominant view of illness was that it was the manifestation of an imbalance within the body, a view revived in 19th-century homeopathic medicine. The expertise of the physician lay in identifying the imbalance and restoring the balance. There were, to be sure, parallel traditions that some illnesses at least were divine afflictions or were caused by natural external agents, but the rational view was that the primary cause was an internal derangement. By the mid-19th century, a scientific view of illness arose that sought a materialistic-chemical explanation of illness, and the defenders of this view opposed the germ theory when it was proposed by Louis Pasteur, Robert Koch, and others. The triumph of the germ theory and the medical education, research, and treatment it provoked did not preclude materialistic and homeopathic causes of illness.

Outline

I. Why we become ill has been an issue from the beginning of recorded history.

- **A.** The oldest and most enduring answer is that illness is a divine visitation.
  - **1.** Typically, illness is perceived as a punishment for moral or ritual misbehavior.
  - **2.** This is reflected in the close connection between healing and the priesthood in ancient Babylon and Egypt but also in ancient Greece.
  - **3.** Apollo was the Greek god of healing, and Apollonian temples/health clinics were built across the Greek world.
- **B.** Sick people came to these temples to pray and to receive treatment from the priest-healers, but naturalistic clinics arose, as well.
  - **1.** In the 5th century B.C.E., Hippocrates established his medical school on Kos, while a rival school flourished in the city of Cnidus.
  - **2.** In the 2nd century C.E., Pergamum was the home of Galen, whose medical writings and theories remained influential for more than 1500 years.
- **C.** Biblically, too, illness is described as a punishment and healing as coming from God.
  - **1.** In Exodus, God says, “I, the Lord, am your healer,” and this theme recurs throughout the Hebrew Bible. Jesus is portrayed as a healer in the Christian Bible.
  - **2.** Illness as divine punishment was a commonplace throughout the Christian Middle Ages and persists in the present day.
- **D.** The view that disease is a natural phenomenon, with natural causes to be dealt with naturally, was developed in the Classical period.
  - **1.** Hippocrates’s *Airs, Waters and Places* discusses the effects of environment on health, while another book rejects the view that epilepsy is a divine affliction.
  - **2.** The Cnidian medical school was focused above all on the course of a disease over time, as if the disease were an entity in its own right, independent of the patient.
  - **3.** In the 1st century B.C.E., the Roman writer Varro, followed in the next century by the Roman writer Columella, wrote of some diseases as caused by “minute animals” entering the body.
  - **4.** In the 2nd century C.E., Galen’s writings summarized and extended a tradition that health is a balance among the 4 “humours” of the body and illness an imbalance.
  - **5.** This tradition survived Galenic theories, reappearing in the 19th century as homeopathy, for example, and as the homeostasis theory of Claude Bernard.
  - **6.** The cause of disease in this still-influential view is a malfunction internal to the body.

E. The idea that the cause of disease is something external that invades and sickens the body preceded the germ theory.
   1. Hippocrates and Varro and Columella were proponents of this idea in antiquity.
   2. The response of quarantine to the outbreak of plague in 1347 suggests a conception of contagion spread from outside the body.
   3. The Renaissance naturalist Girolamo Fracastoro suggested that syphilis, then epidemic, was caused and spread by invisible living things.
   4. With the 17th-century microscope discoveries of invisible "animalcules" in water and bodily fluids, Leeuwenhoek wrote to the Royal Society suggesting a relationship between these creatures and illness.

II. In the 18th century, mechanistic theories of life took strong root, but it was in the 19th century that modern theories of disease emerged and, with them, modern medicine.
   A. In fact, what emerged was a battle between rival scientific theories of disease.
      1. On one side were the men commonly identified as the founders of the germ theory of disease: Louis Pasteur and Robert Koch.
      2. Their argument was that disease was caused by microscopic life forms entering the body and disrupting its normal processes.
      3. On the other side were their opponents, including some of the most prominent names in 19th-century science, among them, Justus Liebig, a defender of the mechanical view of life, and Rudolf von Virchow, for whom all abnormal functioning was cellular malfunctioning.
      4. The germ theory of disease is popularly depicted as one of the great triumphs of modern science, yet from our perspective today, the opposing view was right—or certainly not wrong!
   B. Pasteur anticipated the modern germ theory of disease in his famous paper of 1857 on fermentation.
      1. The idea that fungi and molds were causes of plant diseases and skin diseases in humans was argued in the decades before Pasteur's paper.
      2. Schwann had identified yeast as a living organism responsible for the fermentation of sugar solutions in the mid-1830s.
      3. Pasteur formulated an experiment-based theory of invisible organisms busily at work, constructively and destructively, in organic processes of all kinds, as effects of their life cycles and perhaps playing a role in disease, too.
      4. As microscopes improved, bacteria became visible; viruses were identified in 1898 but were not visible until the electron microscope was introduced in the 1930s.
      5. Opposition to the germ theory was led by Virchow using a journal he founded and a text he published to champion the cell as an "independent unit of life."
   C. Jacob Henle's *Handbook of Rational Pathology* (1846–53) speculated that contagious diseases were caused and spread by microscopic parasite-like living creatures.
      1. Henle had studied under Müller, was a close friend of Schwann, and was the teacher of Robert Koch.
      2. He laid down three conditions for establishing scientifically that an invisible agent was the cause of a disease, and these became the hallmark of Koch's experimental method.
      3. By 1876, Koch had isolated the anthrax bacillus and studied its complete life cycle; in 1882, he isolated the tubercle bacillus and, in 1883, the cholera bacillus.
      4. Meanwhile, working in parallel, Pasteur had been studying anthrax, convinced now that microbes cause disease.
      5. In parallel, Pasteur and Koch showed experimentally that this was indeed the case.
   D. Pasteur resurrected vaccination and foresaw the commercial uses of microorganisms in industrial

processes, in agriculture to control other organisms, and as antibiotics.

1. Pasteur's studies of cholera in 1879 "accidentally" revealed the efficacy of vaccination, initially against animal diseases, then in humans. [Note: Also in 1879, Pasteur isolated the streptococcus bacterium and claimed that it was responsible for puerperal fever; he also isolated staphylococcus, linking it to osteomyelitis.]
2. His 1881 public anthrax challenge led to the mass vaccination of sheep and cattle, and his rabies research isolated a virus.
3. In 1885, Pasteur suggested that dead bacteria could also confer immunity, and in 1890, two students of Koch showed that serum could confer immunity, specifically for diphtheria.

III. Opposition to these new theories of fermentation and disease was not at all irrational; in fact, it was correct.

- **A.** Obviously, the germ theory of disease and the therapies it stimulated led to major improvements in public health.
    1. In the developed world, memories today are very dim—or nonexistent—of the awesome toll taken by smallpox, measles, typhus, cholera, diphtheria, yellow fever, and polio.
    2. Inspired by Pasteur, Joseph Lister, among others, promoted antisepsis to reduce the rate of infection caused by the hands of physicians and their instruments.
- **B.** But there were scientific grounds for opposing the germ theory.
    1. Some people had identifiable germs in their blood but displayed no signs of illness.
    2. Others displayed signs of illness but without visible germs in their blood or tissues.
    3. The atomistic style of thinking here reveals its character: Either germs are *the* cause of disease or they are not.

Essential Reading:

Michael Worboys, *Spreading Germs*.

Ernst Mayr, *The Growth of Biological Thought*.

Questions to Consider:

1. Common sense strongly suggests that factors external to the body cause disease; why, then, was there opposition to the germ theory?
2. Are scientific theories ever the product of a "heroic" individual genius, or does the thinking of a collective find expression through individuals?

Lecture Twenty
The Germ Theory of Disease

The germ theory of disease is the cornerstone of modern scientific medicine, and of course it's another instance of the atomistic style of thinking. But one must appreciate that it was, when it was formulated in the middle of the 19th century, a very controversial idea, and that opposition to the germ theory of disease continued right through the 19th century. That opposition was quite rational and really reflects a fundamental, let's call it, a weakness within the atomistic style of thinking, which is that it claims too much.

The idea that any of these atoms—the atom in matter, the cell as an atom, the germ as an atom, the gene as an atom, the DNA as an atom, as what the gene really is—all fail to be able to generate all of the phenomena that motivate us to study those different areas of science, because they are not the sole causes of any of those phenomena. They act in conjunction with other factors in their environment.

So one can say that the biggest weakness of the atomistic style of thinking is that it diminishes or totally dismisses the significance of relationships—environmental relationships, chemical relationships, physiological relationships, social relationships. There are networks of factors that seem to play, or are perceived, in the course of the 20th century, are perceived as playing significant roles in determining natural phenomena. You can't derive them all, Lego building block-like, from atoms.

So the atomistic style of thinking has certain strengths. Clearly, the germ theory of disease explained a great deal, and it translated into very powerful techno-scientific applications. It was a theory whose technological applications based specifically on that theory were very powerful, and we'll be talking about some of those. Nevertheless, it has limits, and the claim that illness is the consequence of germs is something that we need to appreciate was both controversial and legitimately opposed by some of the greatest biologists of the middle of the 19th century.

But let's step back for a moment and understand the explanatory context within which the germ theory of disease is an idea. And that context, of course, is the question, why do we become ill, and what can we do about it? (That is two questions, or two sides of the same question.) It is not just that we're intellectually interested in knowing, "Why do we become ill?" In the case of illness as opposed, let's say, to the atomic theory of matter, which may not concern many of us at the existential level, when it comes to illness we also want the nature of illness to give us some appropriate regimen for responding to illness when it strikes us.

So now this question, which is clearly prehistoric, and one can hardly imagine human beings that we could relate to who would not think along these lines: Why do we become ill? Certainly the pre-scientific response to this question is that illness is a divine visitation. That implies that the response to illness, the pursuit of healing, takes the form of prayer, purification, and penitence. The three Ps—prayer, purification, and penitence—and that that is the appropriate response to illness.

We find in surviving documents from ancient Babylon, from ancient Egypt, and into the Greek period, that there is a close association between the priesthood and healing, and that temples were healing centers in the ancient world. Certainly this was the case in Egypt and in Greece, where the god Apollo was in some sense the super physician. And his son through a rather complicated birth, Aesculapius, became identified as the patron saint of physicians and the great healer, and was actually killed by Zeus because he had discovered the secret of resurrecting the dead, of staving off mortality so that human beings would not be limited by mortality; which was too threatening to the gods, and so Zeus killed Aesculapius.

So this is an association of Apollo, and through Apollo, Aesculapius, with healing. There were temples of Apollo in the ancient world—on the island of Cos, for example, in the city of Pergamum and the city of Cnidus—that were healing centers, where people went in order to recover from illnesses through prayer, purification, penitence. But also they were in a clean and healthful environment for the most part, and where an attempt was made to give them clean water and a better diet, and so those factors may well have contributed to whatever cures were associated with their stay in the temple healing center.

We're familiar in the Bible, in Exodus, God saying, "I am the Lord your Healer." Jesus was a healer. The identification is very strong; for example, when syphilis arises in epidemic proportion in the 16th century in Western Europe, that it was a divine scourge, that it was a punishment by God for the increasingly secular and promiscuous behavior, compared to the behaviors that the Church preached for people to display. And even in our own time people have claimed that epidemic illnesses are a punishment visited upon us by God, and that the appropriate response is to stop behaviors that God disapproves of.

So a major change in our response to the question, "Why do we become ill and what should we do about it?" is the idea that illness is natural, that illness is a natural phenomenon. And the way to respond to it is within the framework of nature, as opposed to saying that God is punishing me and I need to straighten out my relationship with God in order to recover from this illness, or perhaps that I must just accept it as a divine punishment and show God that I accept my fate.

We can say that at a minimum in the 5th century in ancient Greece that Hippocrates on the island of Cos, where there was a temple of Apollo that was a healing center, founded a school of medicine that for centuries was extraordinary influential, and that taught that illness was strictly natural, and that there were natural remedies for illness. One of his surviving books is called *Airs, Waters and Places*, which talks about the importance of good air, clean water in the place that you live—in siting a town and building a house, to make sure that the air is clean and that the water is clean. Another of his books, on epilepsy, treats epilepsy, which classically had been associated as a specifically divine affliction, as a natural phenomenon.

A rival medical school in the city of Cnidus was focused on prognosis, the idea being that different diseases had different characters. They unfolded within themselves quite independent of the patient, so that if you could identify the pattern of the illness, you could then predict its subsequent development. Then if you were good at this, then you would know that the patient was going to get better, in which case you would definitely want to be their doctor, and then you are given credit for curing them. And if your prognosis is that they're going to die, then the best thing to do is to get out of town so that you will not be accused of having killed them.

But the underlying idea is that diseases have a character of their own, so to speak, independent of the patient who becomes a host to that disease. The island of Pergamum, which also had a healing center, a temple of Apollo on it, subsequently, at the end of the 2nd century C.E., was the home of Galen, who was perhaps the single most influential medical theorist in Late Antiquity, the Middle Ages, and the Renaissance Period, right up to the 17th century. His theory, which we need to pay careful attention to in the context of the germ theory of disease, was that the human constitution was based on the production by the human organism of four fluids that were associated with four humors. There were four different elements that went into the healthy body, and these were blood, phlegm, black bile, and yellow bile, and that the right balance of these four humors was what made you a healthy person: personality-wise, psychologically, but also physiologically.

Now in this conception, illness is quite natural, but illness is internal to the body. You become ill when these four humors are no longer balanced, and the task of the physician is to restore that balance by giving you appropriate natural remedies. If you have an excess of blood, then we do bloodletting. If you have an excess of bile, if you have not enough bile (black bile, yellow bile)….

And this four-humor theory, which was very powerful right into the 19th century as a theory of behavior—even though it was no longer considered a theory of illness after the 17th or 18th centuries—in such terms as melancholy. With melancholy, *melan* is a Greek word for black, so a person is melancholy if they have too much black bile. A person has a choleric disposition if they produce too much yellow bile. That excess of yellow bile makes them angry. They have a quick temper. They're always responding in a very highly temperamental way, and so that's got to be modified. The balance has to be restored. A sanguinary person has a lot of blood, and so they typically have a red face and they're always cheerful; they're always smiling. And a phlegmatic person has too much phlegm, and so like phlegm they are very kind of slow to respond to life situations. Why phlegm is given such a bad rap is not clear to me, but those characterizations of people as phlegmatic, melancholic, choleric, and sanguine are all reflections of this theory of Galen's. The important point is the idea that illness emerges from within as a result of an imbalance.

The echo of this in the 19th century is, of course, homeopathy and the idea that all illness is an internal derangement. And homeopathic medicine to this day continues to focus on restoring a balance within the individual, because if you have that balance then you can fight off whatever illness afflicts you, even if it's an invading germ. If your body is put together right, then, in modern terms today we would say, your immune system will be able to fight off the illness; and if you can't and you become ill, then it's because there's something wrong within you.

The idea, that illness comes from the outside, that illness enters into the body from the outside, that it is unnatural, for example—well, natural in the sense that what comes in is part of nature—but there's nothing wrong with your body. You're as healthy as you can be. You've got as much balance as anyone could want, and nevertheless you somehow inhale or ingest something foreign, and that is what causes you to become ill. We already find signs of this in Late Antiquity alongside these other ideas. The Roman writers Varro and Columella speculate that maybe minute little animals in the foods and in the fluids that we drink enter into the body and they cause disease, they cause illness.

Also what's called a miasma theory, which goes back to Hippocrates on *Airs, Waters and Places*. If good air is what makes you healthy, there's something in bad air—a miasma—there's something like a swamp-like air that is very unhealthy and it's got something in it that, when you inhale it and it gets into your body, causes illness. I mentioned that when syphilis arose as a scourge in the 16th century and spread, and continues to be a serious disease entity in society, while on the one side some people were claiming this is God's punishment for sexual promiscuity, Fracastoro, an Italian naturalist, called it a living contagion. That it was the result of having come into contact with and assimilated a living thing that we could not see, but which was the real cause of the disease.

This was consistent with the earlier response to the plague beginning in 1347, which revived this idea of a miasma, the idea that there was some contagious something that emanated from people who got the disease. And so that's why quarantine was invented, from the word *quarante*, the French word for forty. So for 40 days people who came into a community from outside were required to stay isolated from the community to show that they were not ill. If they didn't become ill during that 40-day period, during the quarantine period, which wasn't always 40 days, but that's the name that it got, then they were permitted to come into the community. Boats that came into harbors, the sailors were required to stay on the boat until they could prove that nobody on the boat was sick, and then they were able to come ashore.

So the idea that illness is the result of something outside the body coming into the body, which sounds to us like a predecessor of the germ theory of disease—and it is—goes back to antiquity. It was revived, especially after Leeuwenhoek and Robert Hooke used their microscope to reveal that there were tiny little creatures swimming around in the water that we drank, for example, and not only in the water that we drank; there was some speculation that maybe these creatures cause illness.

But we can usefully identify the 1850s as the beginning of the scientific germ theory of disease, which is particularly associated with two people: Louis Pasteur in France and Robert Koch in Germany. Koch was a student of a biologist named Jakob Henle, who had studied with Müller, so Johannes Müller's laboratory continued to be highly influential in terms of its students, and its students' students, throughout the 19th century. Pasteur has gotten the better press of the two, but I think that within the scientific community Koch is at least on a par with Pasteur. For many, in fact, he deserves more credit than Pasteur, in spite of the fact that most history books identify Pasteur, especially if they're written in French or translated from French, that Pasteur was the father of the modern scientific germ theory of disease.

In particular, they point to a publication of Pasteur's in 1857 which was an essay that he wrote on fermentation, in which he identified yeast as an organism that was responsible for fermentation. This was not the first time that yeast had been identified as a living thing, that it was not simply a piece of matter, that it was alive, and that it was an organism, and that it played a significant role in fermenting sugar solutions. Pasteur, however, extended these earlier ideas to a speculation, initially, that all living processes involve other living things that, as part of their natural life cycle, fulfill some constructive or destructive function within all other living things. So yeast cells are organisms that play a particular role in the process that we call fermentation, but Pasteur suggested there are other organisms, invisible initially, although as microscopes got better, we saw bacteria by the end of the 19th century.

Viruses were trickier, although they were identified in 1898. It was really only in the 1930s that the tobacco mosaic virus, which was the one that was identified in the late 1890s, was seen inside the electron microscope. And nowadays we also would add to the list of things that cause illness prions, which are proteins or segments of proteins that are associated with a particular range of pernicious diseases. The one that is most famous, of course, is mad cow disease, and it's really only in the last 30 years that prions have been accepted as real and as disease-causing agents. But Pasteur, in a sense, and Koch concurrently in Germany, gave voice to this idea in a scientific form that "germs," as they came to be called, that ordinarily invisible entities entering into the body are the ultimate cause of illness.

Now some of the early opposition to the germ theory of disease came from Rudolf Virchow, who I referred to in a previous lecture in the cell theory of life. Virchow was committed to the idea that cells are the basis of all living phenomena, and therefore if you become ill it's because there is a problem with cells in your body. He wrote a textbook called *Cellular Pathology*, which argued that cellular processes, when they go awry, are responsible for causing illness, just as Liebig, who I also mentioned in that lecture, argued that chemical processes within the cell are the cause of illness, and that the appropriate response is to identify the chemical process that's causing the problem, not to focus on these disease entities that are invisible (for a while, at any rate, before they were actually imaged in the better microscopes of the 1870s), and blame them for illness.

But Pasteur and Koch, more or less in parallel (sometimes one did it first; sometimes the other), were successful, beginning in especially the 1860s and 1870s into the early 1880s, in arguing in a very convincing way that infectious diseases like anthrax, like cholera, like diphtheria, tuberculosis were caused by germs. Now this was not an easy thing to establish. The germ was believed to be an organism in its own right that has its own character, so it's an atom, in a sense. It has a very specific identity, and the same germ always behaves in the same way in everybody's body, and if that is the case, then attacking that germ will be a cure for everybody who has responded pathologically to that particular germ.

Koch's teacher, Jakob Henle, had, in the 1840s, in a textbook that he wrote then on the cell theory, had formulated a set of rules. He also thought that invisible organisms were the cause of disease. He said if you want to prove this scientifically then you have to be able to fulfill three criteria; and Koch extended these to four, but Henle's three criteria are the key.

You have to show the constant existence of the same entity in all people who have this disease, as opposed to the view that whatever causes the disease can take many different forms depending on the patient and the patient's constitution and various other environmental factors. So the idea is if you want to argue that disease is caused by, let's call it a germ, that tuberculosis is caused by the tubercle bacillus, then you have to be able to show that the same entity is responsible for every case of tuberculosis. That's the first criterion.

Second, you have to establish that there is no other thing that is causing the illness. So you have to isolate from any kind of interference any other factor. You have to make sure that no other factor can be associated with the illness—only the entity that you have identified, in this case the tubercle bacillus, for example, which Koch in fact isolated.

And the third criterion is that you have to be able to reproduce the illness using only that entity. If you have isolated that entity, then you have to be able to show that every time you give that entity, the illness follows.

So if you can do those three things—which Henle could not do—then you have made a scientific case that this illness is caused by a germ entering into the body. Koch and Pasteur both did exactly this, famously, for the case of anthrax, which both of them identified and isolated more or less at the same time, depending on who you believe.

Koch began by using serum (that's blood without any cells in it) as a kind of a neutral base, mixing into serum tissue from animals afflicted with anthrax, and then showing that a drop of that tissue-infected serum would cause anthrax in another animal. So you know, that doesn't prove anything, because you could say, "Who knows what was causing it? It could be lots of different things in the blood that was causing it." So what he did was he took what's called eight generations of serum. He took tissues, mixed it with serum; took a drop of that serum mixture, put it in fresh serum; took a drop of that, put it in fresh serum; and he did this for eight specific times in order to show that, no, it can't be anything else. There's one thing in the tissue of the infected animals that is causing the anthrax. But, in fact, this did not convince most scientists of the day.

What Pasteur did, he used sterile urine as the base. He mixed in blood from an anthrax afflicted animal, and he did it for a hundred generations, showing that in each case if you take a drop of blood, mix it with sterile urine, inject that into an animal, they get anthrax. If you take a drop of that stuff, put it in fresh sterile urine, and take a drop of that and inject that into an animal, that animal will get anthrax. And he did this a hundred times, by which time he showed statistically (as we would now say) that anything left from that original drop of blood has disappeared. What has happened is that eventually we had the pure agent that was causing anthrax isolated. And that argument was convincing.

And he famously, in 1881, did this demonstration, a very spectacular and public demonstration, in which he showed, with big press coverage, farmers that here we have cattle and sheep and pigs. We give these animals anthrax and they all die. We give this group of animals anthrax and none of them die, because all of them have been rendered immune. Because one of the things that Pasteur and Koch discovered in the course of the 1860s and 1870s was that animals can be made immune by vaccination. Previously the only kind of vaccination was smallpox vaccination, but Pasteur recognized that animals could be made immune to germs if they had been vaccinated previously. Now, obviously, they had to survive.

Now how did that happen? It was actually quite by accident. He was working with cholera germs (as we would now call them) and in the course of the summer, the heat ruined the serum that contained the cholera in it, and he didn't know that. He injected it into chickens and they didn't die. That was kind of funny. So he said, oh well, the serum was spoiled. So he then a couple of months later injected those same chickens with fresh cholera germs and they didn't die. And so from that he generalized this idea that vaccination can work for all bacterial and then for viral illnesses, because he recognized that there were smaller entities than bacteria that were causing illnesses. Although as I said, it was only in the 1890s that viruses became entities in their own right.

Pasteur and Koch then succeeded in isolating and developing vaccines for anthrax, cholera, diphtheria, and Koch for tuberculosis. That's what he got the Nobel Prize for in fact, was for tuberculosis, which at the end of the 19th century in Europe was responsible for about 1/7 of all deaths in Europe. So it was an incredible killer, and now, finally, we had some scientific basis where we said we can now treat the tubercular patient—although it turned out that the best treatment was penicillin, which didn't become available on a wide basis until after World War II. It was available on a limited basis before that.

So Koch and Pasteur put the germ theory of disease on a firm scientific basis, and the techno-scientific consequences, this idea of finding a technology that's based on a scientific theory: here we have one vaccination and two antisepsis. Along the way, in the 1870s, Pasteur recognized that killing the germs would prevent infection. And in England, Joseph Lister made a career out of antisepsis, and convinced lots of his colleagues, especially in the medical profession, that many illnesses would be prevented by antiseptic procedures. Procedures using acids, for example, killed the bacteria that would be on the medical instruments that they were using, that would be on their hands, in those days when they were operating at a time when amputations were fatal 40–50 percent of the time.

So by the end of the 19th century the germ theory of disease had triumphed, but it also clearly was problematic, because there were situations in which people could have germs inside them and not become ill, and sometimes they displayed symptoms of an illness without any identifiable germ. So the theory has its pluses and its minuses, and as an instance of the atomistic style of thinking, these two go together, as we will see in the next lecture.

Lecture Twenty-One
The Gene Theory of Inheritance

Scope:

Conceptions about inheritance are among the oldest ideas in recorded history and, already in ancient Greece, were connected to ideas about embryological development. In the late 18th century, inheritance was identified as central to a theory of the historical existence of, and contemporary relations among, plants and animals. It was central to the question of the fixity of species, for example; thus, every theory of evolution required a theory of inheritance. Gregor Mendel's idea that inheritance was determined by the combination of discrete agents—"atoms" of inheritance, each with a fixed property or influence—was therefore timely and has proven to be very powerful; yet it was ignored for decades. The recovery of this idea at the turn of the 20th century; its convergence with, and resuscitation of, evolution by natural selection; and its rise to dominance with the "decoding" of the DNA molecule, constitutes one of the great epics of science.

Outline

I. The gene became "real" for most biologists in the years after 1910, but not for all and not even today.

- **A.** There are interesting connections among the atomic theory of matter, the cell and germ theories, and the gene.
  - **1.** The gene was conceived as a discrete unit of inheritance, a "black box" analogous to atoms, cells, and germs, each gene determining one phenotypic character.
  - **2.** Wilhelm Johannsen, who coined the term *gene* in 1909, did not himself believe that the gene was an "atom" of inheritance.
  - **3.** What Johannsen meant by *gene* was a kind of accounting or calculating unit useful as a name for the complex *process* of character transmission.
  - **4.** Inheritance involved a distinctive encapsulated process within the cell, but it was not a matter of transmission of independent black boxes from parents that combine to produce the characteristics of their offspring.
  - **5.** This process, Johannsen believed, involved substances in the nucleus of the cell that interacted during cell division, but it was more complex molecularly than a fusion of black boxes.
- **B.** Genes first became real at Columbia University in 1909.
  - **1.** Thomas Hunt Morgan was an opponent of genes until 1909, when he decided to study mutations in *Drosophila* and very soon discovered that an eye-color mutation could be localized on one chromosome.
  - **2.** Localization implied physical reality for Morgan—as it would for the chemical and physical atom—and over the next six years, he and his graduate students identified more than 100 mutant genes and established the primary features of a gene theory of inheritance.
  - **3.** The climax of this work came in the mid-1920s, with the success of Morgan's student Hermann Muller in artificially inducing mutations using X-rays.
  - **4.** Muller's experiment, for which he received a Nobel Prize, was a "smoking gun" for the reality of genes because the prevailing quantum theory explained X-rays as photon "bullets": in order to cause mutations, the X-ray photon would have to strike a specific, identifiable site where the mutation would take place, namely, a localized, "atomic" gene!
  - **5.** From the perspective of the present, given our growing understanding of how DNA fits into a network of cellular processes, Johannsen seems closer to the mark than Morgan.

II. As with disease, people have always been interested in the nature and causes of inheritance.

- **A.** The problem of inheritance is linked to the problem of explaining embryological development.
    - **1.** One problem is explaining how it is that embryos develop so similarly to their parents, a constancy-of-type problem: Why is it that individuals reproduce "after their kind," as Genesis puts it?
    - **2.** A second problem is individual variation: Why do offspring differ from their parents, typically in very small ways, but often significantly?
    - **3.** Explaining embryological development would clarify the nature of species and genera, whether they are really features of nature or conventional categories (recall the problem of universals).
- **B.** Ideas about inheritance have a long history, but they became scientific only in the second half of the 19th century.
    - **1.** Hippocrates proposed a "pangenesis" account of inheritance not much less sophisticated than the one Darwin held.
    - **2.** In this view, every characteristic of the offspring was represented in the sperm or egg: arms, legs, hair, and so on.
    - **3.** This is reminiscent of Anaxagoras's version of atomism, in which there is a kind of atom for every kind of thing in the world, and organisms grow by separating out the atoms they need.
    - **4.** Four hundred years later, Lucretius popularized this pangenesis theory in his poem *On the Nature of Things*.
    - **5.** Aristotle, by contrast, argued that sperm was a formative cause inside the fertilized egg, hence responsible for the emergence of all the forms in the offspring, while the egg was the "stuff" that was formed by the influence contained in the sperm into a distinctive embryo.
- **C.** Inheritance theory, especially from the 18th century onward, developed in close association with embryology, taxonomy, and evolutionary ideas.
    - **1.** The *preformationist* theory of embryological development explained that development away by denying that there was development: The embryo was fully formed in miniature in the egg or in the sperm.
    - **2.** A rival view, *epigenesis*, argued that development was real, with new forms emerging out of the formless fertilized egg under some unknown forces, vitalistic or mechanical.
- **D.** The central problem of taxonomy, made urgent by the sudden discovery of thousands of new life forms, is whether classification is natural or conventional.
    - **1.** If classification is conventional, then a "species" is just a convenient way of organizing a group of plants or animals that seem to be very similar to one another and that breed true to type.
    - **2.** On the other hand, if classification is natural, then a species is a thing that really exists, and breeding true to type is a sign that there is a natural system for classifying plants and animals.
    - **3.** Carl Linnaeus emerged in the late 18th century as the arch-defender of the natural position, having devised a classification system based on the sexual organs of plants.
    - **4.** Plant sexuality was a (scientific) discovery of the 18th century that remained controversial well into the 19th.
    - **5.** Linnaeus's classification system is still the standard for biologists, but ultimately he had to acknowledge that it was conventional.
    - **6.** The taxonomy problem lies at the heart of the central claim of evolutionary theory that species are not natural categories and that life forms continuously evolve.

III. The gene idea appears as a solution to the problems of inheritance, embryological development, evolution, and taxonomy.

- **A.** Enhanced-microscope studies of structures internal to the nucleus of the cell in the last decades of the 19th century led to modern genetic theory.

1. Around 1880, Walther Flemming identified chromosomes within the nucleus as pivotal to cell division and the transmission of characteristics to the next generation of cells.
2. Concurrently, August Weismann developed his *germ plasm* theory of inheritance keyed to a substance on the chromosome inherited from the parents.

B. Modern gene theory is invariably called Mendelian, but Gregor Mendel had nothing to do with its emergence or development!

1. Mendel's plant-breeding experiments, inspired by the pre-Darwinian evolutionary ideas of his biology professor at the University of Vienna, were published in 1865, but to no effect.
2. In the late 1880s and again in the late 1890s, at least three botanists already committed to a discrete unit within the nucleus of the cell as the solution—an "atomistic" solution—to the problem of inheritance independently discovered Mendel's work and graciously credited him as their predecessor.
3. These men were Hugo de Vries, the first and most important; Carl Correns; and Erich Tschermak. I think William Bateson, who was last to discover Mendel's work, in 1900, also belongs in this group.
4. De Vries published his "Mendelian" theory of inheritance in 1889, three years before he learned of Mendel's work.
5. He subsequently developed a mutation theory to explain individual variation and evolutionary speciation (in place of natural selection).
6. It is De Vries, not Mendel, who founded modern genetic theory, because that theory surely would have developed as it did had Mendel's prior work never been discovered.
7. Mendel receives more credit than he deserves, just as Copernicus, too, receives credit for an idea that was developed into its scientific form by Kepler.

C. Gene theory evolved from a "something" in the nucleus to DNA in a little more than half a century.

1. At the end of the 19th century, this something was a speculative black box on a chromosome, then a real black box after Morgan's work.
2. From the 1930s, the black box was believed to be made up of enzymes, but in 1953, it was revealed to be the DNA molecule.
3. By 1960, the solution to the problem of inheritance and the allied problems of embryological development, taxonomy, evolution, and life itself was the "code" programmed into the DNA molecule.

Essential Reading:

Michel Morange, *The Misunderstood Gene*.

James Watson, *DNA*.

Questions to Consider:

1. With the fate of Mendel's work in mind, are scientific theories dependent on specific individuals or are they a product of a climate of opinion?
2. Are genes "the" answer to inheritance, or are they, in the end, important but not determinative of the complex process we call inheritance?

Lecture Twenty-One
The Gene Theory of Inheritance

The gene idea is a proposed solution to the problem of inheritance. How is it that offspring so closely resemble their parents most of the time, but then always in some small ways and sometimes in some large ways do not resemble their parents? So the problem of inheritance is what motivates the gene idea, explaining the transmission of an organism's characteristics. It is not enough to say that, well, dogs always give birth to dogs, but the specific type of dog always gives birth to the specific type of dog. Well, not always, because sometimes we discover in the litter that some of the puppies look very different from the type that one or both of the parents represent.

There has always been, and in the 19th century especially, with the growth of biology as a science and the focus on the cell, there was a sense that now we are beginning to come close to resolving this truly age-old problem of inheritance; because like illness, inheritance, psychologically, is a very meaningful problem to human beings. We need to feel that our progeny are our progeny. These are *my* children. And in fact even in the legal sense of the term "inheritance," we have a need to establish that so-and-so is truly the offspring of this particular father or this particular mother.

So the problem of inheritance is truly an age-old problem, and it became one that scientists believed that they were approaching a solution to, especially in the second half of the 19th century. But there's something really quite puzzling about the gene that we need to sort of get on the table up front in this lecture; and that is that while the idea of the gene, as we commonly understand it, took form at the close of the 19th century and the first decade of the 20th century, the gene as we commonly understand it, this idea is of a kind of atom, a biological atom—maybe it would be better to call it a *black box*—that controls for a specific characteristic.

So you inherit one gene from the father, one gene from the mother, for a specific characteristic—for example, skin color or hair color—and then the result depends on some relationship between the gene you got from the father and the gene you got from the mother. And for each characteristic there is a gene from one side, from one parent, and a gene from the other parent, and the gene acts as a kind of atom. Each gene codes for (to use current language) a specific characteristic, and the result is a function of the relationship between the genes that you inherit from each of the two parents.

What is sort of ironic is that the name *gene*, that the word gene, was coined about 1909 by a Scandinavian biologist named Wilhelm Johannsen, and Johannsen himself did not believe in the gene as this kind of an atom, as this kind of a discrete particulate unit of inheritance—that's a more correct description, a particulate unit of inheritance. He believed that the process by which embryos developed the characteristics that they did was much more complex than simply inheriting one black box from the father per characteristic, one black box from the mother per characteristic. It's a bit anthropomorphic; let's say one black box from one parent, one black box from the other parent for each characteristic, and then the result had something to do with the relationship between these two genes. We are familiar, for example, with the case of dominant genes and recessive genes.

In 1909 when the word gene now became current, it was actually being used in two very different ways. It was being used to refer to a thing, and a thing that fits very nicely within the atomistic style of thinking that we've been developing in the last few lectures: the atomic theory of matter, the cell theory of life, the germ theory of disease. Even more than the cell and the germ, the gene is like a physical atom in its initial conception because it has a really very specific character and, at least at the time, we're more or less indifferent to exactly what goes on inside the gene that gives it this capability to code for a specific characteristic.

The other reference to the word gene, the one that Johannsen himself preferred, was to what he believed to be a complex process; that there was a process in which something in the nucleus played a key role, but that the process itself was much more complex than a black box here and a black box here fusing to form a new black box that codes for a specific characteristic. And what's ironic is that Johannsen came to the United States at this time in order to lecture at Columbia University. It was exactly at Columbia University, where I think in a lecture he named the gene, that Thomas Hunt Morgan—who was a geneticist with a laboratory at Columbia University that became extraordinarily famous, then he moved to California as a student of technology and kept being famous—Morgan at that time, 1909, 1910, was just shifting from not believing in the gene as an atom into believing in the reality of the gene as an atom. Through his research and his experiments and his graduate students' work between 1910 and 1927 effectively convinced most of the biological community that genes in the sense of black boxes were in fact real.

Now it turns out that Johannsen's intuition was perhaps more correct than Morgan's in that today, in the wake of the greater knowledge that we have of how DNA works, it really turns out to be the case that the word gene refers more accurately to a complex process than to some kind of unilateral directive that comes from the DNA molecule. And we'll be talking about this later on in the lecture.

So like the atom, the gene had to struggle to become real, to become accepted as physically real. This process more or less took place between roughly 1910 and 1927, when a student of Thomas Hunt Morgan's, Hermann Muller, used X-rays to artificially induce mutations in genes, and that convinced the last hold-outs that genes must be real, that there really must be this encapsulated unit within the nucleus that is responsible for the transmission of characteristics, the inheritance of specific characteristics. Because, look, we can actually use gamma ray photons from X-rays in order to change a gene. And so it's got to be real if you can change it.

Morgan sort of initiated this line of thinking when in 1909, 1910, experimenting with fruit flies, which have large chromosomes, he was able—to his surprise initially—to locate a mutation for eye color on a specific chromosome. And again, as we saw with making atoms physically real, it was the process of localization—if you can spatially localize something, then it must exist as a unit. And so he began to believe that there really were such things as genes, that they were located on chromosomes, and that here he had identified a specific site on a specific chromosome that was responsible for eye color, and that various mutations at that specific site were responsible for the eye color of the fruit flies.

Over the next decade or so, he and his students mapped over a hundred mutations in fruit flies onto specific chromosomes and specific regions of specific chromosomes. And in the process they essentially laid down the foundation for the gene theory of inheritance, the rules for the gene theory of inheritance, and of course in the process also made the gene seem to be quite real. So that Muller's work in 1927 was, if you like, the "smoking gun," or it was the occasion that gave people who were still sitting on the fence a reason for switching; although my guess is that by the late 19-teens most geneticists believed that the gene was real.

This is jumping ahead a bit in the story, because the gene idea is quite a complex idea and one that we need to understand the context of the emergence of, just as we did for appreciating the atomic theory of matter, the cell theory of life, and the germ theory of disease. I started off by pointing out that the gene idea is a solution to the problem of inheritance. The context of the gene idea is the problem of inheritance, and that's related to the problem of embryological development. It's related to the problem of individual variation. Why do offspring vary from their parents? They're not always exactly like their parents. In fact, they're almost never exactly like their parents, but they are like enough that we can say, "Oh, there's such a strong resemblance. There is a family resemblance."

So the embryological development is important because that's when the organism acquires its characteristics. The individual variation is important. And then there is a related problem to this that may not seem immediately obvious, and that is the problem of constancy of type. It's a problem to understand what is the mechanism by which the embryo, which seems amorphous, especially in the first phase of development—shortly after fertilization, it just looks like, if you'll excuse the expression, a gooey mess—

how is it that it forms in such a way that it preserves constancy of type? Or we may be more familiar with this expression as “species constancy.” How is it that species give birth to the same species?

It’s as if each species itself was a kind of an encapsulated unit, and it propagated “after its kind,” to use the expression in Genesis, that everything reproduced “after its kind.” And you didn’t have apple trees giving rise to orange trees. They always gave rise to apple trees until human beings intervened and hybridized them in various ways.

So the issue of the constancy of species is also related to this question of inheritance. So the question of inheritance, the problem of inheritance, is a broad problem. It’s one that deeply concerns us, and we see this because even in antiquity there were theories of inheritance, because people were concerned about this problem. And as soon as they started trying to understand nature, one of the problems that was at the forefront of their inquiries was, how do we explain inheritance?

And so, for example, the ancient Greek physician Hippocrates had a theory that was called *pangenesis*; that is to say, in a kind of a common sense way, that within each parent organism there is some process by which every characteristic of the organism has its representation in the sperm and in the egg. That’s why it’s pangenesis. It’s all genesis—all creation. That the fingers, the hands, the nose, the eyes, they all are represented. They are mapped onto (to use a more modern locution), they are mapped onto the sperm in the case of the father, they are mapped onto the egg in the case of the mother; one or the other or both, although at the time people thought it was one or the other. And that’s why the embryo develops the way it does, because it is essentially fleshing out the material that it had acquired from its parents.

Now this is somewhat analogous, you may remember it when I talked about the atomic theory of matter, to Anaxagoras’s version of atomism, in which he thought that every natural object contained lots of different kinds of atoms. There were hair atoms, blood atoms, bone atoms, etc., and that the process of growth was explained by the extraction of the relevant atoms within each particular organism. So when human beings ate bread, digestion was a process in which the bone atoms were extracted from the bread, and blood atoms were extracted, and that’s how we replenished our blood supply, and that’s how we grew our bones; and you can see how that would play out.

Pangenesis is a bit like that. And in fact in the great poem by Lucretius on the *Nature of Things* that I mentioned—Lucretius being one of the means by which Epicures’s atomic theory was propagated to the future—he explicitly describes pangenesis in these Anaxagorean terms.

Aristotle, who spent a great deal of his scientific research in biology, believed that the contribution of the sperm was to transmit the form of the parent (the father, obviously) to the egg, which only was a source of nutrient; so that the form of the offspring only came from the father, and the role of the mother was to nurture that form and to give it materiality. So that is a view of inheritance that remained influential right into the early modern period, and we’ll see how as we go along.

So the problem of inheritance moves into the early modern period together with the problem of embryological development and the problem of constancy of type. Embryological development, as I pointed out in an earlier lecture, especially in the 18th century where we find the roots of modern biology really taking hold and sort of motivating Lamarck at the end of that century to invent the word *biology* to refer to the growing range of studies of the nature of life, embryological development had sort of organized itself around two theories.

The theory of preformationism, which I had referred to—that the embryo is fully formed in a minute microscopic scale within either the egg or the sperm of the parent. So there were Ovists—those preformationists who believed that the embryo was fully formed in each egg of the woman—and so there’s no mystery to development, it’s just a kind of inflation that takes places. And others who believed that the embryo was fully formed in the sperm cell and that, again in an Aristotelian way, that fertilization was the occasion for inflating the minute form of the embryo within the womb.

And then there was a separate group altogether who held that this was nonsense, and that the embryo was initially formless and that it acquired form through a process that was called *epigenesis*, in which some force, some vital force, some uniquely biological force associated with life selectively caused the embryo to develop the specific form that it had—the specific limb structure, the specific skin color, etc.—and that what we needed to understand was that process, that selective process by which form was added to the embryo as it gestated within the womb, in the case of mammals, for example, or within the egg. And that became the key problem; because for reasons that I mentioned in an earlier lecture, preformationism became perceived to be increasingly silly, or at least certainly impossible to continue considering.

So we have, in the 18th century, one focus of biological research on embryological development with a view to understanding how form develops in the embryo, and this is in fact the question of the inheritance of characteristics, inheriting the form characteristics of the parents. Collaterally, there is a growing interest in this problem of the constancy of type. There had been in botanical and zoological circles, especially from the 16th century on, major intellectual battles fought over what I will call the taxonomy problem. How can we organize the tens of thousands of new forms of plants and animals that we are beginning to get specimens of as Europeans started traveling around the world and bringing back to Europe specimens of plants and animals that did not exist in Europe?

So all of a sudden, old-fashioned ways of books and botany which just listed them, or listed them alphabetically—that was a major achievement in the 16th century, at least alphabetical ordering—now the books are so big, and now we have so many specimens, that we have the problem of how are we going to organize them? We talk loosely of genera and species, for example. Later the terms classes and orders were added, and kingdoms and phyla.

Do these represent natural classifications or are they conventional? Is there really such a thing as a species or is that just a convenient way of organizing a group of plants or animals that seem to be very similar to one another and that breed true to type? Is breeding true to type a sign that there is a natural system for classifying plants and animals, that the type is a fact about each living thing, what each living individual is an instance of—it's an instance of a specific species, of a specific genus, of a specific order, a specific class, etc? And this came to something like a head in the 18th century.

One of the most famous people in this protracted battle over the taxonomy problem was Carl Linnaeus. The Linnaean system of classification was based on the natural view that there really are species and genera in nature, and that they can be identified through characteristics of the individual. And in fact Linnaeus picked sexual characteristics of plants in order to identify the species and the genus, believing that the sexual organs of the plants were in a certain sense most fundamental in terms of the reality of the individual. They revealed the type that the individual belonged to.

At the very end of his life, Linnaeus seemed to have acknowledged that in fact his natural system failed and that, after all, his organization was conventional, not real. This is important, because if species are not real then the transmutation of species associated with evolutionary theories is not that radical. The transmutation of species is only an issue if you in fact believe that there are natural types that individuals fit into. This is analogous to an earlier lecture in which I said Plato said "the natural philosopher has to carve nature at its joints." That's what scientists have to do. They have to find the natural joints that divide one form of life from another, for example in our present context, and then they have to give names to those natural divisions of things so that when you say that something is a mammal you're not merely saying it's convenient to call these creatures mammals. You are identifying something fundamental that they all have in common and that distinguishes them from every other living thing in a way that's rooted in their being, not just by convenience.

So, for example, with regard to books we have such things as biology books, biography books; we have history books; we have books in science; we have books about travel. And the question is—these categories make sense; they describe something about the books, but they do not really distinguish a travel book from a book written in the 18th century by a biologist who traveled from country to country and made observations about the people and their institutions, as well as the plants and the animals in that country. So now we have a book that's historical, that's biological, and that's travel: so what category do we put that into? So we begin to see that the categories we generally use are typically conventional, not natural. Now, having said that, it is also the case that these conventional categories do correspond to something in the real world.

So this taxonomy problem is related to the problem of inheritance and embryological development, and it brings with it this notion of sexuality. That's what Linnaeus had isolated as the key to understanding the type that individual plants and later animals belonged to. And so the question began to be raised in the 18th century, is the process of sexual reproduction itself responsible for individual variation? And that's the last piece of the puzzle, because it was in the 18th century that the sexuality of plants was first proposed by a naturalist called Camerarius.

It was very controversial right into the mid-19th century. And now we have, in the 19th century, we can see the context out of which the gene idea emerged as a way of resolving this complex problem involving embryological development, inheritance of characteristics, the whole question of the constancy of types. And we have to add to that the growing sophistication of biological research using increasingly powerful microscopes that gave biologists insight into the structure of cells so that, especially from the 1860s on, and increasingly after the 1870s with a new generation of improved microscopes, biologists were saying, as Ernst Haeckel did in 1866, that something in the nucleus is responsible for the inheritance of characteristics.

Now in the 1870s and the 1880s, we have Walther Flemming saying that within the nucleus there's a structure called the chromosome—it's something on the chromosome. In the 1880s, August Weismann offers what came to be called the germ plasm theory of inheritance. He published that in a textbook about 10 years later, in which he specifically cites sexual reproduction as the source of individual variation, that a substance on the chromosomes is responsible for what we call genetics, and isolates the germ plasm. That is to say, there is some substance that comes from the father in the sperm, something that comes from the mother in the egg, and that these fuse in forming the embryo and provide the key to the inheritance of characteristics.

Now, everybody knows that Mendel invented genetics, so where's Mendel in this story? Well, that's a really peculiar feature of the history of the gene idea. Between 1856 and 1865 this Austrian monk, working in the city of Brno in what was once Czechoslovakia, that Mendel did breeding experiments in order to pursue—if possible, prove—an evolutionary theory that his biology professor at the University of Vienna, Franz Unger, had formulated. And so he designed these experiments, not with a view to inventing genetics, but with a view to confirming, if possible, his teacher's evolutionary theory, quite independent of Darwin's, because Darwin did not publish until 1858, 1859.

So Mendel did these experiments and he used, among other things but primarily, 22 varieties of edible peas that specifically reproduced with constancy to type. He picked the pea because a Scottish biologist named Thomas Knight had done a lot of hybridization experiments with edible fruit trees. And so Mendel, who, like Darwin, carefully studied hybridization and cross-breeding experiments that were done over the previous century by a wide range of biologists in order to test constancy to type, did these experiments, collected his data, gave a report on them in 1865 to his natural historical society, published them in their journal—which was distributed to a number of prominent people, but very few read it—and then drops out of the story. He becomes administratively involved in his monastery, and he drops out of the story.

It was in the late 1880s and 1890s that a number of biologists sort of rediscovered Mendel's work, but after they had independently come to the conclusion that there was something in the cell, something in the nucleus, something on chromosomes that was a discrete unit of inheritance, that coded for specific characteristics. The key idea being the idea of segregation, that there is some specific unit from the mother, a specific unit from the father, and the union of these units gives rise to the characteristics that the offspring possesses.

The key person was a Dutch biologist named Hugo De Vries, and De Vries published a theory in 1889 which was essentially Mendel's work three years before he discovered Mendel's paper. In a survey of hybridization experiments there was a footnote referring to Mendel and his results, and when he looked it up in 1892, he discovered that he had been scooped, so to speak, and he gave Mendel full credit for this, although obviously this must have been disturbing to him.

In the rest of the 1890s, at least three other biologists also accidentally rediscovered Mendel after they had formulated their own ideas; perhaps Carl Correns is the only one who really deserves parallel credit, although De Vries did more of the work, developed a more sophisticated genetic theory on his own. Tschermak and Bateson also were studying the same problem, and history books often talk about what an amazing thing it is that so many people rediscovered Mendel at the same time. But it was really De Vries's work, because he then built on this and published a book on mutation theory in which he argued that mutations in these genes were responsible for variation, and that they were the key to Darwinian evolution, not natural selection. This became a serious debate in the early 20th century.

So now these people were the ones who named Mendelian genetics. They gave Mendel credit for really something that he had earned no credit. If Mendel had not existed, it would not have made the slightest difference, as nearly as I can tell, to the development of genetic theory. And that's a very interesting thing about the history of science. Like Copernicus, Mendel gets a lot more credit than he deserves in terms of the actual development of the theory.

And so now we see how the idea of the gene emerges, but in a very complex form, with a hint that there is something on a chromosome, a substance on chromosomes that is responsible for inheritance. And this something, initially believed to be a protein right through the 1940s, becomes in 1953 the DNA molecule of Watson and Crick; which by 1957 Crick and Leslie Orgel, following a hint from the physicist George Gamow, figured out the so-called genetic code as we know it.

We'll be talking more about the specifics of DNA as the inheritor to what the gene is—the maturation of the gene idea—in a future lecture on molecular biology, but here we see something of the gene idea as another instance of the atomistic style of thinking.

Lecture Twenty-Two
Energy Challenges Matter

Scope:

Motion and forces have been central to the explanation of change—the root problem for natural philosophy since the ancient Greeks—but the ultimate reality until the 19th century was matter. Even for early modern science, matter was the subject of change, matter and its motions alone were conserved, and forces inhered only in matter. The metaphysical dominance of matter was undermined in the mid-19th century with the introduction of the idea of energy. Energy achieved formal recognition as a feature of reality parallel to matter in the new science of thermodynamics. Now energy, too, was conserved, and it was endlessly convertible among numerous immaterial forms. The idea of energy stimulated process theories in science in which patterns and relationships were real. By 1900, it was proposed that energy alone was ultimately real.

Outline

I. The fundamental features of reality for early modern science were matter, motion, and forces, but in the mid-19th century, energy was added to the list.

- **A.** The idea of energy as an elementary feature of reality required a conceptual reorientation for scientists.
  1. Energy does not fit well with the atomistic style of thinking.
  2. The 19th century witnessed the flowering of this atomistic style in the atomic theory of matter, the cell theory of life, the germ theory of disease, and the gene theory of inheritance.
  3. The creation of a new science, thermodynamics, in response to the idea of energy posed a challenge to mechanics, the reigning science of matter in motion.
  4. Thermodynamics forced a reconceptualization of time, because the role of time in thermodynamics is inconsistent with the role that time plays in mechanics.
  5. There is a peculiar irony here—what philosophers might call a Hegelian irony—in the atomistic style of thinking being undermined at the height of its apparently decisive triumph.
- **B.** Recall that the core problem for science is explaining change.
  1. The Parmenidean/atomistic approach to this problem is to reduce change to the interactions of things with changeless properties.
  2. The Heraclitean/process approach to explaining change is to accept change as real and irreducible, and to seek the patterns or laws of change.
  3. For the process approach, the goal of the scientist is to identify the distinctive properties, not of elementary things, but of processes.
- **C.** The focus of modern science, from Descartes on, was on explaining all natural phenomena in terms of matter in motion.
  1. From the time of Descartes to the mid-19th century, the center of attention was matter and the properties it possessed, including intrinsic forces, that explained its motions.
  2. In the mid-19th century, highlighted by the idea of energy, the center of attention became the motions of matter and the patterns or laws of those motions.

II. Heat may seem too prosaic a phenomenon to have provoked such a profound reorientation, but it did.

- **A.** Since the 17th century, attempts to determine what heat *was* proved elusive, in spite of its apparent simplicity.
  1. One view was that heat was motion and, thus, no *thing* at all.

2. The rival view was that heat was the escape of a weightless, invisible thing called *caloric* from an object.
3. No convincing case was made by one side or the other through the 18th century.

B. By the 19th century, disputes over the nature of heat had become bitter.

1. A new urgency to understand the nature of heat was lent by the commercialization of the steam engine beginning in 1775.
2. An attempt to resolve the dispute experimentally by Benjamin Thompson failed, in spite of its description as a success in science texts to the present day.

C. Thompson was convinced by his cannon-boring experiment, but many eminent figures were not.

1. Pierre-Simon Laplace held the caloric view to the end of his life.
2. John Dalton, whose book founded the modern theory of the atom, wrote about as much in that book about caloric as about his atomic theory of matter.
2. Furthermore, Sadi Carnot, an engineer who produced the first scientific analysis of heat engines, also supported the caloric theory.

III. What Carnot contributed to a scientific revolution was every bit as profound for science as the industrial revolution was for society.

A. Carnot set out to measure the efficiency of a heat engine.

1. Using the caloric theory of heat as his framework, he sought and found a quantitative relationship between the fuel burned in a steam engine and the amount of mechanical work produced.
2. Carnot found a limit to the efficiency of any heat engine, regardless of the design, that is still accepted today.
3. In the course of this analysis, Carnot had to define *work* as a *scientific* idea.
4. Fortunately for Carnot, Émile Clapeyron formulated his mostly qualitative ideas mathematically, bringing them to the attention of physicists in 1830.

B. Carnot's ideas belong in the broader context of a discussion of forces in early-19th-century physics.

1. Descartes' mechanical philosophy of nature allowed only contact forces among moving material objects.
2. All natural phenomena had to be reduced to the consequences of collisions among moving matter.
3. Newton embraced a range of non-contact forces, forces acting at a distance, to explain gravity, electricity, magnetism, optical phenomena, and chemical combination.
4. Non-contact forces seemed the only way to explain the full spectrum of natural phenomena.

C. The growing list of forces that, by 1800, were scientifically respectable inevitably raised the question of relationships among them.

1. Were there relationships among heat, light, electricity, magnetism, gravity, mechanical forces, and selective chemical combination?
2. The electric battery proved an important new scientific instrument, replacing spark-generating devices.
3. Humphrey Davy used continuous current to decompose molecules into their elements, revealing a relationship between electrical and chemical forces.
4. Sadi Carnot showed a relationship between heat and mechanical work.
5. Hans Christian Oersted showed that electricity and magnetism were connected.
6. Oersted subscribed to the so-called Romantic nature philosophical movement, whose members believed in the fundamental unity of nature and, thus, the ultimate unity of all natural forces.

7. Michael Faraday extended Davy's work in electrochemistry and Oersted's observation of a connection between electricity and magnetism
8. Faraday invented the dynamo, which connects mechanical action (motion), electricity, and magnetism, and he showed that both electricity and magnetism affect light, suggesting that light is an electromagnetic phenomenon.

IV. These developments converged in the 1840s to produce the new science of thermodynamics.

A. The occasion for the convergence was the study of heat.

1. In the 1840s, James Prescott Joule did a series of carefully controlled, quite simple experiments to determine precisely Carnot's mechanical equivalent of heat.
2. Like Carnot, Joule supported the caloric theory of heat, but unlike Carnot, he did not believe that caloric was conserved.
3. William Thomson, later Lord Kelvin, was aware of Carnot's work (through Clapeyron) and of Joule's work, but he was inclined to the view that heat was motion.
4. Motion is conserved, so if there is a precise relationship between heat and motion, then *something* in this process is conserved.

B. While Joule and Thomson were studying heat, so were a number of Continental scientists, who also were looking for correlations among the forces of nature.

1. In 1847, Hermann Helmholtz published an essay claiming a new conservation law: the conservation of *Kraft*.
2. *Kraft* then meant "force" or "power," but in 1851, William Rankine co-opted the word *energy* to describe what was conserved and gave it a scientific meaning.
3. Thomson called the concept of energy the most important development in science since Newton's *Principia*.
4. From 1850, Rudolf Clausius formed the new science of thermodynamics around an expanded conception of heat as a form of energy.
5. The first law of this new science was that energy was conserved, and the second was that energy could flow only from a hotter body to a colder one, never the reverse.

C. Clausius identified a mathematical quantity he called *entropy* that was a measure of this irreversible flow of heat.

1. In 1853, Thomson announced that this idea implied that time was directional and irreversible, contrary to the role of time in mechanics.
2. Clausius proclaimed as a law of nature that entropy must increase in any closed system; this was soon taken to imply the "heat death" of the Universe.
3. This is reminiscent of the Newton-Leibniz controversy over whether the Universe needs to be "wound up" by God every now and then to prevent it from just this kind of death.

D. The idea of energy is a fundamentally new *kind* of idea in modern science.

1. Energy is real and energy is conserved, but there is no such *thing* as energy!
2. Energy occurs only in specific forms, but those specific forms are not conserved: They are interconvertible.
3. Note that we have no experience of energy in and of itself, nor can we have such an experience.
4. This enhances the distinction between atomistic science and process science, of which energy is a prime example.
5. By the late 19th century, it was proposed that energy, not matter, was the ultimate reality.
6. Furthermore, the energy idea was only one instance of process thinking in 19th-century science.

Essential Reading:

P. M. Harman, *Energy, Force and Matter*.

Y. Elkana, *The Discovery of the Conservation of Energy*.

Questions to Consider:

1. If *matter* is a name for certain stable energy patterns, what is the “stuff” of which energy is made?
2. Is the substantiality of the Universe an illusion, analogous to the illusion of continuous motion in motion pictures?

Lecture Twenty-Two
Energy Challenges Matter

I hope that your seatbelts are firmly fastened, because in this lecture we're going to make an abrupt change of direction. And as you know from the work in the 17th century mechanics, changing direction means a force has to be applied, and so we're going to be shoved in a new direction as we look at the idea of energy.

The idea of energy represents a reorientation of modern science because it is in a certain sense incompatible with the atomistic style of thinking. So here we have, in the 19th century, which is when the idea of energy becomes a scientific idea and becomes incorporated into a whole new science called thermodynamics, which literally means "heat force," that the dynamics of heat—that's thermodynamics—that the rise of thermodynamics in the middle of the 19th century occurs at the highest point of development, at what seems like the triumphal realization, of the atomistic style of thinking. The atomic theory of matter, the cell theory of life, the germ theory of disease, the gene theory of inheritance are all 19th century constructs.

And here we see unfolding an extremely powerful, explanatorily fruitful approach to studying natural phenomena, which is keyed to atoms, literally and metaphorically. A growing conviction that these atoms are real—immediate, universal acceptance practically in the case of the cell, a little more slowly in the case of the germ, split between chemistry and physics in the case of the physical atom, and in the case of the gene, at the end of the 19th and the beginning of the 20th century.

Right at the moment of the greatest flowering of the atomistic style of thinking, there is now emerging a subversion of the atomistic style of thinking from the side of process—the process style of thinking. The atomistic style of thinking is expressive of this Parmenidean substance metaphysics that I've been referring to throughout this course. The process side, which we haven't had much to talk about yet, but between the mid-19th century to the present it becomes increasingly important, and increasingly a source of many of the most important scientific ideas that emerge, associated with Heraclitus's theories that change is fundamental and that we need to explain natural phenomena in terms of change, not reducing change to timeless things. So that's process metaphysics.

So it's an ironic thing, consistent with the philosophy of Hegel, who held that the seed of transformation was always buried in the current stage of the status quo; that the status quo contained within it at any given time some contradiction that undermined the status quo and led to, so to speak, in Hegel's case, the next phase in history. Hegel, of course, I've referred to earlier as the rationalist philosopher who tried to introduce time into deduction, because in the 19th century time had become such an issue for philosophers and then for scientists, as I discussed in the lecture on time.

So it's kind of a cute thing that, from a Hegelian perspective, the triumph of the atomistic style of thinking is now being sort of eaten away by the rise of the non-atomistic style—a process style of thinking. The fundamental problem for science, as I've referred to in a number of lectures, is explaining change. That is in a certain sense the core mission of science—explaining change. And modern science explains change in terms of matter in motion.

The Parmenidean approach is to say that the explanation of change by way of matter in motion is to focus on matter and its properties. So "thinghood" is the key. Atoms are things, cells are things, germs are things, genes are things. They have properties. Their properties are what explain change.

The Heraclitean approach—and by the way, Hegel, in his perhaps most accessible book, *The Phenomenology of Spirit*, sometimes translated as *The Phenomenology of Mind*, uses Heraclitus very much in the introduction to explain what he is trying to do, to bring Heraclitus's process view into the Parmenidean character of deductive reasoning. The Heraclitean view is to say we have to explain change by way of matter in motion by focusing not on matter, not on things, but on motion, on the nature of the process. Processes must also have properties, and they must be relatively fixed properties, because otherwise we won't be able to predict the future, if anything can happen at any time. We've seen this, that's the key to science in any event, the reason why *things* have fixed properties. So processes have to have fixed properties.

And so the focus now shifts from matter to motion, broadly speaking, to processes. And perhaps it may seem odd that something as relatively innocuous and unsophisticated as heat, the study of heat, should be the occasion for this fundamental reorientation of the direction of science from the mid-19th century to the present. We will talk in the next few lectures about the great ideas in the 19th century associated with this orientation.

The study of heat was problematic because at least since Francis Bacon, at the beginning of the 17th century, there had been contrary views of heat. One view holding that heat was simply the motion of particles of matter, and therefore it was not a thing at all. It was a name for motion, for a particular kind of mechanical process. The other view holding that, no, heat is a thing called *caloric*. It's a weightless fluid. Everything is loaded with caloric and when we say that something is hot what we're saying is that for a variety of reasons the caloric is escaping from that thing. A thing is hot when caloric is leaving that thing. When something burns it's losing caloric. Caloric is a thing.

Alternatively, heat is merely a name for the motion of the tiny parts of which matter is composed, and if you make the particles move very rapidly, for example, by rubbing them together through friction, it gets hot because now they're moving more quickly. Notice, you can't see that happening, not even with the microscope, and you can't see the caloric. It is defined in a way that it is in a certain sense not detectable except by its release. So we say, there is caloric coming. That thing is hot; it's losing caloric.

This controversy became increasingly nasty around the turn of the 19th century, and while we think that all sophisticated people were on the side of those who held that heat is motion, as a matter of fact, some of the most eminent scientists of the late 18th and early 19th century strongly believed that heat was caloric, that heat was this weightless fluid that escaped from what we call "hot bodies." They were hot because they were losing caloric. This debate was lent urgency by the introduction of improved steam engines, which were now becoming important commercial objects starting in the last decade or so of the 18th century. And with increasing rapidity in the first half of the 19th century, steam engines powered the new industrial revolution, and the performance of steam engines was very important commercially. Belatedly, scientists began to pay attention to that.

But let me refer to what was supposed to have been a crucial experiment that established that heat was motion, not a thing. This experiment was done by an odd character, a British subject who lived in America at the time of the Revolution, sided with the king, and so was uncomfortable by the outcome of the Revolutionary War. He left America and went back to England, and had a very bizarre career in England, France, and what became Germany over the next decades, along the way marrying Lavoisier's widow and becoming a count, and so he called himself Count Rumford. He decided that he could show, once and for all, that heat was motion. He set up a canon-boring machine, cast-iron canon, the central cylindrical hole in the canon being bored by an iron boring device. And this was in a very large tub of water, and then as the boring device bored the hole in the cast iron blank that the canon was to be made from, the water got hotter and hotter and started boiling. It kept boiling (and you had to keep adding more water) for days, as teams of horses turned the boring machine and kept the cast iron hot enough to boil the water. After a while Rumford said it's obvious that there can't be an infinite amount of caloric in this cast iron. This proves once and for all that heat is motion.

Well it didn't prove it once and for all because, for example, Pierre Simon Laplace, one of the greatest mathematical physicists of that time, quite familiar with all of this work, believed to the end of his life that heat was caloric. John Dalton, who we see as the father of the atomic theory, spent almost as much time in his book that founded the modern theory of the atom defending the caloric theory of heat as he did the atomic theory of matter.

And, interestingly, a French engineer, Sadi Carnot, was interested in the performance of heat engines—not in an abstract scientific theory of heat, but in the performance of heat engines—he believed in the caloric theory of heat. In a book that was published in 1824, which expanded work of his engineer father back in the 1790s, but with many original contributions of his own, Sadi Carnot argued for a law of conservation of caloric because of course there could not be an infinite amount of caloric, as Thomson pointed out in his experiment. So there must be a law of conservation of caloric. But what he did was he set up a relatively simple quantitative relationship between the mechanical output of a steam engine and the caloric lost by the fuel that was used in order to create the heat for the steam engine, in order to transform the water into steam. So you have to use a certain amount of fuel, let's say coal is burned. That coal uses caloric, and we can measure the efficiency of a steam engine by this quantitative relationship which tells us how much work (now work means how much mechanical output did we get from this machine) given this much fuel, given the burning of this much fuel.

These ideas were expressed relatively qualitatively, except for this quantitative relationship having to do with work. So he redefined work, and work now becomes a scientific term and a scientific idea. Not the sort of thing where you get dressed in the morning and you go to work, but that work refers to a very specific scientifically defined quantity; in his case, the relationship between fuel consumed and mechanical output.

These ideas were formulated mathematically by a physicist named Émile Clapeyron, and published again, giving Carnot full credit, and came to the attention of a wider range of physicists who probably would not have looked at Carnot's monograph, which were reflections on the mode of power of heat, which he had published in 1824. But Clapeyron's version contained this same idea relating heat and mechanical work.

Now we have to step back for a moment and say there is something else going on in the background that is very important to the emergence of the idea of energy, and that is another controversy within science over the nature of forces. We have referred to this a number of times. The strict Cartesian view was that the only force that scientists could use in order to explain change by way of matter and motion was mechanical contact. That was Descartes's restriction. For him that was what made philosophy of nature scientific and rational, it only referred to contact forces, because those we could in a certain sense see happening. We needed to quantify those forces and identify the forms that they could take—for example, gravity, electricity, magnetism—and then we would be required to, on this view, explain all natural phenomena in terms of contact forces.

Now I've referred to the fact that, even by the end of the 18th century, Newton gave up on that and claimed that we needed to assume that there was a force called gravity, that whatever it was, it was not a contact force. Electricity and magnetism and chemical attraction and the interaction between light and matter, Newton believed that there was a force that material objects exerted on light, on his little atoms of light, that all of those were non-contact forces. He didn't believe they were mystical, but they were lawful, and they obeyed quantitative relationships as his mathematical theory of gravity did; but they were not contact forces.

In the course of the 18th century, this Newtonian emphasis of force-based physics and chemistry conflicted with the Cartesian view, but even the Continental Cartesians simply absorbed the Newtonian force physics. And increasingly this was necessary, because more and more attention was paid, especially in the second half of the 18th century, on the study of electricity (secondarily magnetism). People were beginning to do lots of experiments with electricity and magnetism; discovering the law of electric charges and magnetic attraction and repulsion, that these obeyed a law analogous to Newton's theory of gravity. The laws had the same form as the form of Newton's equation for the action of gravity.

And so we had this set of forces: heat was in some sense a force; electricity is a force; magnetism is a force; and of course mechanical contact is a force. We have a suite of forces, and we ask, are there any relationships among these forces? Well, at the end of the 18th century, through the work of Luigi Galvani and Alessandro Volta, the battery was invented, electric current was discovered and was sort of captured in the batteries, so that much more sophisticated experiments could be done with electricity than when we only had sparks to deal with. Among many other researchers, Humphrey Davy did work showing that you can electrically decompose molecules into Lavoisier's new "elements," and so there is a relationship between electricity and chemistry. We have a relationship between heat and mechanical action of work.

In 1820, a Scandinavian physicist, in the course of giving a class lecture in physics, made a startling observation. He had nearby a small battery hooked up to a little electric circuit, and nearby there was a compass that was not there for any specific reason, and as he was lecturing he sort of played with the on/off switch of the electric circuit he had set up to demonstrate to his students the flow of current electricity. And as he's lecturing he notices that the compass needle jumps every time he turns the electric current on or off—either way. So he gets through the lecture and then he starts studying this phenomenon systematically and publishes this. There is an interesting connection between electricity and magnetism. Without any physical connection between the electric circuit and the nearby magnetized compass needle, there is some kind of a relationship. The electric current generates some kind of a force that attracts the magnet.

Now, Oersted was himself sort of a member of the Romantic nature-philosophy movement, which was primarily rooted in Germany, and the Romantic nature-philosophers, for reasons having to do with their philosophy—and they included in their membership the great German poet and intellectual Goethe—believed that all the forces of nature were one. That this range of forces—electricity, magnetism, gravity, heat—that they were all fundamentally one force, that nature was at its deepest level unified. And Oersted thought that here was a contribution to proving that. Look at this. Electricity and magnetism are related somehow.

A few years later, Michael Faraday in England—who had been an apprentice to Humphrey Davy, who had done this work in electrochemistry showing this relationship between electrical force and chemical force because electricity can decompose molecules, break the bonds—Faraday devoted many years of his life to the relationship between electricity and magnetism, in the process inventing the dynamo, which is a way of getting an electric current out of the relationship between electricity and a magnet. So, discovering that if you move a magnet around a conducting wire, a current automatically flows through that wire. If you leave the magnet stationary, but move the conductor, then an electric current flows through that wire. In effect, there is an endless amount of electricity to be gotten as long as you continually move one or the other, either a magnet or a conducting wire, in the presence of the other. So again we have a relationship between mechanical action, electricity, and magnetism, so that we have such a thing as electromagnetism.

Faraday went on to show that electricity affects light, and magnetism affects light, leading him eventually to speculate that maybe light itself is an electromagnetic phenomenon. We see here a step-wise unification of the different forces of nature. Oh look, there are important connections between—and there is no such word; the scientific idea of energy hasn't emerged yet.

It was in the 1840s that a British physicist named James Prescott Joule did a systematic study of what Carnot had been talking about, looking for the quantitative relationship between mechanical action and heat, which is the measure of work. And he came up with equations describing how much heat you can get from mechanical action by rotating a paddle inside a beaker of water and measuring the temperature rise of the water as a function of the amount of what we would call energy that was put into the paddle—the rate at which the paddle turned, and how large the paddle was. So the amount of work that was done mechanically to rotate the paddled transforms into a specific amount of heat being raised in water, and in different fluids there is a different relationship.

Now Joule himself did not accept the conservation of caloric. He thought that caloric was consumed in the process of converting mechanical action into heat. But his work was familiar to William Thomson, subsequently named Lord Kelvin, who was familiar with Carnot's work through Clapeyron and recognized that if you assumed that matter was atomic, which Thomson was not inclined to do at the time, and if you assumed that heat was motion, not caloric, then it looked to him that heat had to be a conserved quantity. Something was being conserved here, although we don't know exactly what it is that's being conserved in Joule's experiments. It can't be the caloric, because he's saying "heat is motion" now, and not caloric.

In the course of the 1840s, a number of researchers were looking into the convergence of all of these ideas that I've been referring to. Finally, in 1847 the German physicist Hermann Helmholtz published a monograph which explicitly announced, so to speak, the conservation of *kraft*—the German term *kraft*, which really means more like force or power. But in 1850 the British physicist William Rankine sort of adopted the word *energy*, giving it its scientific meaning. And the conservation of energy now emerged as a fundamental principle.

I must say, the centerpiece of this work was the heat studies. It was a kind of a bonus that we had in the background going on the recognition that chemical forces, electrical, magnetic, light, gravity, they are also forces and forms of energy, and they also figure into this new concept of energy. Kelvin shortly afterwards identified it as the most important development in physics since Newton's *Principia*—since Newton's theory of gravity—because he recognized that this fundamentally altered the character of physics, moving us away from the atomistic style of thinking towards a process view.

A new science emerged in the 1850s, especially through the work, among others, of Rudolf Clausius, that acquired the name thermodynamics, which shows the central role of heat in all of this. And the science of thermodynamics includes within it as its first law the conservation of energy. Energy can neither be created nor destroyed. Not just heat energy; whatever form it takes, energy can be transformed, but it cannot be created or destroyed. And the second law is the famous one, that heat can only flow from a hotter body to a colder body. It cannot flow from a colder body to a hotter body.

Clausius identified a mathematical quantity associated with the flow of heat that he gave the name *entropy*. He pointed out that in all natural processes, in all processes in a closed system where energy is not flowing into the system, this mathematical quantity called entropy always increases. It never decreases.

And just a few years later, maybe even a year later, Kelvin, reading Clausius, recognized that this means that time is irreversible; so the arrow of time emerges within thermodynamics out of the recognition that energy in a system always becomes to some degree unavailable. It's not destroyed; it simply becomes unavailable. This is a very controversial notion, and in a later lecture on self-organization, we will see how in the last third of the 20th century the notion of entropy was qualified. But at the time it was recognized that this implies what was called the *heat death of the universe*; that in time, the universe is going to become cooler and cooler; it's going to lose energy. It's going to take a long time, but eventually the universe is going to die.

This goes back to that controversy between Newton and Leibniz over whether the universe needs to be wound up, and that back to the 13th, 14th century metaphor that the universe is a clockwork mechanism. God created the universe in the beginning. Did God create it in such a way that it will go on forever, or does it lose a little bit of motion, momentum, energy? The concepts are redefined over the last eight hundred years, but here we have the idea that, no, it turns out that Leibniz was wrong on this one, and that the universe in fact is winding down. There is an end to all structure, order, to life especially, as energy increasingly is lost with entropy increasing—lost in the sense it becomes unavailable, in the same way that if you drop a tennis ball from a height of three feet it cannot bounce back to three feet. A certain amount of energy is lost as friction when the ball deforms when it hits the ground.

So the rise of the science of thermodynamics now brings into physics the idea of energy. Now, there is something fascinating about this idea of energy. Energy is only physically real in specific forms, but no specific form of energy is really energy. Energy has a generic character, but it only manifests as heat energy, gravitational energy, chemical binding energy, electrical energy, magnetic energy. You can convert electricity into magnetism; magnetism into electricity; and magnetism into light. You can convert heat into mechanical work. You can convert mechanical work into heat and into electricity. And there are strict rules about all of these transformations. That is why energy has to be conserved; because if it were not conserved, you would not have strict rules that there are limits to the transformation of one form of energy into another.

But we have no experience of, and there can be no experience of energy in and of itself. That is not because we don't have the instruments for it. It's because energy only manifests itself in specific forms, and yet we believe that each specific form is a specific instance of a generic phenomenon, and a generic quantity. It's the generic quantity that is conserved, not the specific form of it, because the specific form can be transformed.

So that is a fascinating idea in its own right, and it enhances the gulf between atomistic "thinghood" thinking and process thinking. And energy is immaterial. There is a conservation of matter, conservation of energy. Energy is not material, but it has the explanatory characteristics of matter. It has properties. Energy has properties. Energy exerts causal influences. It is a force that acts on material objects and changes them.

So by the middle of the 19th century, starting from the 1860s on, energy becomes an increasingly powerful idea in every branch of science. So much so that the Irish physicist, George FitzGerald, around 1880 developed a theory (we will talk a little bit more about this in the next lecture) in which matter itself is produced by energy; that matter is derivative, and that energy is the only fundamental reality, and that matter is just another form that energy can take.

So here is, I think, one facet of the rise of process thinking in science. We are going to explore a number of other facets of process thinking, undermining, so to speak, the atomistic style of thinking, starting especially from the second half of the 19th century; but only undermining it in the sense that it undermines the unilateral character of atomistic style of thinking, saying that *only* atomistic style of thinking is necessary in order to explain change. The process view does not deny that there is merit to the atomistic style of thinking, but we will talk more about that in future lectures.

Lecture Twenty-Three
Fields—The Immaterial Becomes Real

Scope:

It is ironic that the apparently climactic development of modern science in the 19th century saw the foundation of its conception of reality—materialistic determinism—undermined by developments internal to science. Energy was one immaterial reality, and electric, magnetic, and electromagnetic fields were another, soon to be supplemented by the aether field and field theories of gravity. The idea of the field went deeper into the metaphysics of modern science than adding new immaterial realities, however. The seemingly insurmountable difficulty of formulating a plausible physical mechanism for the action of fields, for how they transmit energy and forces, led to a reconceptualization of the nature of scientific theories. It became increasingly orthodox to argue that scientific theories described human experience, that their truth was not a function of correspondence with a reality existing independent of experience, but of our evolving experience of how nature behaves.

Outline

I. The introduction of fields as elements of physical reality in the 19th century was epochal for the evolution of modern science.

- **A.** The idea of the field is related to the idea of energy.
  - **1.** Energy is real, but it is not material, hence not a thing in the traditional sense.
  - **2.** If it is not material, it should not be real, according to the dominant modern scientific view that all natural phenomena are caused by matter in motion, as in Laplace's famous declaration of the exhaustiveness of materialistic determinism.
  - **3.** Energy is immaterial but lawful action in the spirit of Heraclitus: to understand nature is to understand its *logoi*, its laws or rules.
- **B.** But the law that energy must be conserved, that all forms of energy are interconvertible only in rule-governed ways, does not tell us *how* energy acts.
  - **1.** How is electrical energy, for example, transmitted within a conductor or propagated through space?
  - **2.** The broader issue is the continuing concern over the nature and the reality of non-contact forces, forces that act at a distance but are nevertheless consistent with science, as Newton said, not magical, as the Cartesians said.

II. The central role in the idea of fields of energy and force as the solution to how energy and forces act was played by a self-educated, working-class Englishman named Michael Faraday.

- **A.** Faraday's researches in electricity and magnetism, largely qualitative because he was weak in mathematics, brought the issues latent in Newtonian action-at-a-distance physics to a head.
  - **1.** Electromagnetic induction led Faraday to theorize about how electric and magnetic forces propagated through space and through conducting bodies.
  - **2.** Rejecting both the reality of a vacuum and action at a distance, Faraday speculated that "electrical bodies" were surrounded by a "dielectric" medium that, when stimulated by a flow of current, created a state of "electric tension" transmitted through the medium that caused a current to flow in a nearby body.
  - **3.** In fact, he proposed that all of space was filled by a form of matter for which he adopted an ancient Greek name, *aether*.
  - **4.** The aether (or ether) constituted an absolute backdrop for ordinary matter and its interactions, its contiguous particles carrying and propagating electric, magnetic, and electromagnetic forces and light.

B. From his electrochemical studies, Faraday concluded that molecules were electrically polarized and, thus, responsive to electrical forces.

1. For years, Faraday gave different accounts of electrical and magnetic phenomena: mathematical, in terms of lines of force, and physical, in terms of the action of polarized contiguous particles.
2. Faraday believed that the lines of force were physically real and sought, unsuccessfully, a theory that described them as embodied in matter.
3. In 1844, Faraday definitively gave up the atomic theory as physically real.
4. His position was that matter was continuously distributed in, but not identical with, space, which was property-less.

C. In rejecting atomism, Faraday explicitly denied the impenetrability of matter and its indivisibility.

1. In 1845, Faraday used the term magnetic *field*, which quickly caught on, and in 1846, he proposed a physical interpretation of his lines of force as reflecting the structure of matter.
2. Faraday was influenced by experiments showing that magnets could rotate a light beam, suggesting that light was, in fact, an electrical phenomenon and that the lines of magnetic force were physically real.
3. This conclusion was further reinforced by his 1852 experiments with iron filings, which he considered a definitive demonstration of the physical reality of magnetic energy fields and the means by which they acted.

III. Faraday's ideas were developed by others with better mathematical skills, especially William Thomson and James Clerk Maxwell.

A. Thomson was a major influence in science generally and in public affairs affecting science.

1. In the 1840s, Thomson noted the implications of Fourier's "analytical" theory of heat and an analogy between the form of Fourier's equations for the flow of heat and the equations describing Faraday's electrostatic forces.
2. This suggested the possibility of a physical analogy, as well; that is, he asked: Do electric and magnetic forces "flow" through a medium analogous to the flow of heat by way of contiguous material particles?
3. Fourier's example notwithstanding, Thomson devoted decades to the search for a mechanical model of the aether from which its functions as carrier and transmitter of non-contact forces could be deduced.

B. The idea of the field reached maturity in the work of James Clerk Maxwell.

1. Maxwell took up the problem of a physical model of the aether that would satisfy the criteria of Faraday's field concept.
2. The problem was complicated by the need for the aether to carry and propagate non-contact forces without absorbing any of their energy or interfering with the motion of the planets.
3. In addition, a new wave theory of light had displaced Newton's corpuscular theory by the 1850s, and the aether was a "natural" medium for those waves, but it now also had to transmit light waves without affecting them in any way.

C. In 1865, Maxwell published a truly epochal work in physics titled "A Dynamical Theory of the Electromagnetic Field."

1. Maxwell united electricity, magnetism, and light into a single mathematical framework, interrelating them by a single set of equations from which all relevant phenomena could be deduced.
2. The field was now firmly established as physically real, but Maxwell had "settled" for a strictly mathematical description of it, à la Fourier's theory of heat.

3. In 1873, Maxwell argued that there were an “infinite number” of hidden physical mechanisms that could generate observed behaviors, while a single mathematical description could be confirmed empirically.
4. The mathematical theory satisfies all the empirical requirements without specifying the physical mechanism involved.
5. Note well, however, that regardless of the physical mechanism, the field is fundamentally incompatible with atomism.
6. Where the atom is localized in space and discrete, the field fills all of space and is continuous.

D. Maxwell could not altogether give up the underlying physical mechanism.

1. Descartes had argued that knowledge of nature had to begin with hypothetically assumed premises because God could have created Nature in an infinite number of ways.
2. Maxwell noted that an infinite number of physical mechanisms could generate the relevant observed phenomena, but after all, the aether-field *is* real and must have *some* form, so he continued to attempt physical models!

E. In the last third of the 19th century, there was near unanimity among physicists that the aether was the physical realization of real fields that transmitted energy and (non-contact) forces.

1. There was vigorous disagreement among physicists over the nature of the aether, its physical form, and structure, but no disagreement over its reality right into the 20th century.
2. The Irish physicist George Fitzgerald championed an electromagnetic aether against the material theory of the aether proposed by Thomson (by then, Lord Kelvin).
3. Fitzgerald argued that the electromagnetic aether was the ultimate physical reality, with matter merely a stable electromagnetic energy pattern, or “knot,” in the aether.
4. This is, of course, a complete turnabout from the atomistic style of thinking because now atoms *become* energy!

F. Physicists attempted to measure the physical effects of the aether, especially the Earth’s velocity relative to it.

1. Sophisticated experiments by Albert Michelson and Edward Morley using a new instrument of Michelson’s design yielded zero.
2. Fitzgerald and Hendrik Lorentz, independently, explained this by noting that if both the aether and all matter are electromagnetic, then matter in motion and the aether must interact in such a way as to cancel the effects sought.
3. This solution made the electrodynamics of moving bodies a central problem in physics, and in 1905, Einstein published a paper that confirmed the mathematics of the solution but dissolved the aether.

Essential Reading:

P. M. Harman, *Energy, Force, and Matter*.

Mary Hesse, *Forces and Fields*.

Questions to Consider:

1. Practically speaking, what difference does it make to us if scientific theories are true because they describe reality or because they describe experience and tell us nothing about reality?
2. Is it enough to say that a scientific theory is true because it “works” in practice, allowing us to control experience?

Lecture Twenty-Three
Fields—The Immaterial Becomes Real

The subject matter of this lecture is the idea of the field. A somewhat abstract idea, but one that becomes concrete in terms of physical reality in the course of the 19th century, but without ever becoming a "thing" in the classic atomistic sense.

The idea of the field is closely coupled to the idea of energy. It is a natural response to the growing recognition that energy is a constituent of physical reality without being a classical substance, without being a material thing. It is something, but it is not a material. Notice that this is a serious problem for the dominant materialistic determinism of 18th and 19th century science. Whether Cartesian or Newtonian, the 18th and 19th century natural philosophers were committed to a materialistic determinism that all natural phenomena can be explained in terms of matter in motion.

This is what Laplace had given voice to, that idea that if we knew the position and the momentum of every particle of matter in the universe at a given time, we could predict the future and retrodict the past with unlimited precision. That is an expression of this commitment to materialistic determinism, but here we have, in the case of energy, a recognition that an immaterial something is also physically real as signified by the fact that it exerts forces. It acts as a cause, and therefore we have to attribute physical reality to it, and we cannot explain certain kinds of natural change without reference to energy.

Indeed, today it's almost inconceivable to try to eliminate the concept of energy from physics. If you had a choice between either energy or matter, nowadays I don't think there'd be much of a debate that people would give up the ultimate reality of matter (physicists would) in favor of the ultimate reality of energy, if it really had to be an either/or decision. Energy is a kind of packaged dynamism. Energy puts a scientific bound around dynamism—action—and is scientific in the sense that we now define energy in a way that action is describable in terms of equations, for example, in terms of observing a conservation law.

And so this is, I think, quite literally a realization of Heraclitus's claim that change is fundamental, and that there are multiple *logoi*, in Greek—*logos* is the singular; *logoi* is the plural. He said there is not just one logos that guides the universe—logos here standing for rule or law, that's the way we would probably translate it today—that there is not just one law that controls everything going on in the universe, but there are multiple logoi. There are many rules that are characteristic of the multiple processes that are responsible for change in nature.

Energy is a way of sort of capturing and packaging in a way that modern science accepts action, change, the logoi underlying natural phenomena. But the question has to be, how are the forces that are associated with electrical energy, magnetic energy, gravitational energy, electromagnetic energy, light—how are they transmitted? How are they transmitted within a magnet, let's say, and how are they transmitted outside? How are they propagated through space?

Now the man who played a pivotal role in this was Michael Faraday, the very man who was responsible through his researches for showing that electricity, magnetism, and light are all intimately connected—and by the way, through his invention of the dynamo, he created another instance of 19th century techno-science that became extraordinarily important in terms of its impact on society; namely, the generation of electricity. Because although it took approximately 40 years, eventually Faraday's dynamo, which was central to electromagnetic theory in the 19th century, was commercialized and became electric generators that exploited the principle of the dynamo to generate electricity. And of course Thomas Edison built the first central electricity generating station in 1882, and just taking advantage of the fact that if you could mechanically rotate a magnet around a conducting wire, current would flow, and then you could distribute that electricity and use it to activate Edison's incandescent light bulbs.

Now the question that Faraday increasingly became concerned with was, how are these forces (the ones that he worked with especially: electricity and magnetism) propagated, and what is this process by which this takes place? And in the 1830s and 1840s especially, Faraday studied this, and published in this area.

Faraday is an interesting character. He came from a poor family that was in a particular sect within the Baptist church in England—a Sandemanian Baptist—and he became enamored of science, apparently having attended a public lecture at the Royal Institute in London which was designed to disseminate scientific ideas to the public. He eventually promoted himself to Sir Humphrey Davy as an assistant, became self-educated, and eventually took over Davy's position when Davy retired.

Faraday was weak in mathematics, because he was self-educated and he himself admitted that he didn't seem to have much of a gift for mathematics, which is odd given the increasingly intense mathematization of physics in the 19th century. But his qualitative understanding of the phenomena that he studied made him a very powerful and innovative thinker. Although it sounds incredible from our perspective, Faraday opposed atomism. He did not believe in the reality of atomism. He did not believe that there was such a thing as a vacuum in nature, and so, like Descartes, he believed that matter was continuously distributed and infinitely divisible; that matter was penetrable; that, in fact, two bits of matter could occupy the same space at the same time under certain circumstances. He was committed to ideas that were quite Cartesian even though at the time everybody, especially in England, considered themselves to be Newtonian.

What Faraday required was a medium for the transmission of, especially, electric and magnetic forces. And he proposed that there was, in fact, a new form of matter that completely filled space, and that is why there was no such thing as a vacuum up there in interstellar space, let's say. The entire universe was filled with a form of matter that was called *aether*, from a Greek term, and that in addition to the ordinary matter, there was this background stuff that literally filled the universe and was the background to all natural phenomena, and manifested its presence through the transmission of such immaterial forces as electricity, magnetism, and electromagnetism. And then the question comes up, well, how about gravity, how about chemical? Set that aside for the moment.

In 1845 Faraday introduced the term *field* to describe the way that electric and magnetic forces existed within this material medium, this aether (I'm going to call it aether, not aether, because it sounds pretentious). The aether is the substrate that electric and magnetic forces exist in, and the field is a way of referring to the way that electric and magnetic influences flow through the aether, the way they propagate (are transmitted) through the aether.

So Faraday supposed that matter comes in the form of electrically polarized molecules. How can you have molecules without atoms? Better not to ask. The matter comes packaged in electrically polarized, let's call them molecules (but they are not truly atom-based molecules in the sense that we talked about the atomic theory of matter), and that's what gives rise to electric and magnetic forces. And the fields surround, through what he called initially a dieletric medium—there is a kind of an electric medium that surrounds electrically charged particles; a magnetic field that surrounds magnets—and these are clearly immaterial, but they are real because, for Faraday, they are embedded, so to speak, in this material aether that fills all of space. So it's not mystical. He is proposing some kind of mechanical material model here for what he called the electric field, the magnetic field. Later we'll see it becomes more famous as the electromagnetic field when we unite electricity, magnetism, and optics.

Faraday proceeded along two lines of thinking sort of simultaneously. That is, he sometimes referred to the field in its physical manifestations, to electric and magnetic forces in a physical way, giving a mechanical explanation of them. Then sometimes he just referred to them mathematically, using a very simple mathematical description, and then he talked about lines of force. There are magnetic lines of force, there are electrical lines of force, and that is the way one electrically charged particle attracts or repels another electrically charged particle, depending on the charge, and the same thing for magnets. And the way that magnets and electrically charged particles interact is also through these lines of force, which initially he described mathematically.

But in the middle of the 1840s he started referring to these mathematical lines of force as physically real and as manifestations of the underlying structure of matter; that these lines of force told us something about the internal constitution of matter at the most fundamental level. And he did an experiment which clearly affected his thinking and still affects lots of people's thinking, which is extraordinarily simple, but it allows us to visualize these lines of force. He sprinkled very fine iron filings on a piece of, let's say paper (in high school we generally did it on a piece of paper); and you hold a magnet underneath and you sort of move the magnet around a little bit. What happens is that the iron filings (and I'm sure you've seen this), the iron filings line up and form visible manifestations of these lines of force—a sort of football-shaped concentric, roughly elliptical line, so that the whole thing looks a bit like a football. But they are very specific lines that are separated from one another, and if you shake them up again and do the thing over again, you'll get those same things back.

So Faraday saw this as a physical manifestation of his mathematically described lines of force, and that reinforced his view that what we were seeing here in fact was a manifestation of the underlying mechanism by which, within nature, electricity and magnetism propagated and existed in terms of the form of the structure of matter; so that matter had an intrinsically electrical structure. On the outside it looked electrically neutral, but on the inside it had an electrical character.

Faraday is the key player in the development of the concept of the field into the 1840s, when William Thomson (Lord Kelvin)—the same fellow who sort of intervened in Joule's experiments on the mechanical equivalent of work, converting mechanical action into heat, and brought Carnot's and Clapeyron's ideas together with Joule's and sort of redirected them away from the specific form that Joule put his results in—Thomson intervened here in Faraday's researches. He was familiar, being a mathematically oriented physicist, with the work of Joseph Fourier, a French physicist who after many years of having problems getting it published, finally published in 1822, 1823 an essay of his called *An Analytical Theory of Heat*. What Fourier did was to say, "Look, I want to get away from this whole controversy that's ripping a part of the physics community apart about whether heat is motion or heat is caloric. I have come up with a set of equations that describe the flow of heat, independent of whether heat is caloric. Whatever it is—I don't care what it is. What I can tell you is how it behaves. My equations describe how heat behaves."

What Thomson noticed was that the form of those equations was strikingly similar to the form of the equations describing the flow of electricity and magnetism through these fields that Faraday was developing. Using mathematical tools that Faraday did not have, Thomson decided that there must be some kind of physical analogy at work as well here. That it's not just a curious mathematical coincidence that these equations describing the flow, metaphorically speaking, of electricity, the propagation of electromagnetic forces, have a similarity in form to the equations describing the flow of heat in a thermally conducting body. There must be some physical connection, and that gives us some clue as to what the aether must be like in order to support the transmission of electric and magnetic forces—what the field must be like. He persisted for decades in attempting to come up with a mechanical model that did justice to the increasingly sophisticated mathematical description of the aether and electric and magnetic fields.

James Clerk Maxwell, the great Scottish mathematical physicist of the 19th century, especially the second half of the 19th century, one of the handful of the greatest of all physicists of all times, right up there with Archimedes and Newton and Einstein, Maxwell picked up on this problem and initially tried to advance Faraday's and Thomson's work within the framework of a mechanical or material model of the aether. He tried to take this idea seriously that Faraday's electric and magnetic fields existed within and were propagated through this space-filling stuff called the aether.

This posed serious problems in terms of, well, the aether fills all of space, but it can't slow down the planets as they orbit the sun, for example, so it can't interfere with the mechanical motion of material objects. It's got to explain electrical phenomena, it's got to explain magnetic phenomena, and it turns out that Faraday's hunch that light was an electromagnetic phenomenon, it has to also explain electromagnetic phenomena. And it must not interfere with the propagation of light waves from the sun to the earth, for example. So it can't slow them down or interfere with them in any way.

And this was collateral with the development in the mid-19th century of a wave theory of light, replacing Newton's atomic theory of light. That's a story in its own right, that Newton's atomic theory of light was discarded in the first half of the 19th century, in the course of that 50 years, in favor of a wave theory of light. Light was a wave. What kind of a wave? A wave has to exist in a medium. You can't have ocean waves without the ocean. What happens if you take away the water? You can't have any waves.

So again the aether became the medium that transmitted light waves from one glowing body out into its environment; let's say the light that comes from the sun. But anything that you heat up so that it becomes glowing, then it's radiating light waves, and in the case of the sun we have what we believe is empty space. Of course with Faraday's point of view you don't have empty space. Space is filled with the aether. Well, in that case, you don't have to worry about what is carrying the light waves. Light is a wave motion in the aether.

In 1865 Maxwell published a seminal work, which was a mathematical description of the electromagnetic field, and this is perhaps one of the most important single works in the history of modern science—a mathematical description of the electromagnetic field. First of all, the term field occurs. Secondly, the term electromagnetic occurs. What we now have is a single field that is responsible for electrical forces, magnetic forces, and, it turns out within this essay, that he has got an account that light is truly an electromagnetic phenomenon. It is an electromagnetic wave. It is a combination of electric and magnetic waves that travel together, that are coupled together. And that's what makes light an electromagnetic phenomenon.

Maxwell's equations allow us to deduce from them all known electrical phenomena, all known magnetic phenomena, and all known optical phenomena. So this theory, this mathematical theory of the electromagnetic field, is an early instance of the unification of forces within physics. We have the unification of electricity, of magnetism, and optics within Maxwell's equations of the electromagnetic field in 1865 in that paper.

In his seminal textbook in 1873 called *A Treatise on Electricity and Magnetism*, Maxwell insists that the pursuit of the mechanical model of the aether, and the attempts to identify the material structure of the aether, taking it seriously that all of the space of the universe is filled with this aether stuff, is hopeless, and that all we can have is a mathematical model analogous to Fourier's analytical theory of heat (analytical in that title, by the way, refers to algebra). So the analytical theory of heat is an algebraic theory of heat which eschews the whole issue of what heat is and describes the process of the flow of heat in a hot body, or in any body that's thermally conducting.

What Maxwell says is what we can have is a mathematical theory of the electromagnetic field. It describes the processes of electricity, magnetism, and light, their behaviors, but it does not tell us what electricity, magnetism, and light are, nor does it tell us what the field is that transmits and exerts electric and magnetic forces, for example. So an electrically charged particle exerts a force on another electrically charged particle across ostensibly empty space or through the aether—it exerts a force on it—and the size of that force is described by the intensity of the electric field at any point in space.

Notice, by the way, that one of the things about the field idea that is fundamentally incompatible with the atomistic style of thinking is that a field, by definition, is continuously distributed in space. A field fills space. In principle, the field generated by a single charged particle extends throughout the universe, and any other charged particle anywhere in the universe will experience a force because it is in the electric field generated by our initial charged particle. Atomistic thinking says that the causes of natural phenomena are sharply localized in physical atoms, chemical atoms, cells, germs, genes. Remember, localization was one of the keys to convincing people that atoms are real, that germs are real, that genes are real. Cells, because of the improved microscopes, people were able to actually see the cells.

And Maxwell insists on this, because, he says, echoing something that Descartes had written in his *Principles of Philosophy*, namely that there are an infinite number of ways that God could have created the universe. So what we have to do is just find a way that allows us to deduce, propose, hypothesize a set of principles that God used, and then they are justified if we can deduce from them the way nature actually behaves. And that's the best we can do.

Newton rejected that idea because that kind of hypothesizing, he said, was sort of like fantasizing, and that we could, in fact, identify the true causes of natural phenomena. But what Maxwell says is there are an infinite number of potential mechanical models of the aether, and there is no possibility of isolating one of these as the correct model. There are an infinite number of models that can fit the observed behavior of electromagnetic phenomena. In spite of which, Maxwell proposes a mechanical model. Everything I've said before is correct. In 1865 and in 1873 he insists on a mathematical theory of the electromagnetic field, and after making it clear that that is the good science; nevertheless, he proposes a mechanical model because he says, after all, there must be a mechanical model. The aether is real and must have some form, and there can't be the electromagnetic phenomena without the aether, so let's see if we can come up with a model that will be satisfactory. And, of course, it wasn't satisfactory.

In the course of the 1870s and the 1880s, there was an effectively universal commitment on the part of the physics community to the reality of the aether. Virtually nobody that I'm aware of doubted the reality of the aether. There were quite strong controversies as to the nature of the aether, what the structure of the aether was, but there was no doubt that the aether was real, that it was, as a famous physicist said as late as 1900, "One thing we can be certain of as all the theories of 19th century physics," we look back on them and how they're changing and how they have changed, and how they've been challenged, "one thing we can be certain of as," so to speak, the conceptual framework of physics matures, "is that the aether is real." That was around 1900. It would cease being real pretty soon.

But in the 1870s and 1880s—I mentioned at the end of the last lecture, for example, that the Irish physicist George FitzGerald in 1880 postulated an electromagnetic aether, that produced what we call matter as a kind of a stable knot of electromagnetic energy, so that matter was not a fundamental constituent of reality. It was analogous to a molecule in relation to an atom. Molecules are made up out of atoms. Molecules are real, of course, but they are reducible, so to speak, to the atoms that compose them.

In the case of FitzGerald, he's saying that energy is the ultimate reality and matter is a peculiar package of energy. Matter is a stable knot of energy in the greater electromagnetic field which fills all of space, and whose character is such that it accounts for all of electromagnetic phenomena, and then it actually accounts for all the phenomena of physics and chemistry through those knots that we call matter, and the particular properties that different knots have. If you've been a Scout then you know that there are many different kinds of knots and they have different properties, so it's not as if there is only one knot. Matter occurs in a number of different forms with different properties, and they then account for all of physics and chemistry.

Now this is quite an incredible turnabout from the atomistic style of thinking. What he's saying is that the electromagnetic aether is the ultimate reality, the sole ultimate constituent of reality. Concurrently, Lord Kelvin (the same William Thomson) rejected the idea of electromagnetic aether and formulated another form of the aether—what's called an elastic solid model of the aether. Again, the problem with it is accounting for all of the different things that the aether has to do.

In the 1880s Albert Michelson—an American physicist, the first American to win the Nobel Prize in physics—Albert Michelson, first alone and then with another physicist named Edward Morley, built a really sophisticated device for detecting the presence of the aether by measuring the earth's velocity relative to the aether. These experiments in the 1880s, performed at what is now the Case Western

Reserve Institute of Technology in Cleveland, all came out with a null result. There was no motion of the earth relative to the aether.

This was really puzzling because, after improving his equipment, everyone agreed that Michelson's device, called an interferometer, would be capable of measuring the velocity of the earth through the aether. And the fact that the velocity kept coming up zero when the data are appropriately massaged for error, because no results are always exactly anything, so the convergent result was zero—this was a real puzzle.

George FitzGerald and the Dutch physicist Hendrik Lorentz came up with an explanation. The explanation goes back to Faraday's idea that matter is ultimately electrically polarized on the inside. And they explained the null result of the Michelson-Morley experiments by saying that because of the existence of the electromagnetic aether, matter, when it travels through the aether, since matter is electrically polarized internally, atoms are electrically polarized internally, then they interact with the field in such a way that they shrink in the direction of their motion by exactly the amount that would reveal the absolute motion of the earth relative to the aether. They actually become shorter as a function of their speed in such a way that it cancels out the measurement of that speed.

This became known as the Lorentz-FitzGerald contraction or the FitzGerald-Lorentz contraction, depending on whether you're Dutch or Irish, I guess, and was a very important result because it showed that there was an electrodynamic character to mechanics—a force-based electrical character.

And this sets the scene really for Einstein's 1905 papers on the photoelectric effect and the special theory of relativity. It explains why the special relativity paper is called *On the Electrodynamics of Moving Bodies*. Einstein was going to be showing that all of these phenomena can be explained without reference to the aether. Einstein never disproved the existence of the aether; he just offered theories in which the aether simply does not occur. And the aether quietly disappeared from physics between, roughly speaking, 1905 and 1925. But we'll be talking about that in subsequent lectures.

Lecture Twenty-Four
Relationships Become Physical

Scope:

From Aristotle to the mid-19th century, relationships were considered predicates of subjects and had no reality in their own right. This is consistent with Parmenidean substance metaphysics and its expression in atomism in its various manifestations. The attribution of reality to energy and fields challenged substance metaphysics from the side of process metaphysics, but energy and fields seem to have a “tangible” character, even if immaterial. Not so relationships, yet by the end of the century, they, too, were recognized as causally efficacious and possessing properties and reality in their own right. Chemists discovered that the arrangement of atoms within molecules, including their spatial arrangement, determined the physical and chemical properties of molecules. The invention of symbolic logic provided a calculus of relationships and their inherent properties. Molecular biology, especially the decoding of the DNA molecule; network theory; and information theory showed that these relationships were physically real, further reinforcing process metaphysics.

Outline

I. What makes the idea of structure as a feature of physical reality important is that it conflicts with the historic preference for identifying reality with “thinghood.”

- **A.** The reality of immaterial fields survived the dissolution of the aether into unreality.
  - **1.** That fields are fundamental features of physical reality, on a par at least with energy and matter, is essential to 20th-century physics.
  - **2.** Fields remain real even when their supposedly necessary substrate, the aether, itself conceived as either material or electromagnetic, drops out of reality.
  - **3.** We have now seen both energy and fields become firmly established as immaterial realities within ostensibly materialistic 19th-century science.
  - **4.** This challenges atomistic thinking by making it necessary to identify processes and their properties or laws.
  - **5.** Energy and fields become, in effect, immaterial “substances” in an explanatory sense.
- **B.** It would be a mistake, however, to see the rise of process thinking as a debunking of atomistic thinking.
  - **1.** The theories we have discussed that reflect what I have called a “Parmenidean approach” to explaining nature are very powerful theories: They unquestionably work.
  - **2.** The theories that reflect what I have called a “Heraclitean approach” are also powerful and also work.
  - **3.** A predilection for either/or thinking makes many feel that only one of these can be the “right” approach, when some combination of the two may be correct.
- **C.** Even more than the idea of energy or the idea of fields, the idea of relationships—relationships of *structure*—pushes the scientific attribution of reality to immaterial agents.
  - **1.** Understand that structure here means relationships *among* the parts of an object, quite apart from characteristics inhering *in* each part.
  - **2.** Energy and fields seem to have at least a quasi-thing-like character, but a relationship is *really* abstract.
  - **3.** The growing recognition of process thinking—the recognition among mid-19th-century chemists that structural relationships have properties of their own, coming at the same time as the recognition of energy and fields—seems, to use a Freudian term, like a “return of the repressed.”

II. The story of the idea of structure begins in France.

A. In 1837, Auguste Laurent proposed what he called a *nucleus theory* of molecules.

1. Laurent was a young chemist who had studied under the famous chemist Jean-Baptiste Dumas.
2. Laurent, adopting the atomic theory of matter, proposed that certain molecules had properties that were a function of the geometric arrangement of their constituent atoms.
3. At the time, chemists assumed that molecular properties derived from the constituent atoms and, for those who adopted the atomic theory, from the precise proportions among those atoms: CO_2, H_2SO_4, and so on.
4. Laurent's idea was that molecules could have their atoms arranged in geometric patterns, such that the pattern defined a "family" of compounds with similar properties—*even if* the individual atoms were exchanged with different atoms, as long as the pattern was preserved.

B. This came to be called a *substitution theory*, and Laurent's professor, Dumas, adopted it and aggressively promoted it.

1. Dumas extended the theory by identifying many more compounds that possessed this property, and Laurent's nucleus theory was, to his chagrin, soon called Dumas' *type theory*.
2. Both were ridiculed for decades by some chemists, in particular by Wöhler and Liebig, who dismissed the idea that spatial arrangement could have physical properties of its own.
3. Many other chemists, ironically including some of Liebig's best students, incorporated the type theory into their research, achieving important results.
4. Note that the attribution of physical significance to spatial arrangement of atoms within a molecule implicitly strengthens the case for the reality of atoms, as opposed to treating them only as convenient heuristics.

C. The next step in making structure real came from Louis Pasteur, who worked with Laurent when they were graduate students and, like Laurent, studied under Dumas.

1. Pasteur's first research project was provoked by an 1844 report that some tartrate crystals—wine dregs—were optically active and some were not, even though both kinds were chemically identical.
2. Pasteur discovered in 1849 that *all* tartrate crystals are optically active but that the acid crystallizes into one of two forms that rotate light in opposite directions.
3. It follows that the same atoms have different spatial arrangements in these molecules and that the spatial arrangements cause different physical properties.
4. In the late 1850s, Pasteur noted that penicillin mold preferentially feeds off just one of these forms and speculated that the three-dimensional arrangement of the atoms, perhaps as a helix, was important.
5. The upshot of all this was that to explain the properties of molecules, you needed to know the atoms of which they were composed, the numbers of each atom, and how those atoms were arranged in space.
6. That is, you needed to know the effects that were caused by a relationship.

D. From the mid-1840s, the research programs of chemists following the Dumas-Laurent type/nucleus theories produced important results and created the field called *stereochemistry*.

1. In the 1860s, August Kekule and his students showed that aromatic hydrocarbons constitute a family of compounds based on a single structure: a hexagonal "ring" of carbon atoms.
2. The properties of each member of the family are determined by which atoms are attached to the carbon atoms and at which points.
3. Stereo-chemical research revealed that carbon atoms can form long chains; this became the basis of polymer chemistry and the plastics industry.

III. The idea of structure/relationships as an elementary feature of nature is far deeper than chemistry, though it revolutionized chemistry and its applications.

A. The abstract character of structure becomes clear in the case of symbolic logic.

1. Logic was dominated for more than 2200 years by Aristotle's subject-predicate formulation, in which only subjects have properties and relationships are "accidental."
2. As we have noted, though, deductive inference was strictly a function of form.
3. The invention of a symbolic notation for reasoning had as powerful an effect on 19th-century studies in logic as the invention of a symbolic notation for mathematics in the 16th and 17th centuries.
4. Augustus de Morgan, George Boole, Charles Sanders Peirce, Giuseppe Peano, and Gottlob Frege are among the pioneers of this innovation.

B. Almost immediately, symbolizing reasoning led to the recognition that relationships possessed properties of their own, independent of the terms (*relata*) they related!

1. Given a relationship, we can begin to identify its logical properties regardless of who or what is related.
2. Some of these properties are transitivity, symmetry, and reflexivity; we can determine the logical properties of the parent relationship, for example, without knowing who the parent and child are.
3. George Boole's *Laws of Thought* was a particularly seminal contribution to symbolic logic.
4. Boole's symbolic notation for how we think when we reason logically was soon recognized as capable of being implemented in electrical circuits.
5. It took another 70 years before Claude Shannon did that, but when he did, he created the designs for the logic units built into all computer chips.

C. The study of relationships in and of themselves became characteristic of many major developments in 19th- and 20th-century mathematics.

1. Differential geometry, a kind of highly generalized, abstract geometry, is an example, and it became important to quantum theory.
2. The study of topology, that is, of freeform spatial relationships, anticipated by Leibniz in the late 17th century, is another example.

Essential Reading:

Mary Jo Nye, *Before Big Science*.

I. Grattan-Guinness, *The Norton History of the Mathematical Sciences*.

Questions to Consider:

1. How can we use language to refer to the world if meaning is strictly a function of relationships internal to the language?
2. How can scientific theories give us power over experience if theories are like languages, the meanings of their terms being a function of relationships internal to the theory?

Lecture Twenty-Four
Relationships Become Physical

At the end of the last lecture, the aether disappeared but fields didn't disappear. Fields and the physical reality of fields are fundamental to the general theory of relativity and to quantum theory. That is to say, fields are absolutely fundamental to our most powerful theories of matter, energy, space, time, and gravity.

So what we have to appreciate here, and it's even more startling, is that the fields remain real, immaterial fields remain real, even when the material substrate that was proposed in order to explain how these fields could be physically real drops out of sight. The field is immaterial but it is a source of forces. Energy is transmitted, forces are transmitted through the field, and the field fills space, but it is not a material thing.

The aether was invented in order to explain how a pattern of energy and forces could exist filling space without something material supporting it, and that was the reason why Faraday proposed the aether. He also, of course, is the one who named and proposed the field. So the electromagnetic field continues to exist even when the aether drops away, and becomes central to relativity theory and quantum theory, the two great theories of 20^{th} century physics, the ones that here at the beginning of the 21^{st} century give us our most profound descriptions of reality at its most fundamental level.

Now, what we've seen in the last two lectures is the idea of energy and the idea of the field—those two, as I said in the last lecture, are closely related—that represent a challenge to the atomistic style of thinking, and that attribute physical reality to immaterial entities, and furthermore, to entities that are continuously distributed in space as opposed to atoms which are sharply localized in space. But it may be that energy and fields still have some of the qualities of a substance.

It sounds like an oxymoron to talk about an immaterial substance, but the original meaning of the term "substance"—*substantia*, that which stands under something else—could be applied. We would have to redefine what we mean by a substance so it's not a thing now like an atom with fixed properties, but that energy and fields are in some broader sense of the term, in a redefined use of the term "substance," that they also represent substances and stand under natural phenomena; but with a nod in the direction of Heraclitus's notion that process is the ultimate reality, not atoms.

I think that we need to recognize the power of the atomistic style of thinking. The fact that it is challenged does not detract from the great successes achieved by the atomic theory of matter in physics and chemistry, by the cell theory of life, by the germ theory of disease, by the gene theory of inheritance. The challenge doesn't change their results, but it reminds us that it is always possible to abuse a good idea by pushing it too far.

And again, as I've mentioned earlier, and will have occasion to say again, it reveals a tendency on our part to either/or thinking. Either the Parmenidean atomistic approach or the Heraclitean process approach, whereas in fact what we really should be saying as we look back at the history of scientific ideas is that these are complementary approaches very consistent with ideas that we will see emerging in the lecture on quantum theory. That there are complementary concepts that are logically contradictory, but in fact work together very well to give more powerful explanations than either one or the other—either "thinghood" or process.

This lecture is going to push the attribution of reality to immaterial entities—attributing reality to them because they have causal consequences that could not be explained without attributing reality to them—and will focus on relationships. First, on structural relationships in 19^{th} century chemistry, because structure is a spatial relationship.

The idea that relationships are physically real, that relationships have a causal character, that they can be causal agents independent of the *relata*, is a very powerful idea. And perhaps, depending on your own sort of psychology, it may be more of a challenge to the atomistic style of thinking than energy and fields were, because fields certainly sound like things of a kind even though they aren't material, and energy seems to have some kind of non-material solidity to it. But relationships are truly abstract, and attributing reality to relationships is, I think, a powerful revelation of the return, in the 19th century, of a process approach to explaining natural phenomena.

I had referred earlier to our tendency to an either/or approach in many areas of life; that either this is the right way to do it or that is the right way to do it, but resisting the idea that both may be necessary, even though they seem to conflict with one another, but that they can be reconciled within a broader vision. It is somewhat reminiscent of Freud's theory of repression in which Freud, in a famous series of lectures that he gave at Clark University on his one and only visit to the United States (that's in Worcester, Massachusetts), referred to the return of the repressed: that repressed feelings and ideas are continually knocking at the door, asking to be introduced back into the consciousness.

In the 19th century it's as if the process approach to natural philosophy was knocking at the door and saying, "Look, you guys are obsessively focused on the atomistic style of thinking. Let us in. Let us in by way of energy, by way of the field, and now by way of the physical reality of relationships."

So let me start this part of the story by way of 19th century chemistry and a very startling revelation, or a startling discovery, or idea, if you prefer. In 1837 a young French chemist named Auguste Laurent proposed what he came to call a nucleus theory of chemical structure. If you take seriously the idea that molecules are composed of atoms, that chemical substances have a molecular character, and that they are composed of atoms; until Laurent, and really for another decade after him, the overwhelming majority of chemists accepted the idea that the properties of a molecule are determined by the atoms that make up the molecule.

So CO_2, carbon dioxide, has one carbon atom and two oxygen atoms. And the properties of carbon dioxide—that it is a gas and that it behaves in the ways that it does—are determined by the fact that it is a combination of one carbon atom and two oxygen atoms. H_2SO_4 (sulfuric acid) has the properties it has because it has two hydrogen atoms, one sulfur atom, and four oxygen atoms. So you have described a substance, in this view, when you have identified the atoms that make it up and the proportions in which they exist. So you have CO in carbon monoxide, CO_2 gives you carbon dioxide, and H_2SO_4 gives you sulfuric acid. But other combinations of hydrogen, sulfur, and oxygen would give you different substances.

So that was the prevailing view when Laurent came on the scene with this strange-sounding idea that the spatial arrangement of the atoms within a molecule, all by itself, had some consequence for the physical properties of the molecule. Now I want to describe this carefully, because we're going to see another variant of this idea in a moment. Laurent's idea was that in certain substances the atoms were clustered into a geometric form in such a way that even if you substituted different atoms at the vertices of this geometric structure—if you like, think of a triangle, that the atoms are arranged in a triangle, and at each vertex you have a different atom—there are certain substances where the geometric form is responsible for the properties of the molecule. And if you substitute different atoms at the vertices of that triangle you will have a family of substances with roughly the same properties, even though you have changed the atoms. So the idea is that somehow the geometric shape of the molecule, which is obviously an immaterial thing, the shape is itself responsible for the properties of the molecule, because you can substitute. So it's a substitution theory. You can't just substitute anything, of course, because not all atoms will get together with all other atoms. But within a relatively wide range, you can substitute atoms for the ones in any given triangular configuration of this stuff, and if the new combination remains triangular then it's going to have family resemblance properties.

As I said, Laurent called this his nucleus theory of substitution chemistry. His teacher, Jean-Baptiste Dumas—obviously much more famous than Laurent—picked up on this, and to some extent to Laurent's dismay, he became identified with this substitution theory in chemistry, although he called it a type theory. He expanded it by doing experiments involving many other substances, and to some extent I think it’s only fair to say that Dumas maybe originally came up with this idea independently of Laurent, but he was certainly aware of Laurent’s work, and then subsumed Laurent’s work into his.

Dumas developed this type theory in which you have types of substances, types of chemical molecules that have a distinctive spatial arrangement of the molecules, and when you substitute, it’s essentially the same as Laurent’s, but it’s more sophisticated and of wider application. Laurent died relatively young, or he may have developed his theory along somewhat the same lines.

It is important to notice that Laurent and Dumas were mocked for decades by some of the leading German chemists, especially Justus Liebig and a colleague, Wöhler, a very important 19th century chemist, for having been the first person to synthesize a molecule that exists within living beings—urea in this sense. He synthesized urea. Wöhler and Liebig made fun of this idea—this was a ridiculous idea, that the spatial arrangement of molecules was itself responsible for physical properties of the molecule, not just the atomic constitution. Here you can change the atomic constitution and get similar properties.

Liebig was not just a famous chemist in his own right. His power came from the fact that his laboratory trained generations of new scientific chemists. Ironically, some of his most prominent students, in spite of his mocking Dumas, in fact adopted the Dumas model as the basis for their own research programs, and synthesized important chemicals using the substitution reactions that were suggested by Dumas’s theory. We will talk a little bit more about that in a moment.

Another irony, which I think is quite rich and directly relevant to these lectures, is that the substitution model, by attributing reality to the physical arrangement of the atoms within the molecule, reinforced the physical reality of atoms even as it was attributing physical reality to the immaterial phenomenon called a relationship, a spatial relationship, which was given the name “chemical structure” only much later. They would not have talked about structure. Chemical structure refers to the spatial arrangement of the atoms within a molecule. So that’s quite ironic. That spatial arrangement is immaterial physical reality—it is process-like, based on the dichotomy that I set up—and it reinforces the physical reality of the atoms (atomistic style of thinking) because it says that they are sharply localized at the vertices of the geometric shape.

This is not a shift of gears, but we have to shift personality: to Louis Pasteur, who as a young man was a graduate student with Auguste Laurent in Dumas’s laboratory. They both did research as graduate students in Dumas’s laboratory. In the 1840s, Pasteur took as his research project for his doctoral dissertation a problem that was published in 1844 by a chemist named Eilhard Mitscherlich, who published an observation that the crystals of tartaric acid come in two types: one type is optically active and one type is not.

Now this sounds more obscure than it really is. Tartaric acid is the residue of wines, what forms at the bottom of a bottle of wine if you leave it stand for a very long period of time, or in wine casks. It was a very important byproduct, because it can ruin the taste of wine. Pasteur’s success in this eventually is what led him to be called in by the wine industry to study the process of fermentation, leading to his famous 1857 publication on fermentation that led to the germ theory of disease.

But in the 1840s, Pasteur is a young researcher and he picks up on this topic and decides to study the crystals of tartaric acid that form quite naturally, and has this curious observation, that tartaric acid has two forms—one is optically active and one is not. By optically inactive, it means that if you pass light through these crystals nothing happens to it. It goes through it as if it were just glass. If it’s optically active, then it does something to the light. It rotates the plane of polarization of light. Light waves are polarized, or can be polarized, and going through one type of tartaric acid their polarization is changed coming out compared to going in, and the other crystals act just like glass.

Now Pasteur discovered through a very careful experiment that he designed (and this became the hallmark of his whole career), that Mitscherlich was wrong. There is only one type of tartaric acid crystal, which is optically active, but the tartaric acid crystallizes in two geometric forms. One form rotates the plane of polarization of a light wave, let's say, to the right, and the other one rotates it to the left.

It so happened that in the crystals Mitscherlich was studying, one specimen was dominated by the crystals that rotated light in a single direction, whereas the other specimen was a combination of the two, and since one was rotating it to the right and one was rotating it to the left, when he observed the light it looked as though there had been no rotation whatsoever. The two rotations effectively cancelled each other out. He was wrong about that.

But the implication of Pasteur's work which was immediately drawn, is the same atoms are arranged spatially in the crystals of tartaric acid in two different ways, and lead to two different kinds of properties. So here, the spatial arrangement of the same atoms within the tartaric acid crystal, type A and the other, they affect light in different ways. They exert different forces on light.

Pasteur shortly noticed that penicillin mold, for example, differentially ate. If you fed penicillin mold tartaric crystals, they preferred one of these two to the other. So the penicillin could distinguish between the left-hand and the right-hand versions of the tartaric acid crystals.

Now we have a strong reinforcement of the idea of structure that Laurent and Dumas had developed. There, it was different atoms maintaining a kind of semi-constancy of type, and the properties of the molecule had a family resemblance, in spite of the fact that you had changed the atoms, and the causes were attributed to the geometric shape of the molecule. In Pasteur's work, the same exact atom. So knowing the chemical formula does not give you enough information to predict the properties of a molecule, because you now have to know something else. You have to know: how are those molecules arranged in space? That is a really dramatic instance of the attribution of reality to an immaterial entity, really a relationship.

In the course of the rest of the 19th century this became increasingly important, especially as the field that's called *stereochemistry* became prominent. Stereochemistry is the study of the spatial arrangement of atoms within molecules. In the 1860s, August Kekulé, a German chemist, and his graduate students showed that there is a family of compounds called aromatic hydrocarbons (hydrogen and carbon atoms) that have a ring structure, a six-sided ring structure (a hexagonal structure). Depending on which atoms you stick on the vertices you can dramatically change the properties of the molecule that results in a controlled way; these are relatively simple chemical reactions.

One of these is benzene, a very important compound that has a ring structure, but it's symptomatic of a whole family of compounds, and this unleashed a tremendous amount of research in stereochemistry. It also had as a byproduct the discovery that carbon atoms can form long chains, and in the 20th century this became the basis for polymer chemistry. You can have long chains of carbon—atoms that form a backbone—and then by attaching different molecules at different points on this chain, you generate basically a tremendous range of artificial materials, synthetic materials—plastics, for example. The term "plastics" that was whispered to Dustin Hoffman in *The Graduate* refers to what turned out in retrospect to be sort of like the peak of transformation of these kinds of carbon chain molecules into plastics materials of a wide range. Obviously, we are still surrounded by plastics—but not just plastics; there are whole families of synthetic materials that are produced by exploiting this stereochemistry.

We need to look a little more closely at how powerful and how deep this idea of attributing reality to relationships ran in the 19th century. It was not just in the area of chemistry. Although I personally don't see how you could quibble with the idea that spatial relationships are immaterial, and attributing causal properties to spatial relationships is a serious undermining of the atomistic style of thinking as uniquely correct. Clearly, knowing the matter of which a molecule is composed, everybody acknowledges by the end of the 19th century, is not enough in order to explain what the properties of the molecule are and why the molecule behaves as it does.

But the recognition of relationships as real runs much deeper than chemistry. One of the great intellectual developments of the 19th century is the rise of symbolic logic. Into the 19th century the one piece of Aristotle that had survived the rise of modern science was his writings on logic. Aristotelian logic—this sort of epitome of Greek logic of the 4th century B.C.E.—survived into the 19th century, and it was a fundamentally subject–predicate logic. That is to say, the fundamental entities in the logic are subjects, which possess various kinds of predicates, and then we reason about the relationship among subjects and predicates based on certain forms of inference, like the types of valid deductive arguments or inductive arguments.

This subject–predicate logic is very much an echo of this Parmenidean substance approach to explaining natural phenomena. Things with properties, subjects with predicates, are the bases of explaining all natural phenomena.

In the 19th century, a group of thinkers across Europe—Augustus De Morgan and George Boole in England were particularly important in the beginning; Charles Sanders Peirce in the middle of the 19th century; later Giuseppe Peano in Italy; Gottlob Frege in Germany at the beginning of the 20th century; and Bertrand Russell back in England—invented and developed symbolic logic, something that Leibniz had attempted but didn't get very far with at the end of the 17th century.

Symbolic logic had the symbolic notation for logical arguments. Reducing logical arguments to a symbolic form instead of a verbal form was just like what we saw happen to algebra. When we shifted from word equations to symbols it led to an explosion in the growth of mathematics. Similarly, in the 19th century there was an explosion of logic now recognizing that relationships had a character of their own, and had properties of their own that were quite independent of what it was that was being related. The subject drops out and the relationships remain.

So, for example, being a parent is a relationship—A is the parent of B is the name of a relationship. So we don't care who A and B are. But we can talk about the nature of that relationship. It is, for example, not a reflexive relationship. Reflexivity is a property of some relationships, but not of being a parent. If A is the parent of B, B is not the parent of A. It is not a symmetric relationship. A cannot be the parent of itself—that means it's not reflexive—and if A is the parent of B, then B can't be the parent of A—that means it's not a symmetric relationship. If A is the parent of B, and B is the parent of C, A is not the parent of C (grandparent maybe, but not the parent of C), so it's not a transitive relationship.

So we can start reasoning about the properties: transitivity, symmetry, and reflexivity. And we can say, well, what's the relationship between reflexivity and transitivity? If a relationship is reflexive, is it also transitive? Is it also symmetric or not? And symbolic representations of these relationships became increasingly not just fun intellectually but they started generating real results in mathematics, and led to a serious reconceptualization of the nature of mathematics and the ground of mathematics.

Along the way, George Boole published a book that was effectively a handbook on the laws of thought, which reduced human reasoning to this kind of symbolic notion that he and De Morgan and others had been developing for describing logical arguments. These were called *The Laws of Thought*. We could now symbolize thought.

Well, it was a very interesting exercise at the time, but within a couple of decades Charles Sanders Peirce in America noticed that Boole's *Laws of Thought* could be simulated in an electrical network. Nothing happened with that in the 1860s or '70s when Pierce wrote it down, largely because the overwhelming majority of Pierce's writings were not published until after he was dead. But in 1948 Claude Shannon, then at Bell Laboratories, published a theory of information that we will be talking about in a lecture on information theory which in fact is based on Boole's *Laws of Thought*, incorporated into an electrical network that became the basis for the design of virtually all computer chips. But we'll be talking about that in the future. And that lecture, by the way, will sort of put the capstone on this notion of attributing reality to immaterial entities, because while relationships become real in this lecture, in that lecture information becomes physically real. Information becomes a source of causal action.

It was the study of relationships in their own right, independent of the *relata*, the things that they related, that is very characteristic of major developments in 19th century mathematics, many of which turned out to have fruitful applications in the 20th century. I'll just mention a few of them. Differential geometry is one—kind of a universalized geometry, very abstract, it became very, very important in quantum theory. And topology—the study of spatial relationships in a very generalized way; a subject that had been started by Leibniz, dropped out of sight for over 150 years, and then suddenly was sort of rediscovered at the end of the 19th century. Topology looks at, like I said, generalized spatial relationships and has become very important to mathematical research in the 20th century.

The idea that relationships have properties of their own—that they have a physical reality of their own as causal agents—spread from chemistry and mathematics, or I should say they had much wider recognition than in chemistry and in mathematics.

For example, in sociology through the work of Émile Durkheim, and in linguistic theory through the work of Ferdinand de Saussure, who argued that a language was a system of relationships, and the specific noises that were made had nothing to do with meaning, that the meaning derived from the relationships among the sounds that were made. Durkheim argued that social relationships determine social behavior. This reinforces the challenge to the atomistic style of thinking from the side of attributing reality to immaterial non-things, to entities that are physically real but are not things.

In the next lecture we're going to see how the idea of evolution is the basis of a theory in which process is the key to the explanation of the theory, not things with properties. Process is quite clearly, in the case of evolution, the key to what evolution comes to explain, and we'll be taking that look at the theory of evolution in the next lecture.

Timeline

9000 B.C.E.....................Domestication of grains and fruits begins

7000 B.C.E.....................First evidence of copper smelting; evidence of drilled teeth

6000 B.C.E.....................Earliest evidence of wine making; large-scale settlements in the Middle East

4500 B.C.E.....................Horizontal loom weaving

4000 B.C.E.....................Modern wooly sheep

3500 B.C.E.....................Sumerian cuneiform writing

3000 B.C.E.....................Beer brewing in Sumer; earliest gold jewelry; twill weaving using warp-weighted loom

2800 B.C.E.....................Bronze in use in Sumer; Egyptian hieroglyphic writing

2000 B.C.E.....................Spoked-wheel chariots

1800 B.C.E.....................Egyptian medical and mathematical papyri; Babylonian Code of Hammurabi; alphabetic writing in Ugarit

1500 B.C.E.....................Iron manufacturing; cast bronzes in China; vertical loom weaving

1300 B.C.E.....................Earliest Chinese inscriptions; Phoenician alphabetic writing

1250 B.C.E.....................Glass manufacture in Egypt

1000 B.C.E.....................Steel making on a limited scale

800 B.C.E.......................Hellenic Greeks adopt Phoenician alphabet

700 B.C.E.......................Homeric epics written down

500 B.C.E.......................Cast iron in use in China

5th century B.C.E...........Thales, Pythagoras, Parmenides, Heraclitus, Anaxagoras, Empedocles

4th century B.C.E...........Plato, Aristotle, Euclid, Epicurus

3rd century B.C.E...........Roman conquest of Greece; Archimedes, Apollonius, Aristarchus

2nd century B.C.E. ....Antikythera machine

1st century B.C.E. ....Vitruvius; Chinese invention of paper

1st century C.E...............Pompeii buried by Vesuvian ash; Frontinus on aqueducts of Rome

2nd century C.E..............Hero of Alexandria’s book of machines; Baths of Caracalla in Rome; watermill complex near Arles; Ptolemy and Galen

451 ....Conquest of Rome by Goths

521 ....Justinian closes Athenian philosophy schools

1086 ....Domesday Book inventory of England

1092 ....Start of the First Crusade

1170 ....Universities of Bologna and Paris founded

1268 ....First weight-driven mechanical clock

1329 ....Start of the Hundred Years’ War between England and France

1347 ....First outbreak of plague in Europe

1350 ....Petrarch founds the Humanist movement/idea of progress

1415 ....Brunelleschi rediscovers perspective drawing

1425 ....Jan van Eyck introduces oil-based paints

1453 ....Gutenberg introduces printing with movable metal type

1487 ....Vasco da Gama sails around Africa to India

1492 ....Columbus's first voyage to the New World

1512 ....Michelangelo completes the Sistine Chapel ceiling painting

1515 ....Ferdinand Magellan begins first around-the-world voyage

1543 ....Copernicus's *On the Revolutions of the Heavenly Spheres*; Vesalius's *On the Structure of the Human Body*

1554 ....Gerard Mercator's mathematics-based maps of Europe

1600 ....William Gilbert's *On the Magnet*; Giordano Bruno burned at the stake in Rome

1609 ....Kepler's *New Astronomy* claims elliptical planetary orbits

1610 ....Galileo's telescope-based *Sidereal Messenger*

1618 ....Start of the Thirty Years' War

1619 ....Kepler's *Harmony of the World*

1620 ....Francis Bacon's *New Organon*

1628 ....William Harvey's *On the Motion of the Heart and Blood in Animals*

1632 ....Galileo's *Dialogue Concerning the Two Chief World Systems*

1637 ....René Descartes introduces algebraic geometry

1638 ....Galileo's *Discourses on Two New Sciences*

1648 ....Treaty of Westphalia ends the Thirty Years' War

1660 ....Royal Society of London founded

1665 ....Robert Hooke's *Micrographia*

1666 ....French Royal Academy of Science founded

1673 ....Anton Leeuwenhoek's first published microscope observations

1684 ....Leibniz's first calculus publication

1687 ....Newton's *Principia Mathematica*

1704 ....Newton's *Opticks*; Newton's first calculus publication

1709 ....Jacob Bernoulli introduces modern probability theory

1750 ....Thomas Wright's Newtonian cosmology

1758 ....John Dollond patents color-corrected microscope lens

1767 ....James Hargreaves's spinning jenny

1771 ....Richard Arkwright's water-powered spinning "frame"

1776 ..............................U.S. Declaration of Independence; Adam Smith’s *The Wealth of Nations*

1776 ....Watt-Boulton steam engines commercially available

1782 ....Lavoisier discovers oxygen, initiates chemical revolution

1789 ....French Revolution

1794 ....Erasmus Darwin’s poem *The Botanic Garden*

1799 ....Laplace’s *Celestial Mechanics*

1800 ....Volta invents the electric battery

1807 ....John Dalton introduces modern atomic theory; 1807

1807 ....Georg Friedrich Hegel’s *Phenomenology of the Spirit*

1807 ....Robert Fulton’s *Clermont* steamboat

1809 ....Jean-Baptiste Lamarck’s *Zoological Philosophy*

1822 ....Joseph Fourier’s analytical theory of heat published

1824 ....George Boole’s laws of thought; Sadi Carnot’s *Reflections on the Motive Power of Heat*

1828 ....George Stephenson’s *Rocket* steam locomotive

1830 ....Michael Faraday invents the dynamo

1835 ....Charles Darwin returns from his global voyage on H.M.S. *Beagle*

1835 ....Adolphe Quetelet founds social statistics

1838 ....Friedrich Bessel measures the distance to star Cygnus 61

1838/39 ....Mathias Schleiden and Theodore Schwann’s cell theory of life

1844 ....Samuel F. B. Morse’s pilot installation of an electric telegraph

1845 ....Faraday introduces the field concept

1847 ....Hermann Helmholtz proclaims conservation of *Kraft* (meaning “force” or “power”); the term “energy” would be introduced in 1850

1849 ....Louis Pasteur discovers two forms of tartaric acid crystals

1850 ....William Rankine coins *energy* for *Kraft*; Rudolph Clausius founds thermodynamics, coins the term *entropy*

1851 ....William Thomson proclaims the arrow of time

1856 ....William Perkin discovers the first synthetic dye

1857 ....Pasteur’s essay on fermentation founds the germ theory of disease

1858 ....Alfred Russel Wallace’s essay on evolution by natural selection

1859 ....Darwin’s *On the Origin of Species*

1862 ....Morrill Land Grant Act triggers growth of engineering education in the U.S.

1865 ....Mendel publishes results of his researches

1865 ....Maxwell’s *A Dynamical Theory of the Electromagnetic Field*

1865 ....Auguste Kekule announces the ring structure of the benzene molecule

1865 ....First effective transatlantic telegraph cable

1877 ....Robert Koch isolates the cause of anthrax

1879 ....Pasteur introduces modern vaccination

1882 ....Koch isolates tuberculosis bacterium and, a year later, cholera

1882 ....Thomas Edison inaugurates centrally generated electricity

1885 ....Pasteur shows that dead bacteria confer immunity

1895 ....Roentgen discovers X-rays

1896 ....Henri Becquerel discovers radioactivity

1898 ....Marie Curie names *radioactivity*, isolates polonium, then radium

1897 ....J. J. Thompson discovers the electron

1900 ....Hugo de Vries and others rediscover Mendel's results; Max Planck's quantum hypothesis

1903 ....De Vries's *The Mutation Theory*; William Bateson coins the term *genetics*

1903 ....Ernest Rutherford and Frederick Soddy determine lawful randomness of radioactive decay

1905 ....Einstein's "miracle year" of publication

1910 ....Thomas Hunt Morgan localizes the "gene" for fruit-fly eye color

1910 ....Ernest Rutherford's Solar System model of the atom

1912 ....Henrietta Leavitt Swann's variable-star cosmic "ruler"

1913 ....Niels Bohr's quantum theory

1914 ....World War I begins

1915 ....Einstein's general theory of relativity

1918 ....World War I ends

1923 ....Edwin Hubble announces that Andromeda is a galaxy

1925 ....Heisenberg and Schrödinger found quantum mechanics

1926 ....Heisenberg uncertainty principle; statistical interpretation of quantum mechanics

1929 ....Hubble announces the expanding Universe; Paul Dirac founds quantum electrodynamics

1931 ....Electron microscope invented

1935 ....Karl Jansky detects radio signals from the Sun

1935 ....First virus "seen" using electron microscope

1936 ....Alan Turing publishes his principle of the universal computer

1938 ....Warren Weaver coins the term *molecular biology*

1939 ....World War II begins

1945	First atomic bombs; World War II ends; ENIAC becomes operational
1947	Transistor invented at Bell Labs
1947–1949	George Gamow and colleagues propose the Big Bang theory
1948	John von Neumann constructs EDVAC; Claude Shannon founds mathematical information theory
1953	Watson and Crick announce the double-helix structure of DNA
1956	Dartmouth conference on artificial intelligence
1957	*Sputnik I* orbits the Earth
1958	Jack Kilby and Robert Noyce invent the integrated circuit
1963	Penzias and Wilson detect microwave background radiation; Edward Lorenz triggers chaos theory
1964	Murray Gell-Mann and George Zweig found quantum chromodynamics
1969	Neil Armstrong walks on the Moon
1971	First test of ARPANet, leading to the Internet in the 1990s
1971	Electro-weak unification wins acceptance
1972	Recombinant DNA research begins
1973	DEC introduces first “mini-computer” PDP-8
1973	Standard model of quantum field theory formulated
1980	Alan Guth’s inflationary theory of the Universe; dark matter proposed
1981	IBM PC introduced
1984	String theory becomes “respectable” in physics
1989	Disintegration of the Soviet Union
1990	Hubble Space Telescope launched into orbit
1991	Tim Berners-Lee introduces the World Wide Web
1995	Sixth quark, called *top*, discovered
1998	Dark energy proposed
2000	Human genome decoded

Glossary

aether: In 19th-century physics, a name for a universal space-filling form of matter or energy that served as the medium for immaterial fields of force.

algorithm: A series of well-defined operations that, if followed precisely, is guaranteed to solve a specified problem.

alphabetic: A name for a writing system that constructs the words of a language out of intrinsically meaningless symbols, in contrast with syllabic or ideographic writing systems.

amino acid: Typically in biology, this refers to one of 20 variants of a complex molecule—in which an NH_2 grouping of atoms shares a carbon atom with a so-called carboxyl group—out of which living cells construct proteins.

analytic geometry: Using algebraic equations to represent geometric forms and to solve problems in geometry or problems in algebra that previously had been solved using geometry, a Greek preference that was still common through the 17th century.

axiom: A statement whose truth is self-evident, hence, can be used for purposes of inference without requiring a proof that it is itself true. Sometimes used loosely for a statement that we are to take as true without further proof because true statements can be inferred from it deductively.

binary system: In arithmetic, a number system employing only two symbols, 0 and 1, to represent all possible numbers and the results of all arithmetic operations; more generally, any strictly two-place characterization of phenomena: for example, on-off or true-false.

block printing: Printing texts by carving the writing symbols into a block of wood that is then inked and pressed onto the writing surface.

cartography: Mapmaking.

central-vanishing-point perspective: A technique for creating the illusion of depth on a two-dimensional surface, for example, a wall or a canvas, such that the viewer "sees" the content of a painting as if the depth were real.

chromatic aberration: Distortion that worsens as magnification increases, caused by the fact that the focal point of a lens is a function of the frequency of the light rays striking it, while natural light contains multiple frequencies, leading to multiple foci and blurry images.

classification problem: Identifying classification categories that organize some set of objects into groups in ways that reflect features of those objects rather than values projected by the classifier.

coal tar: The residue, long considered waste, from burning coal in a closed vessel in order to generate a flammable illuminating gas that was sold for lighting (gaslight) and for cooking and heating.

coke: Burning piles of coal in a controlled way, such that only the outer layer of the pile is consumed, converts the inner material into coke, which can substitute for charcoal in iron-making, dramatically lowering costs.

concrete: A construction material composed of a binder or cement; an aggregate, typically sand and/or gravel; and water. Modern concrete, so-called Portland cement, is very similar to Roman cement, which used quicklime, pozzolana (volcanic ash soil), gravel, and water. The strength of concrete comes from the chemical combination of the water with the binder.

contingent: Dependent, for example, on context, time, or circumstances, hence, not necessary.

conventionalism: The view that classification categories—*tree*, *fish*, *planet*—have no reality apart from the individual objects being classified and reflect features of those objects that have attracted the selective attention of the classifier.

cosmos: Ancient Greek name for the Universe as an ordered whole, though not all Greek philosophers meant by *cosmos* everything that is, as we do.

cuneiform: A way of writing in which the symbols of a writing system are inscribed into a medium, for example, into clay tablets using a stylus.

deduction: A form of reasoning in which the truth of an inferred statement, the conclusion of a logical argument, is guaranteed, that is, follows necessarily, from the truth of some other statements, the premises of that argument.

demonstration: Literally, a "showing," but in reasoning, a deductive logical argument.

dialectic: In Greek logic, a form of reasoning in which the premises of an argument are not known to be true—either self-evidently or deductively—but are assumed to be true in order to explore their logical consequences.

digital: In modern technology, the representation of any phenomenon in discrete numerical terms, typically binary, in contrast with continuous analog representations. Where analog computers are customized to specific problems, digital computers have a universal character (if the numerical representation is valid!).

double-entry bookkeeping: Introduced to the West from Islam circa 1200 and popularized during the Renaissance, this method of record-keeping allowed precise tracking of debits and credits at a time when the scale and complexity of commerce were growing.

dynamo: A machine, commercialized from the 1870s, based on Michael Faraday's dynamo principle of about 1830, in which an electric current flows in a conductor as the result of the relative mechanical motion of the conductor and a magnet.

electrochemistry: Using electric currents to dissociate chemical compounds into their constituent elements, thereby identifying the constituents and permitting the study of "pure" elements.

electro-weak theory: The 1960s theory developed by Sheldon Glashow, Abdus Salam, and Steven Weinberg that unified the electromagnetic force, exerted by photons, and the so-called weak nuclear force, exerted by a family of particles called intermediate vector bosons, that is associated with radioactivity but also affects the electron family of particles, quarks, and neutrinos.

emergent property: A property of a whole that is not displayed by the individual parts of the whole *and* has causal consequences of its own.

empiricism: The view that all knowledge claims are ultimately validated by observational experience.

engineering drawing: A means of exhaustively characterizing the form of a three-dimensional object, however complex, using two-dimensional drawings. Renaissance engineers adapted perspective drawing to achieve this end and invented cutaway and exploded representations to show how machines were built; later, engineers and architects adopted orthogonal projections as a standard.

Enlightenment: A name given by 18th-century intellectuals to their age as one in which reason was used to improve mankind's physical, moral, social, and political condition.

enzyme: Enzymes are proteins that function as catalysts in metabolic processes; that is, they enable reactions but are not consumed in those reactions. Like all proteins, they are composed of amino acid complexes.

epicycles: A name for hypothetical centers of uniform circular motion for the planets to account for the fact that, viewed from the Earth, the planetary motions seem to be neither uniform nor circular.

ether: See **aether**.

feedback: A term popularized by Norbert Wiener's cybernetics theory in the 1940s, feedback refers to returning a portion of the output of a system or process to its input. Positive feedback reinforces the input, leading to a continually increasing output up to the limits of a system; negative feedback reduces the input and can, thus, be used to regulate the ratio of output to input.

floating point arithmetic: A scheme for representing numbers of any size compactly for purposes of automated calculation, as in a computer.

fractal: A name coined by the mathematician Benoit Mandelbrot to describe a family of shapes that occur throughout nature and are describable by a particular family of highly abstract mathematical functions. These shapes violate the traditional conceptualization of objects as being one, two, or three dimensional.

germ plasm: In the 1880s, August Weismann argued that sexually reproducing organisms inherit their distinctive character through a line of sexual cells, the germ plasm or germinal plasm, that is wholly isolated from the life experiences of the organism—hence, no inheritance of acquired characteristics, contra Lamarck. For us, DNA is the germ plasm.

hieroglyphics: An ideographic writing system, such as the one initially used by the ancient Egyptians in the 3rd millennium B.C.E. It evolved over the next 2000 years into increasingly stylized symbols that eventually represented syllables rather than ideas.

hydrostatics: The study of floating bodies in equilibrium, whose principles were first formulated by Archimedes in the 3rd century B.C.E. He also studied hydrostatics, the behavior of fluids, for example, water, in motion and the pressures they exert, which is directly relevant to the design and construction of water clocks and water- and air-powered machinery.

ideographic: A writing system in which each symbol, typically pictorial, expresses an idea.

induction: A form of reasoning in which the truth of some statement follows only with some probability from the truth of other statements; hence, it may be false even if those other statements are true, in contrast with deductive reasoning.

innovation: Not a synonym for invention but the form in which an invention is realized in the course of a process that integrates invention, engineering, and entrepreneurship.

kinetic theory of gases: The mid-19th-century theory developed especially by Clausius, Boltzmann, and Maxwell that the observable properties of gases—pressure, temperature, and viscosity—and relations among them are the result of, and are explained by, the motions of vast numbers of unobservable atoms or molecules of which they are composed; furthermore, these motions have only a statistical description.

logic: The name given to the study of forms of reasoning and their rules, independent of what the reasoning is about.

logical proof: See **proof**.

metaphysics: The study of the ultimately real, as opposed to what only appears to be real. The term occurs first as a description of an otherwise unnamed text of Aristotle's that deals with the first principles of being.

modern science: A name for an approach to the study of natural phenomena that emerged in the 17th century, was extended to social phenomena in the 18th century, and is considered to have developed into what we mean by *science* today.

mutation: A discontinuous variation typically in some heritable attribute of a cell, organism, or today, a DNA molecule, by comparison with its "parent." Hugo de Vries made mutations the basis of his 1901 theory of inheritance and of evolution, replacing natural selection with mutations.

nanotechnology: The manipulation of matter and the creation of structures on a molecular scale, with features measured in nanometers, billionths of a meter, or about 10 angstroms on an alternative scale. A DNA molecule is about 4 nanometers wide, and the read/write head of a state-of-the-art hard drive floats about 3 nanometers above the disk.

naturalism: The view that nature is the sum total of what is real, a view espoused by Aristotle against Plato's view that the ultimately real were supra-natural forms.

nucleosynthesis: The synthesis of the rest of the elements out of the hydrogen that is assumed to have been the universal form of matter in the early Universe.

perspective drawing: See **central-vanishing-point perspective**.

plasm: See **germ plasm**.

polymer chemistry: The study and manipulation of the properties of large molecules built on long, linear chains of carbon atoms. Plastics are polymers.

population genetics: Statistical models of the distribution of genes in large populations of randomly breeding individuals. Conceptually, the development of population genetics in the 1920s echoes the ideas underlying the kinetic theory of gases, statistical mechanics, and thermodynamics and the statistical laws of radioactivity and quantum mechanics.

process metaphysics: The view that reality is ultimately characterized by, and is to be explained in terms of, rule-governed processes, as opposed to the substance metaphysics view.

proof: A proof is a logical argument in which the truth of the statement to be proven is shown to follow necessarily from statements already accepted as true, hence, a deductive logical argument.

proteins: Complex, typically very large molecules made up of combinations of the 20 amino acids living cells manufacture, each protein possessing a distinctive spatial arrangement, or folding, of its components. Proteins, which determine cell metabolism, are manufactured on molecules called *ribosomes* in response to instructions from DNA via messenger RNA.

quantum chromodynamics (QCD): The quark theory of matter that developed in the 1960s in which hadrons, protons, neutrons, and all other particles that respond to the so-called strong nuclear force—thus, not electrons and neutrinos—are built up out of some combination of six quarks held together by gluons. Quarks and the electron-neutrino family of particles, called *leptons*, are now the *really* elementary forms of matter.

quantum electrodynamics (QED): The theory that developed in the 1940s out of Paul Dirac's 1929 quantum theory of the electromagnetic field. It describes the interaction of electrons, protons, and photons and is, thus, the quantum analogue of Maxwell's electromagnetic field theory.

rationalism: The view that deductive reasoning is both the only route to truth and capable of discovering all truths.

reverse engineering: Decomposing an artifact or a process in order to identify its components and mode of operation.

rhetoric: In ancient Greece, techniques of persuasive arguing that use the power of speech to win arguments, as opposed to the use of logical reasoning to prove the point.

science: Literally, knowledge, but for mainstream Western philosophy since Plato, it means knowledge that is universal, necessary, and certain because what we know is deducible from universal problems, not from individual facts.

semiconductor: A substance that is capable of being either a conductor of electricity or an insulator, depending on certain subtle and controllable changes in its makeup. Virtually all electronics technology since the 1960s has been based on semiconductor materials, especially silicon.

skeptics: Philosophers who deny the possibility of universal, necessary, and certain truths about nature; hence, they deny the very possibility of knowledge à la Plato-Aristotle and that anyone has achieved it.

spectroscope: An optical device that separates the many individual frequencies that make up the light incident upon it. Because the atoms of each element, when excited, radiate a distinctive set of frequencies, the elements in starlight and in laboratory specimens of matter can be identified.

spinning jenny: The name given to the single-operator–multi-spindle machine invented by James Hargreaves in the 1760s that revolutionized the production of cotton thread.

spontaneous symmetry breaking: An idea adopted by physicists in the 1960s to explain how a uniform state of affairs can evolve into a non-uniform one.

standard model: The name for the quantum theory that unified the electro-weak theory and quantum chromodynamics, hence, the electromagnetic, weak, and strong forces. Since the 1970s, this theory has matured into our most powerful theory of matter and energy.

statistical mechanics: An extension of the ideas underlying the kinetic theory of gases by Boltzmann, Maxwell, and J. Willard Gibbs and developed further by others in the 20th century, including Einstein, for deriving observable properties of systems of material bodies from statistical models of the behavior of their parts.

statistical thermodynamics: The development of the kinetic theory of gases led Boltzmann and Maxwell to apply statistical models to the laws of thermodynamics and, thus, to energy flows.

stereochemistry: The study of molecular properties that derive from the spatial arrangement of the atoms in a molecule, as distinct from the properties that derive from the atomic composition of the molecule.

string theory: The name given to one approach to the final step in unifying the four fundamental forces in nature by uniting the standard model of quantum theory with the force of gravity, now described by the general theory of relativity, which is not a quantum theory. String theory proposes that all forms of matter and energy at all levels are variations on fundamental entities called *strings* that vibrate in 11-dimensional space-time.

substance metaphysics: The view, tracing back to the teachings of Parmenides, obscure even in antiquity, that the ultimate constituents of reality are timeless, changeless "things" with fixed properties, out of which all changing things are constructed and by means of which all change is to be explained.

syllabary: A writing system in which each symbol stands for a syllable in that language and the set of symbols/syllables allows the construction of all words in that language.

symbolic logic: A symbolic notation for recording and analyzing logical arguments and their properties, developed in the 19th century and leading to a revolution in logical theory and to the creation of a new discipline: mathematical logic.

symmetry: Initially descriptive of properties of mathematical forms, in the 19th and, especially, the 20th centuries, it was made into a fundamental principle of the physical world in physics, chemistry, and biology. In physics, symmetry plays a central role in so-called gauge theories, which attempt to unify the four fundamental forces in nature by supposing that they are the "debris" of symmetries that defined

uniform forces in the very early history of the Universe but fragmented as the Universe cooled. See **spontaneous symmetry breaking**.

system: An ordered whole of mutually adapted parts keyed to the functionality of the whole.

taxonomy: A taxonomy is a systematic classification scheme that may be explicitly artificial, such as the familiar public library Dewey decimal system for classifying books (*not* created by the philosopher John Dewey!), or it may be natural. See **classification problem**.

techno-science: A name for technologies whose design and effective operation are dependent on scientific knowledge. Historically, technological innovations were quite independent of scientific theories, but this situation began to change in the 19th century. The commercial exploitation of these technologies led to the systematic coupling of science and engineering in industrial corporations, research labs, and academe.

temperament: See **tuning system**.

transistor: A device, invented at Bell Labs in 1948 by William Shockley, John Bardeen, and James Brattain, that exploits the properties of simple solid semiconductors to perform electronic functions then performed by much larger, less reliable, more expensive, and more power-consuming vacuum tubes.

tuning system: In music, a set of mathematical relationships among the notes of the octave that, when applied to the construction of musical instruments, maintains harmonies among the notes and minimizes dissonances. Tuning systems were inspired by Pythagoras's insight that mathematical relationships distinguish music from noise, but no one has discovered a single temperament or tuning system that is dissonance-free. Western music over the past 200 years employs equal temperament, a system in which the octave is divided into 12 equally spaced tones.

verisimilitude: Renaissance Humanist idea of the truthfulness of history writing that employs imaginative reconstructions and, by extension, the truthfulness of paintings that obviously are not what they seem to be.

water frame: A name given to the large water-powered version of Hargreaves's spinning jenny built by Richard Arkwright; together with related water-powered machinery for carding and weaving, the water frame initiated the mass-production era, setting the stage for the steam-power-based Industrial Revolution.

Biographical Notes

abu-Kamil (c. 850–930). Early Islamic algebraist, born in Egypt, and author of an influential text translated during the Renaissance containing 69 algebraic problems and their solutions.

al-Khwarizmi (c. 780–c. 850). The earliest known Islamic algebraist. His book of problems and solutions, along with that by abu-Kamil, influenced the shift of European mathematics from geometry to algebra.

Anaxagoras (c. 500–428 B.C.E.). Greek philosopher who proposed that all material objects were composed of a vast number of atoms of many different properties.

Archimedes (c. 287–212 B.C.E.). Greek mathematician and physicist whose combination of deduction and experiment influenced Galileo and Newton. He formulated a mathematics-based theory of the so-called simple machines and founded the science of hydrostatics.

Aristarchus of Samos (c. 320–c. 250 B.C.E.). Greek mathematician and astronomer who used trigonometry to estimate the distances to the Sun and Moon and proposed a Sun-centered Solar System that Copernicus read about in a text by Archimedes.

Aristotle (384–322 B.C.E.). Greek philosopher born in Macedonia, where his father was physician to the king. He studied with Plato for many years but then founded his own rival school, also in Athens. His comprehensive writings, especially on logic and nature, and his metaphysics, were extremely influential for more than 2000 years.

Avery, Oswald (1877–1945). American bacteriologist (born in Canada) who, together with Colin MacLeod and Maclyn McCarthy, argued in the early 1940s, based on their experiments with pneumonia bacteria, that DNA was responsible for inheritance.

Avicenna (980–1037). Islamic philosopher (Aristotelian) and physician, whose masterwork, *The Canon of Medicine*, became a standard text, alongside Galen's, for more than 500 years in European medical schools.

Bacon, Francis (1561–1626). English educational reformer; also reformer and "father" of the experimental method in modern science described in his book *The New Organon* (1620); and political opportunist. Became Lord High Chancellor under King James but was convicted of bribery.

Bernard of Clairvaux (1090–1153). Extremely influential 12th-century French theologian and Church leader, head of the Cistercian order of monasteries that extended over much of Europe. He opposed the rising secular intellectualism that became institutionalized in the emerging universities and especially persecuted the philosopher Peter Abelard.

Bernard, Claude (1813–1878). French biologist, founder of experimental medicine, and an extremely prolific author of research publications, many of whose results remain valid today. He was a positivist, favoring facts over concepts, and championed a homeostatic view of metabolism.

Bernoulli, Jacob (1654–1705). Swiss mathematician, member of a family of outstanding mathematicians in the 17th and 18th centuries, whose posthumously published *The Art of Conjecturing* pioneered probability theory and its application to political and commercial decision-making.

Bohr, Niels (1885–1962). Danish physicist, deeply philosophical as well, whose 1913 proposal to quantize the orbital motion of electrons became the foundation of quantum mechanics. In the late 1920s, with Werner Heisenberg, he formulated the Copenhagen Interpretation of quantum mechanics.

Boltzmann, Ludwig (1844–1906). Austrian physicist who founded statistical mechanics and statistical thermodynamics, posited the kinetic theory of gases (with James Clerk Maxwell), and insisted on the physical reality of atoms.

Boole, George (1815–1864). British mathematician who founded modern mathematical logic by introducing a symbolic notation for logical reasoning. His 1854 book, *An Investigation into the Laws of Thought*, was of immense influence in the history of information theory, computers, and artificial intelligence research, as well as in mathematical logic.

Boyle, Robert (1627–1691). Irish natural philosopher, heir to the title earl of Cork, and member of the Oxford group of natural philosophers that founded the Royal Society of London. Boyle conducted experiments with Robert Hooke, using an air pump of their design, on the physical properties of air; these were considered exemplary of the experimental method of the study of nature. He was an atomist and an early "scientific" chemist.

Brahe, Tycho (1546–1601). A Danish astronomer, the greatest observational astronomer of the pre-telescope era, who used instruments of his own design in an observatory funded by the Danish king. He rejected Copernicus's theory for his own version of an Earth-centered Universe. His data were used by Johannes Kepler to support Kepler's claim that the planets move in elliptical orbits.

Brunelleschi, Filippo (1377–1446). Italian painter, sculptor, and architect; famous for his rediscovery of perspective drawing and his innovative design and construction plans for the cathedral in Florence with its vast dome and cupola.

Bush, Vannevar (1890–1974). American engineer, science administrator, head of the World War II Office of Scientific Research and Development, author of the report that launched large-scale postwar federal support for research, and computer pioneer.

Cardano, Jerome (Girolamo) (1501–1576). Italian mathematician, physician, and founder of probability theory applied to gambling games. He promoted the study of algebra and published Tartaglia's solution to the cubic equation.

Clausius, Rudolf (1822–1888). German physicist and a founder of thermodynamics, Clausius introduced the concept of entropy, implying the irreversibility of time and the "heat death" of the Universe. With Maxwell and Boltzmann, he also created the kinetic theory of gases.

Comte, Auguste (1798–1857). French social and political philosopher and philosopher of science; founder of positivism—basing knowledge on facts, not ideas—and of sociology.

Copernicus, Nicolaus (1473–1543). Polish astronomer and physician whose theory of a moving Earth eventually redirected astronomy. Copernicus spent years studying in Italy after graduating from Jagiellonian University in Krakow and became proficient in Greek, translating into Latin the work of an ancient Greek poet recovered by the Humanists. It is interesting that Copernicus used virtually the same data that Ptolemy used yet reached dramatically different conclusions.

Crick, Francis (1916–2004). English physicist. After working on radar and magnetic mines during World War II, Crick collaborated with James Watson on the spatial arrangement of the atoms in DNA molecules; the two shared the Nobel Prize for that 1953 discovery.

Ctesibius (3rd century B.C.E.?). A Greek "mechanic," son of a barber, who invented a wide range of useful machines, including a complex water clock and a water organ, that were developed further by others over the next 300 years.

Curie, Marie (1867–1934). Born in Warsaw, Curie moved to Paris with a newly married older sister in 1891 and married Pierre Curie in 1895. They shared a Nobel Prize in physics in 1903 with Henri Becquerel for the discovery of radioactivity, named by Marie in 1898. After Pierre's death in 1906, Marie became the first woman professor at the Sorbonne, and in 1911, she was awarded the Nobel Prize in chemistry for her isolation of radium.

Dalton, John (1766–1844). Not the first atomist of modern times—Boyle and Newton were among his many predecessors—Dalton's *New System of Chemical Philosophy* (1807) became the foundation of 19^{th}-century atomic theories of matter, first in chemistry, later in physics.

Darwin, Charles (1809–1882). Born into a wealthy English family, Darwin married a cousin, Emma Wedgwood, and devoted his life to biological science. In addition to his theory of evolution, Darwin published extensively on many subjects and would be considered a major 19^{th}-century scientist independent of evolution.

Darwin, Erasmus (1731–1802). Charles Darwin's paternal grandfather and author of several once-popular (although later mocked) epic poems on nature that incorporated evolutionary ideas of his own.

Davy, Humphrey (1778–1829). An English physicist/chemist, Davy was extraordinarily productive in both "pure" and applied research, pioneering electrochemistry and discovering the elements sodium and potassium, as well as inventing a safety lamp for coal miners, an electric arc lamp, and a process for desalinating seawater.

Dee, John (1527–1608/09). English mathematician and mystical nature philosopher. Dee was actively involved in training ship pilots in the new mathematical techniques of navigation and in mathematical cartography, as well as promoting mathematics literacy for the public. He designed "magical" stage machinery for plays and made the first translation into English of Euclid's *Elements*.

Descartes, René (1596–1650). Descartes was a founder of modern science, modern philosophy, and modern mathematics. He promoted a deductive method for acquiring knowledge of nature and developed a rigorously mechanical philosophy of nature in which only contact forces were allowed: no action at a distance. He made epistemology (the theory of knowledge) central to philosophy, and he invented analytic geometry, making algebra central to mathematics.

De Vries, Hugo (1848–1935). Perhaps the leading figure in founding modern genetics, De Vries, a Dutch botanist, rediscovered Mendel's ignored earlier work after developing his own similar theory and gave the credit to Mendel. He developed an influential theory of mutations as the "engine" of evolution.

Dirac, Paul (1902–1984). Trained initially as an engineer at Bristol University in England, Dirac became one of the greatest theoretical physicists of the 20^{th} century. His 1929 relativistic theory of the electron became the cornerstone of quantum electrodynamics, the most important theory in physics in the mid-20^{th} century.

Dolland, John (1706–1761). An English weaver by training, Dolland became a self-educated scientist, developing and patenting the first compound microscope lenses corrected for chromatic aberration.

Dumas, Jean Baptiste (1800–1884). A French chemist who developed a technique for calculating relative atomic weights, Dumas also pioneered structuralism in chemistry through his theory of substitution of atoms in geometric "types" of molecules.

Einstein, Albert (1879–1955). Given all that has been written about him, perhaps the most amazing fact about Einstein is that, in 1904, no one, with the exception of his closest friend and sounding board, Marcel Grossmann, would have predicted his subsequent accomplishments. In spite of his epochal 1905 papers, his reputation flowered only from 1911. He was appointed director of the Kaiser Wilhelm Institute for Physics in 1914 and, in 1915, published the general theory of relativity. He resigned in 1933 and settled at the Institute for Advanced Studies in Princeton, which was created in part to provide a "home" for him.

Empedocles (c. 490–430 B.C.E.). An early Greek natural philosopher who formulated a four-element theory of matter—earth, air, fire, water—that, together with attractive and repulsive forces, lasted into the 18^{th} century.

Epicurus (341–270 B.C.E.). A Greek moral philosopher primarily, who adopted Democritus's atomic theory of matter and adapted it to his moral and social views. Against Anaxagoras, he held that atoms differed only in size, shape, and weight and that all properties of material objects derived from diverse configurations of their constituent atoms.

Erasmus of Rotterdam (1466–1536). One of the great Humanist scholars and the first author, it is said, to live wholly off his fees from publishers based on the sale of his books, especially his bestselling *In Praise of Folly*.

Euclid (c. 300 B.C.E.). A Greek mathematician, whose synthesis of 200 years of Greek mathematics into an axiomatic system in his book, *The Elements*, was of incalculable influence in Western philosophy, mathematics, and science, right down to the present day. Almost nothing is known of his personal life.

Euler, Leonhard (1707–1783). One of the greatest mathematicians of all time and, perhaps, the most productive. Born in Basel, he lived most of his adult life in Germany or Russia, writing on pure and applied mathematical problems even after he became blind. He encompassed all of mathematics but contributed especially to "analysis," another name for algebra, and made important contributions to astronomy, optics, mechanics, and engineering mechanics: the rigorous solution of engineering problems.

Faraday, Michael (1791–1867). A gifted and highly prolific experimental physicist and chemist, Faraday was effectively wholly self-educated, though he was never proficient in mathematics. He became Humphrey Davy's assistant at the Royal Institution in London through an accident, and he was later Davy's successor. He discovered the dynamo principle in 1830, and invented the concepts of electric and magnetic fields and lines of force, predicting that light was an electromagnetic phenomenon. He rejected the atomic theory.

Fischer, Emil (1852–1919). A German organic chemist famous, first, for his synthesis of sugars and, later, for synthesizing amino acids, then combining them to form proteins. His lock-and-key metaphor for how enzymes act on cell molecules was and remains a powerful heuristic in molecular biology.

Fourier, Joseph (1768–1830). French mathematical physicist whose *Analytical Theory of Heat* was extremely influential, both in terms of its equations and in separating descriptive physics from metaphysics. His use of simple trigonometric functions to model any periodic behavior, however complex, remains one of the most powerful tools in science and engineering.

Francesca, Pierro della (1420–1492). One of the great Renaissance painters, he was also a mathematician and wrote perhaps the first account of perspective drawing as a mathematical technique, *De prospectiva pingendi*. This then became a staple of 15th-century artist's manuals, especially after Leone Alberti's influential *Della pittura* (1436).

Galen (c. 129–199). Greek physician and medical theorist, prolific writer and experimenter, and physician to various Roman emperors. Galen was to medieval and Renaissance medicine what Aristotle was to philosophy: the authority. His theory of health as a balance among four humors was influential into the 19th century, though his anatomy and physiology were overthrown in the 16th and 17th centuries.

Galilei, Galileo (1564–1642). Italian mathematical physicist and founding "father" of modern science, combining deductive reasoning and extensive experimentation à la Archimedes. Born in Pisa, he became a professor of mathematics first there, then in Padua, after his telescope-based observations of the Moon's irregular surface and Jupiter's moons made him famous. His condemnation for teaching Copernicus's theory as true came in 1633.

Galilei, Vincenzo (1520–1591). Galileo's father; Vincenzo was a musician and a music theorist at a time of intense controversy over tuning systems and their mathematical models. He broke with his teacher, Zarlino, who defended an expanded Pythagorean system, in favor of equal-temperament tuning. Vincenzo's books reveal clever experimentation to support his claims.

Gamow, George (1904–1968). Born in Russia, Gamow moved west after earning his Ph.D., studying the new quantum physics first in Germany, then with Bohr in Copenhagen, before settling in the United States. He predicted the quantum tunneling effect in 1929; proposed the Big Bang theory of cosmology in the late 1940s, predicting the microwave background radiation detected in 1963; and proposed that the sequence of bases in the Watson-Crick DNA model was a code for producing proteins out of amino acids.

Gutenberg, Johann (c. 1397–1468). Widely but by no means unanimously considered the inventor of movable-metal-type printing. Almost nothing about Gutenberg's life and work is free of uncertainty except that he was born in Mainz on the Rhine River, apprenticed as a goldsmith but became a printer, and printed a number of deluxe copies of the Bible using metal type in the early or mid-1450s.

Guth, Alan (1947–). American physicist who, in 1980, proposed the inflation model of the Universe, preceding Gamow's Big Bang. Subsequent refinement by others, as well as by Guth, and detailed observation of the microwave background radiation's minute non-uniformities led to a consensus in favor of the inflation model.

Hegel, G. F. W. (1770–1831). A German philosopher, Hegel was the single most influential philosopher of the 19th century, the creator of a system that integrated deduction, history, and time. He held that reality is the deterministic unfolding in time of reason, which manifests itself as nature and as the human mind.

Heisenberg, Werner (1901–1976). A German physicist, Heisenberg invented, in 1925, what was later called "quantum mechanics." Over the next five years, he formulated the famous uncertainty principle and, in collaboration with Bohr, an interpretation of quantum theory that was probabilistic and strictly empirical. Bohr broke with Heisenberg over the latter's role as head of Germany's wartime atomic bomb research effort.

Helmholtz, Hermann (1821–1894). A physicist and pioneering neuro-physiologist, Helmholtz was Germany's leading scientist in the second half of the 19th century. He formulated the scientific principle of the conservation of energy, studied the transmission of signals in nerves, and developed a theory of hearing that became the basis for designing stereo audio equipment.

Heraclitus (c. 540– c. 480 B.C.E.). Other than that he lived in the Greek city of Ephesus in what is now Turkey and probably wrote before Parmenides, not after, nothing is known about Heraclitus. That he wrote one or more works on philosophy is known, and in these, he clearly insisted on the reality of change, suggesting that the object of knowledge is the *logos*, or orderliness, of processes, not timeless objects and their properties.

Hero (or Heron) of Alexandria (flourished c. 60). A Greek "engineer" before the term existed, Heron created a school for engineering in Alexandria and left behind a number of books describing mechanical and optical machines based on physical principles, including the action of compressed air, water, and steam.

Hertz, Heinrich (1857–1894). A German physicist who, in the 1880s and independently of Oliver Lodge in England, confirmed the prediction of Maxwell's theory of electromagnetic waves traveling freely through space. This finding became the basis for the broadcast radio technology developed 10 years later by Guglielmo Marconi.

Hippocrates (c. 460–377 B.C.E.). A Greek physician, medical theorist, founder of a medical school, and teacher. His school was on the island of Kos, where he was born, and pioneered a wholly naturalistic approach to illness and treatment.

Hoffman, August (1818–1892). An eminent German organic chemist, Hoffman was called to London by Prince Albert to teach at the new Royal College of Chemistry, where his student William Perkin synthesized the first artificial dye from coal tar. Hoffman later returned to Germany, founded the German

Chemical Society, and played an active role in German chemists' dominance of the commercial dye industry and the many important industrial applications of coal-tar chemistry.

Holland, John H. (1929–). American computer scientist and creator of "genetic" algorithms: computer programs based on Darwinian evolution and genetic theory that display adaptation. Holland is a theorist of complex systems and self-organization and was actively involved with the Santa Fe Institute and World Economic Forum, in addition to teaching computer science at the University of Michigan.

Hooke, Robert (1635–1703). An English natural philosopher, Hooke collaborated with Robert Boyle on experiments to determine the properties of air, studied the properties of metallic springs, and invented a spiral spring-controlled balance wheel for a watch (replacing the pendulum). He was a pioneering microscopist, invented numerous scientific instruments, attempted a theory of gravity, and played a leading role in the rebuilding of London after the great fire of 1665.

Hoyle, Fred (1915–2001). An English physicist, Hoyle, together with Herman Bondi and Thomas Gold, proposed the Steady State theory of the Universe as a counter to Gamow's Big Bang theory, a name mockingly assigned by Hoyle. Hoyle also wrote science fiction and argued that life came to Earth from space.

Hubble, Edwin (1889–1953). Hubble was a midwestern American astronomer who became director of the Mt. Wilson observatory in 1919 and, with its 100-inch reflecting telescope, soon discovered that the sky was filled with galaxies, contrary to the consensus view that the Milky Way was the Universe. In 1929, Hubble announced the expansion of the Universe and devoted the rest of his life to observations aimed at determining its size and age.

Huygens, Christiaan (1629–1675). A Dutch mathematical physicist, mathematician, and astronomer, Huygens was a central figure in the creation of modern science, first to demonstrate that curved motion required a force and to recognize Saturn's rings as such. He developed a wave theory of light; made important contributions to algebra, probability theory, optics, and mechanics; developed accurate pendulum clocks and their theory; and independently of Hooke, invented a spring-balance wheel-driven watch.

Joule, James Prescott (1818–1889). An English physicist whose experiments on the quantitative relationship of mechanical motion and heat led, in the hands of others, to the idea of conservation of energy and the creation of thermodynamics.

Kekule, Friedrich August (1829–1886). A German organic chemist, Kekule is best known for his contributions to structural chemistry, especially the hexagonal ring structure of benzene and his prediction of the tetrahedral form of the carbon atom's valence bonds, which became the basis of polymer chemistry in the 20^{th} century.

Kelvin, Lord/William Thomson (1824–1907). An Irish-born mathematical physicist, Thomson was knighted for designing and overseeing the laying of the first successful transatlantic telegraph cable in 1866. He played key roles in the development of thermodynamics and electromagnetic field theory but was wedded to the reality of the aether and believed that the Earth was probably only 100 million years old and, thus, too young for Darwin's theory of evolution to be correct.

Kepler, Johannes (1571–1630). A German astronomer who first formulated the modern conception of the Solar System, which is very different from that of Copernicus. The data Kepler used came from Tycho Brahe, whose assistant he became when Brahe relocated to Prague. When Brahe died, Kepler took the data and applied them, first, to a Pythagorean theory of his own that failed to match the data; he then let the data guide his theorizing, arriving at elliptical orbits, not circular ones.

Khayyam, Umar (1048–1131). Islamic mathematician, astronomer, and poet who had effectively achieved a general solution to the cubic equation centuries before Tartaglia, and whose text *Algebra* anticipates Descartes' invention of analytic geometry.

Koch, Robert (1843–1910). A German biologist who, with Louis Pasteur, founded bacteriology and formulated the germ theory of disease. His Nobel Prize was for discovering the bacterium that causes tuberculosis, then rampant, but he developed methodologies for isolating microorganisms that resulted in his discovery of anthrax and cholera bacteria, as well.

Lamarck, Jean-Baptiste (1744–1829). Lamarck was almost 50, with very modest credentials as a botanist, when in 1793 the committee running the French revolutionary government made him a national professor of invertebrate zoology. His theory of the emergence of all life forms from a common ancestor by natural forces was an important predecessor of Charles Darwin's theory, and one of which Darwin was acutely aware.

Laplace, Pierre-Simon (1749–1827). A French mathematical physicist and theoretical astronomer of great influence who managed to prosper under Louis XVI, the revolutionary government, Napoleon, and the restored Bourbon monarchy! He proved the long-term stability of the Solar System under Newtonian gravitation, developed a mathematical theory of the origin of the Solar System out of a cloud of gas, published an important essay on probabilities, and championed a rigorous materialistic determinism.

Laurent, Auguste (1807–1853). At one time a graduate student of Dumas (above) contemporary with Pasteur, Laurent seems first to have developed a theory that the spatial arrangement of atoms in a molecule determines properties of the molecule. His "nucleus" theory was subsequently overwhelmed by Dumas' extension and adaptation of it, a source of some bitterness to Laurent.

Lavoisier, Antoine de (1743–1794). Unlike Laplace, Lavoisier did not survive the French Revolution. His research led him to believe that combustion involved combination with one component of air, which he named *oxygen*. This led him to propose a "revolution" in chemistry, one that laid the foundation for the modern theory of elements. His widow married Benjamin Thompson (below).

Leavitt, Henrietta Swan (1868–1921). An American astronomer, Leavitt graduated from what became Radcliffe College and became a human "computer" at Harvard College Observatory, eventually rising to head of a department there. Her specialty was variable stars, and she identified 2400 new ones, especially the Cepheid variables that she recognized as providing a cosmic "ruler" for measuring absolute cosmic distances.

Leibniz, Gottfried (1646–1716). A German philosopher, mathematician, and physicist, Leibniz, like Descartes, was influential in all three of those areas. He formulated a rationalist, deterministic but anti-materialistic philosophy; invented the calculus independently of Newton (publishing first), using a notation that has become universal; anticipated late-19th-century topology and symbolic logic; and first called attention to the quantity in mechanics that we call kinetic energy.

Liebig, Justus von (1803–1873). A German chemist of enormous influence, partly through his own mechanistic theories of chemical reactions, but largely through the many subsequently prominent students trained in his laboratory. Liebig studied the chemistry of fermentation long before Pasteur and never accepted that the cause was a living organism (yeast). He also dismissed the significance of atomic structure within molecules and the early germ theory of disease.

Linnaeus, Carl (1707–1778). Swedish botanist whose binomial system for classifying plants based on their sexual organs became universally adopted. An aggressive proponent of his system as a natural one, he was forced to acknowledge late in life that it seemed to be conventional, which implied that species and genera were conventional, not immutable features of reality.

Lucretius (c. 99/94–c. 55/49 B.C.E.). Roman poet and natural philosopher whose epic poem in hexameters, *On the Nature of Things*, disseminated Epicurus's atomic theory of matter and morality, somewhat modified by Lucretius.

Mach, Ernst (1838–1916). An Austrian experimental physicist of note but remembered mostly for his theory of scientific knowledge as based on perceptual experience and incapable of penetrating to a reality behind experience, which is why he opposed the reality of atoms.

Maxwell, James Clerk (1831–1879). One of the greatest of all mathematical physicists, Maxwell was born in Edinburgh. He became, in 1871, the first professor of experimental physics at Cambridge University and established the Cavendish Laboratory there. Under the leadership of Lord Rayleigh, J. J. Thomson, and Ernest Rutherford, the laboratory became a leading center for important new developments in physics into the 1950s.

Mendel, Gregor Johann (1822–1884). An Austrian monk and botanist, Mendel lived in the Augustinian monastery in Brünn (Brno) effectively for the last 40 years of his life, becoming abbot in 1868, which ended his experimental work on plants. Mendel twice failed to pass the exams for an advanced teaching license. In between failures, he spent three years at the University of Vienna studying science and mathematics and, on returning to the monastery in 1854, began the years-long breeding experiments that resulted in his posthumous fame.

Mercator, Gerard (1512–1594). Mercator was born in Flanders and, after a religious crisis that led to his becoming a Protestant, studied mathematics in order to apply it to geography and cartography. He migrated to the Lutheran town of Duisberg in Germany in 1552, living there for the rest of his life and producing the first modern maps of Europe over the next 10–15 years. In 1569, he produced a map of the Earth based on his projection of its surface onto the inner surface of a cylinder. He coined the term *atlas* for a collection of maps.

Morgan, Thomas Hunt (1866–1945). An American geneticist, Morgan began his career as an embryologist, studying fertilization at the cell level. In 1907, after becoming a professor at Columbia University, he shifted his research to the mechanism of heredity. Initially critical of the gene concept, he became a major proponent of it after 1910 and trained a number of influential students, among them, Hermann Muller (below).

Morse, Samuel F. B. (1791–1872). Morse was a financially unsuccessful American artist who, returning from Europe in 1832 after a three-year stay, learned about electromagnetism from a fellow passenger. Morse became obsessed with the idea of an electric telegraph and, eventually, with advice from the physicist Joseph Henry, among others, succeeded in getting Congress to fund a pilot line from Baltimore to Washington in 1843. This inaugurated the commercialization of the telegraph using Morse's code.

Muller, Hermann Joseph (1890–1967). Born in New York City, Muller attended Columbia University and received his Ph.D. under Thomas Hunt Morgan's direction in 1916, by which time he was Morgan's active collaborator in research and publication. His Nobel Prize–winning discovery of genetic mutations induced by X-rays was made while he was at the University of Texas, but he spent the mid-1930s at the Institute of Genetics in the Soviet Union, leaving because of his opposition to Lysenko's anti-Mendelian theories, which were approved by Stalin. He returned to the United States in 1940.

Müller, Johannes (1801–1858). Müller was a German physiologist who was committed to the vitalist view of life and to Romantic nature philosophy, yet his research laboratory, first at the University in Bonn, then in Berlin, was the training ground for an extraordinary group of influential life scientists, virtually all of whom were mechanists!

Newton, Isaac (1642–1727). Great both as an experimental and as a theoretical physicist, Newton's "miraculous year" was 1665, when an outbreak of plague caused Cambridge University to close and he went home. In notebooks he kept then, there are the clear antecedents of most of his great ideas in

mechanics, optics, mathematics, and astronomy. Newton devoted much of his time (and the bulk of his surviving writing) to biblical chronology and interpretation and alchemical researches, yet he was the single most important architect of modern science. He was autocratic as warden of the Royal Mint and as president of the Royal Society, and suffered a mental breakdown in the early 1690s, perhaps poisoned by his alchemical experiments.

Pacioli, Luca (1445–1517). Renaissance mathematician, befriended by Piero della Francesca, and tutor to, and friend of, Leonardo da Vinci. Pacioli published a summary of 15th-century mathematics in 1494 that included an extensive description of double-entry bookkeeping and commercial arithmetic generally. His 1509 book, *On the Divine Proportion* (the famous Greek "golden ratio"), was written in Italian and illustrated by Leonardo. It describes the application of mathematical proportions to artistic depictions, for example, of the human body.

Parmenides (born c. 515 B.C.E.). One of the earliest and most influential Greek philosophers, in spite of the fact that his only work is lost, a poem of some 3000 lines, apparently, of which 150 are known because they are cited by other Greek philosophers. Parmenides's rigorously logical characterization of the concepts of being and becoming provoked atomistic theories of nature, in contrast to Heraclitus's process approach and influenced the view, dominant since Plato and Aristotle, that reality was timeless and unchanging and that knowledge and truth were universal, necessary, and certain.

Pascal, Blaise (1623–1662). A French mathematician and physicist, in 1654, Pascal had a vision that led him to cease almost all secular intellectual activity, although he designed a public transportation system for Paris that was built the year he died. He made important contributions to projective geometry and probability theory before turning to philosophical and theological themes. His *Pensées* has been in print since publication.

Pasteur, Louis (1822–1895). A French chemist, Pasteur became the very embodiment of the natural scientist, for the French at least. With Robert Koch, he formulated the germ theory of disease, but he also contributed to the creation of stereochemistry and established the value of chemical science to industry through his work on fermentation, pasteurization, vaccination, and silkworms.

Petrarch (1304–1374). An Italian poet, born in Arezzo, Petrarch was named Poet Laureate of Rome in 1341, largely because of an epic poem in Latin on the great Roman general Scipio Africanus, who defeated Hannibal. He was a great admirer of Dante, whose *Comedy* (called "divine" by Petrarch's admirer Boccaccio) was in Italian, not Latin. Petrarch instigated the Humanist movement and the collection of ancient manuscripts in order to recover models of the best writing, feeling, and thinking.

Planck, Max (1858–1947). The German physicist who initiated the quantum physics "revolution" with his 1900 solution to the black-body radiation problem. Planck remained in Germany in spite of his outspoken opposition to Nazi policies, and his only surviving son was gruesomely executed as an accomplice to an assassination plot on Hitler. After World War II, the Kaiser Wilhelm Institute was renamed the Max Planck Institute(s).

Plato (428–347 B.C.E.). The quintessential Greek philosopher from the perspective of the subsequent history of Western philosophy, Plato was one of Socrates's students and the teacher of Aristotle. "Plato" was his nickname—his given name was Aristocles—and he was initially a poet and, as a young man, a competitive wrestler. He was an elitist by birth and inclination, and the relationship between the "real" Socrates and the character in Plato's dialogues is, at best, loose.

Prigogine, Ilya (1917–2003). A Russian-born chemist who was raised, educated, and rose to fame in Belgium. He moved to the United States in 1961, first to the University of Chicago, then to the University of Texas, while retaining his Belgian academic affiliation. He demonstrated that many far-from-equilibrium physical and biological systems were self-organizing and stable and displayed adaptation.

Pythagoras (c. 572–c. 479 B.C.E.). A Greek philosopher and mathematician with a strong metaphysical/mystical bent. Pythagoras promoted a total lifestyle conception of wisdom and created schools and self-contained communities in which people could live in accordance with his teachings. His most enduring accomplishments are the idea of deductive proof, which essentially created mathematics as we know it, and the idea that mathematical forms are the basis of all natural order.

Quetelet, Adolphe (1796–1874). A Belgian astronomer-in-training whose lasting achievement was social statistics, especially the idea of statistical laws, which challenged the prevailing belief that laws were necessarily and exclusively deterministic.

Rumford, Count/Benjamin Thompson (1753–1814). A Royalist, Thompson fled the colonies to England in 1776, returning to the colonies as a British officer, then went to Europe after the war. He distinguished himself in Bavaria as minister of war and minister of police, becoming de facto prime minister, and was made count of the Holy Roman Empire in 1791. He instituted workhouses for the poor and new uniforms, marching formations, diet, and weapons for the army. In addition to his experiment in 1799, which proved that heat was motion, he founded the Royal Institution in London to teach science to the public, enjoyed a short-lived marriage to Lavoisier's widow, and endowed a science professorship at Harvard.

Rutherford, Ernest (1871–1937). Born in New Zealand, Rutherford went to Cambridge in 1895 to study with J. J. Thomson, then to McGill in Montreal as professor of physics, before returning for good to England in 1907. He was professor of physics in Manchester until 1919 when he moved to the Cavendish Laboratory at Cambridge as J.J. Thomson's successor. His 1908 Nobel Prize was in chemistry for his work on radioactivity, but he and his students made many fundamental contributions to atomic and nuclear physics.

Schleiden, Mathias (1804–1881). A German botanist who, with Theodor Schwann proposed the cell theory of life. Schleiden was originally a lawyer who turned to the study of botany after a failed suicide attempt. In 1838, he published an essay in a journal edited by Johannes Müller, proposing that cells are the basis of all plant life and are formed in a process that begins inside the nucleus of a progenitor cell. In an 1842 text, he argued that a single, mathematically describable physical force underlies all natural phenomena, including life.

Schrödinger, Erwin (1887–1961). Schrödinger was born in Vienna and received his Ph.D. there, in physics. He was an Austrian artillery officer during World War I and became a professor of physics in Zurich in 1921. It was at Zurich in 1925 that he developed his version of what was called "quantum mechanics," which unlike Heisenberg's version, was based on 19th-century deterministic wave physics and was interpretable as offering a conceptual "picture" of microphysical nature. Succeeding Max Planck as professor of theoretical physics in Berlin in 1927, he fled the Nazi takeover in 1933 for London; he returned to Vienna in 1936, only to flee again, this time, to Ireland until 1956 and yet another return to Vienna.

Schwann, Theodor (1810–1882). Schwann was born and educated in Germany and served from 1834–1838 as Johannes Müller's laboratory assistant in Berlin, but after a paper on yeast as a factor in fermentation was derided, he accepted a professorship in Belgium, where he spent his entire academic career. It was his 1839 book, *Microscopical Researches on the Similarity in the Structure and Growth of Animals and Plants*, that proposed the cell theory as the universal basis of both plants and animals, hence, of all life forms. Schwann thus extended Schleiden's cell theory of plant life, with which he was quite familiar; for this reason, the universal cell theory is attributed to them jointly.

Shannon, Claude (1916–2001). Shannon was born in Michigan and did his graduate work at MIT, receiving his master's and Ph.D. in mathematics in 1940 (with these in two different areas of applied mathematics). He joined Bell Labs in 1941. During the war, he worked on mathematical models for predictive antiaircraft firing. The technological applications of Shannon's theories in computer logic

circuit design, telephone switching circuits, computer networks, and electronic and optical information transmission and storage devices have had an incalculable social impact.

Shapley, Harlow (1885–1972). An American astronomer, Shapley originally planned to become a journalist after attending a new university journalism program in his home state of Missouri. He became an astronomer because the program was delayed and he chose to take astronomy courses while he waited! At Princeton from 1911 to 1914, Shapley did important observational work on double stars and variable stars and was, thus, well positioned, after his move to Mt. Wilson Observatory in 1914, to use Leavitt's variable-star–based cosmic "ruler" to estimate the size of the Milky Way and distances to the Magellanic Clouds.

Swift, Gustavus (1839–1903). Born and raised on Cape Cod, Swift dropped out of school after eighth grade and, at the age of 16, had his own butchering business, which prospered and expanded with each relocation. He and his partner moved to Chicago in 1875, and in 1878, he went his own way, commissioning the first successful refrigerated rail car. It was delivered in 1880, and a year later, he had 200 cars carrying 3000 dressed beef carcasses a week to New York City.

Tartaglia, Niccolò (aka Niccolò Fontana) (1499–1557). Tartaglia was a mathematician and engineer; as a boy, he was slashed through the cheek by a French knight, hence, his nickname, "stammerer" ("Tartaglia"). He discovered the general solution to the cubic equation (though Khayyam may have anticipated him, independently) and the parabolic trajectory of cannonballs. He made the first Italian translations of Euclid and Archimedes.

Thales (c. 624/620–c. 570/546 B.C.E.). According to Aristotle, Thales was the first Greek natural philosopher, speculating that water or some fluid was the universal "stuff" out of which all material objects were composed.

Thompson, Benjamin. See **Count Rumford**.

Thompson, Joseph John (1856–1940). Thompson was born near Manchester in England and planned on studying engineering, but because the family could not afford the apprenticeship fees for engineering training, he switched to physics, winning a scholarship to Cambridge—where he spent the rest of his life—and a Nobel Prize (in 1906). In 1884, he succeeded Lord Rayleigh, who had succeeded Maxwell, as Cavendish Professor of Physics and was succeeded in turn by Ernest Rutherford when he resigned in 1919 to become Master of Trinity College. His Nobel Prize was for discovering the electron and for studies of the conduction of electricity in gases, establishing the electron as a particle. (Thompson's son George won the Nobel Prize for physics in 1937 for showing that electrons behaved like waves!)

Thomson, William. See **Lord Kelvin**.

Virchow, Rudolf (1821–1902). A German biologist and another student of Johannes Müller's, Virchow focused his research on the cell, especially cellular pathologies, which he believed to be the basis of all disease. In the mid-1850s, he insisted on the principle that cells arise only from other cells by a process of division, utterly rejecting the possibility of spontaneous generation or other cell formation theories current at the time, among them, Schleiden's. His text *Cellular Pathology* was influential, and its ideas were the basis of his rejection of the Pasteur-Koch germ theory of disease. Like most biologists prior to the mid-1870s, Virchow defended the inheritance of acquired characteristics.

Vitruvius (fl. 1st century B.C.E.). Almost nothing is known about Vitruvius's personal life (even his full name is conjectural!), but the influence of his *On Architecture* since the Renaissance has been immense. The book was discovered in 1414 by the Humanist scholar Poggio Bracciolini and popularized by Leone Alberti in a major work on art and architecture, *On the Art of Building* (1452), that was dedicated to Pope Nicholas V, who initiated the construction of the Vatican complex.

Wallace, Alfred Russel (1823–1913). Wallace was born into a poor Welsh family and left school at 14 to become a surveyor under an older brother. Self-educated by local standards, he became a teacher at a workingman's school in 1844 when he met a young naturalist, Henry Bates, and discovered his true vocation. They traveled to Brazil together in 1848 to gather specimens for wealthy British collectors, and Wallace returned to England with crates' worth, all of which were lost when the ship sank approaching the English coast. He then spent 20 years, from 1842–1862, in the Malay Peninsula, collecting specimens and studying the distribution of plants and animals; this led to the essay proposing evolution by natural selection that he sent to Darwin in 1858 for his advice as to publication. Wallace became one of England's greatest naturalists, but he never accepted the extension of evolution to man. He was an aggressive supporter of radical social reform and of "scientific" spiritualism, believing in life after death.

Watson, James (1928–). Watson studied zoology at the University of Chicago and received his Ph.D. from Indiana University in 1950, where he was influenced by T.H. Morgan's former student Hermann Muller. Watson's Ph.D. thesis, under Salvador Luria, was on the effect of X-rays on bacterial cell division. In 1951, he met Maurice Wilkins, who had with him copies of X-ray diffraction patterns of DNA crystals, and Watson decided to spend time at the Cavendish Laboratory at Cambridge studying them. There he met Francis Crick and began their epochal collaboration.

Watt, James (1736–1819). A Scottish mechanic and instrument maker who opened a shop in Glasgow circa 1756 and began working for faculty members at Glasgow University. While repairing a Newcomen engine, Watt saw that the efficiency would be improved dramatically by separating the cylinder and the condenser. He built a crude working model in 1765, but a reliable engine for commercial application required solving problems involving valves, precision machining (for the day), and lubricants. Watt's partnership with Mathew Bolton from 1774 was heaven-sent, initiating the steam-power–based Industrial Revolution of the 19th century and freeing Watt to develop progressively more efficient and more useful designs that Bolton put into production.

Bibliography

Agricola, Georgius (Georg Bauer). *De Re Metallica*. Herbert Hoover, trans. New York: Dover, 1950. Bauer was a sort of chief medical officer for the Fugger mines in the 16th century, and this is a translation—by Herbert Hoover before he became president—of his survey of contemporary technologies related to mining, including medical technologies, of course.

Allen, Garland. *Life Science in the Twentieth Century*. Cambridge: Cambridge University, 1981. A solid history of biology in the first half of the 20th century.

Aristotle. *The Complete Works of Aristotle*. Jonathan Barnes, ed. Princeton: Bollinger, 1982. Aristotle's logical works include the *Prior* and *Posterior Analytics* and the *Rhetoric*. His scientific works include *On the Heavens*, *On Physics* (nature), *On the Soul*, *On Generation and Corruption*, and the *Generation of Animals*.

Augustine. *Confessions*. London: Penguin Books, 1961. Book 11 contains his penetrating analysis of time, and his style of writing reveals how intertwined his religious commitments were with his reasoning.

Bacon, Francis. *The New Organon*. New York: Bobbs-Merrill, 1960. Part 1 is the account of what we think of as the modern experimental method. Important and very readable.

Baeyer, Hans Christian von. *Information: The New Language of Science*. New York: Phoenix Press, 2004. A short, clear, current account of the emergence of information as a feature of reality on a par with matter or even superior to it as the "stuff" of reality.

Baird, Davis. *Thing Knowledge: A Philosophy of Scientific Instruments*. Berkeley: University of California Press, 2004. A provocative monograph on the connections among ideas, the artifacts we call instruments, and knowledge claims.

Barabasi, Alberto-Laszlo. *Linked: The New Science of Networks*. Cambridge, MA: Perseus, 2002. This book is a joy to read, and without having to confront an equation, you will learn a great deal about how mathematical forms can have properties that affect physical systems—here, networks, which are, of course, relational structures. Very highly recommended.

Barber, Elizabeth Wayland. *The Mummies of Urumchi*. New York: Norton, 1999. Barber is a historian of ancient textiles, and this analysis of what we can learn from the clothing on a mummified, 3200-year-old Caucasian family found in central Asia is fascinating. Highly recommended.

Barbour, J. Murray. *Tuning and Temperament*. New York: Dover, 2004. A clear and correct account of the responses of musicians, composers, musical instrument makers, and philosophers to Pythagoras's claim that musical harmonies are mathematical. Recommended.

Bernoulli, Jacob. *The Art of Conjecturing*. Edith Dudley Sylla, trans. Baltimore: Johns Hopkins University Press, 2006. Sylla's introductory chapter to Bernoulli's 1709 text is a wonderful essay on the early history of applying mathematics to real-world decision-making. Recommended.

Bernstein, Peter. *Against the Gods: The Remarkable Story of Risk*. New York: Wiley, 1998. A well-written and highly informative popular history of practical applications of probability theory. Recommended.

Bertalanffy, Ludwig von. *General Systems Theory*. New York: George Braziller, 1976. A reprint of Bertalanffy's pioneering text on the systems idea. Dated, of course, but reading it puts you in touch with original thinking.

———. *Problems of Life*. New York: Dover, 1952. Here, Bertalanffy focuses on applying the systems concept in biology but also makes connections to other sciences.

Billington, David P. *The Innovators: The Engineering Pioneers Who Made America Modern*. New York: Wiley, 1996. An easy-to-read, insightful series of vignettes about the commercialization of key technological innovations in the 19th century. Recommended.

———, and David P. Billington, Jr. *Power, Speed and Form: Engineers and the Making of the Twentieth Century*. Princeton: Princeton University Press, 2006. Billington and his historian son extend the earlier model to eight key 20th-century innovations.

Biringuccio, Vannoccio. *Pirotechnia*. New York: Dover, 1990. Like Agricola's book, this is a 16th-century survey of technologies available to "engineers" of the period, focusing on uses of fire, heat, and explosives but ranging more widely.

Bolter, J. David. *Turing's Man*. Chapel Hill: University of North Carolina Press, 1984. Bolter was a humanist scholar responding to the very early stages of the computer's penetration of society, but his book remains a valuable reflection on a socially transformative technology.

Braudel, Fernand. *The Wheels of Commerce: Civilization and Capitalism, 15th–18th Century*. New York: Harper and Row, 1979. This is the second volume of a magisterial three-volume work of social history. Highly recommended.

Buchwald, Jed Z., and Andrew Warwick, eds. *Histories of the Electron*. Cambridge, MA: MIT Press, 2001. A first-rate professional history of science, this collection of essays examines in detail the discovery of the electron in 1897, the response of physicists to that discovery, and the impact of the electron on physics theory.

Carroll, Sean B. *Endless Forms Most Beautiful: The New Science of Evo Devo*. New York: Norton, 2005. Evolutionary development, the *Evo Devo* of the title, is a leading expression of Darwinian theory today, and this book describes it very well.

Cercignani, Carlos. *Ludwig Boltzmann: The Man Who Trusted Atoms*. Oxford: Oxford University Press, 1998. A new, very good biography of Boltzmann by a physicist; describes his contributions to physics, among them, to the physical reality of atoms. Recommended.

Ceruzzi, Paul. *A History of Modern Computing*. Cambridge, MA: MIT Press, 2003. A good history by a professional historian of technology.

Chandler, Alfred D., and James W. Cortada. *A Nation Transformed by Information*. Oxford: Oxford University Press, 2000. The authors examine the impact of information technologies on U.S. society.

Cline, Barbara Lovett. *Men Who Made a New Physics*. Chicago: University of Chicago Press, 1987. Very readable, short intellectual biographies of a handful of physicists who fashioned relativity and quantum theory in the first half of the 20th century. Recommended.

Cohen, I. Bernard. *The Birth of a New Physics*. New York: Norton, 1985. Cohen was a great historian of early modern science; this short monograph is an account of mechanics emerging as the foundation of physics in the 17th century. Recommended.

Cohen, Jack, and Ian Stewart. *The Collapse of Chaos*. New York: Viking, 1994. This lively book focuses on the maturation of chaos theory into complexity theory, carrying James Gleick's earlier book *Chaos* into the early 1990s.

Coleman, William. *Biology in the Nineteenth Century*. Cambridge: Cambridge University Press, 1977. An excellent, short history of major ideas at the heart of 19th-century biological theories. Highly recommended.

Cooper, Gail. *Air-Conditioning America*. Baltimore: Johns Hopkins University Press, 1998. A good history of the co-evolution of air-conditioning technology and its commercial, industrial, and residential applications.

Copernicus, Nicolaus. *On the Revolutions of the Heavenly Spheres*. New York: Prometheus, 1995. You can—and should—read book 1 of this epochal work to experience Copernicus's revolutionary idea firsthand. (The rest of the book requires serious effort!)

Cortada, James W. *Before the Computer*. Princeton: Princeton University Press, 2000. An interesting history of calculator and tabulator technologies in the 19th and early 20th centuries and how they affected the conduct of business and business strategies.

Cutcliffe, Stephen H., and Terry Reynolds. *Technology and American History*. Chicago: University of Chicago Press, 1997. An excellent collection of essays from the journal *Technology and Culture* on how technologies have changed American society. Recommended.

Darwin, Charles. *On the Origin of Species*. Cambridge, MA: Harvard University Press, 1966. Reading Darwin's argument for what we call evolution is a powerful experience. Highly recommended, as is comparing it to Alfred Russel Wallace's essay "On the Tendency of Varieties to Diverge Indefinitely from Their Type" (download it from the Internet).

———. *The Descent of Man*. London: Penguin, 2004. The extension of evolution to mankind came 12 years after *Origin* (and Wallace rejected it!). Highly recommended.

Debus, Alan. *Man and Nature in the Renaissance*. Cambridge: Cambridge University Press, 1978. A classic monograph in a wonderful series of history-of-science monographs by Cambridge University Press. Recommended.

Dennett, Daniel C. *Darwin's Dangerous Idea*. New York: Simon and Schuster, 1996. Provocative, even controversial, but Dennett is a leading philosopher and a defender of a strict, strictly atheistical reading of Darwinism.

Descartes, René. *Discourse on Method* and *Rules for the Direction of the Mind*. London: Penguin, 1999. These two short works are Descartes' prescriptions for a deduction-based methodology as the foundation for modern science.

———. *The Geometry*. New York: Dover, 1954. Title notwithstanding, this long essay, published in 1637, proposes substituting algebra for geometry as the basis of mathematics.

Dohrn-van Rossum, Gerhard. *History of the Hour*. Chicago: University of Chicago Press, 1996. An excellent history of the weight-driven clock and its impact on late-medieval and Renaissance society. Highly recommended.

Drachmann, A. G. *The Mechanical Technology of Greek and Roman Antiquity*. Madison: University of Wisconsin Press, 1963. A scholarly monograph reviewing just what the title promises. Out of print but available used.

Drake, Stillman, and I. E. Drabkin. *Mechanics in Sixteenth-Century Italy*. Madison: University of Wisconsin Press, 1969. The authors, leading historians of early modern science, give a detailed account of the state of the art in which Galileo was trained. Modest mathematics required, but very informative.

Edgerton, Samuel Y., Jr. *The Heritage of Giotto's Geometry: Art and Science on the Eve of the Scientific Revolution*. Ithaca: Cornell University Press, 1994. Out of print, but a good introduction to the idea that Renaissance painting techniques contributed to the rise of modern science. Highly recommended. Edgerton's *The Renaissance Discovery of Linear Perspective* covers the same material.

Einstein, Albert. *Relativity: The Special and General Theory*. London: Penguin, 2006. In his own words, writing for a general audience, Einstein describes relativity theory, aiming at a broad conceptual understanding. Highly recommended.

Eiseley, Loren. *Darwin's Century: Evolution and the Men Who Discovered It*. New York: Anchor, 1961. Eiseley wrote beautifully about science, and the virtues of this book include its clarity and readability. Recommended in spite of many more recent works on this topic.

———. *The Firmament of Time*. New York: Atheneum, 1960. Here, the writing is center stage. The theme is the naturalization of time and man in the 19th century. Highly recommended.

Eisenstein, Elizabeth L. *The Printing Revolution in Early Modern Europe*. Cambridge: Cambridge University Press, 2005. An important scholarly study of the social impact of print technology—this is an abridged and illustrated edition of Eisenstein's two-volume *The Printing Press as an Agent of Social Change* (1984)—attributing that impact primarily to features of the technology. Adrian Johns's book (below) takes issue with this view.

Eldredge, Niles. *Darwin: Discovering the Tree of Life*. New York: Norton, 2005. Eldredge is an important evolutionary biologist. Here, he traces the development of the ultimate unity of all life forms in Darwin's thinking.

Elkana, Yehuda. *The Discovery of the Conservation of Energy*. Cambridge, MA: Harvard University Press, 1974. A very good, nontechnical history of the idea of energy and the foundation of thermodynamics. Recommended.

Euclid. *Euclid's Elements*. Dana Densmore, ed. T. L. Heath, trans. Santa Fe, NM: Green Lion Press, 2002. You probably hated it in high school, but this is one of the truly great works of the mind, exemplifying reason and knowledge for mainstream Western intellectuals right down to the present. Read it to appreciate the mode of reasoning it exemplifies. Highly recommended.

Galen of Pergamon. *On the Natural Faculties*. New York: Putnam, 1916; in the Loeb Classical Library series and reprinted by Kessinger in 2004. In this work, Galen pulls together many strands of Greek and Graeco-Roman medical thought and theory, as Euclid did for Greek mathematics and Aristotle for Greek logic.

Galilei, Galileo. *Dialogue Concerning the Two Chief World Systems*, 2nd rev. ed. Berkeley: University of California Press, 1962. This is the book that caused Galileo's trial for heresy. Did he advocate the view that the Earth moved around the Sun? Is this a "fair" scientific treatment of a controversial issue? Highly recommended.

Gamow, George. *Thirty Years That Shook Physics*. New York: Anchor, 1966. Gamow remains one of the least known of the great 20th-century physicists. This is a wonderful autobiographical memoir, often funny and somewhat irreverent, of the creation of quantum mechanics. Very highly recommended.

Gille, Bertrand. *Engineers of the Renaissance*. Cambridge, MA: MIT Press, 1966. Newer complement to Parsons (below) by a good French historian of technology; out of print but available used.

Gimpel, Jean. *The Medieval Machine: The Industrial Revolution of the Middle Ages*. New York: Holt, Rhinehart and Winston, 1976. Gimpel was an "amateur" historian in the best sense and an enthusiast for medieval and Renaissance technology as both beautiful and socially important. Easy to read yet packed with information. Highly recommended.

Gingrich, Owen. *The Book Nobody Read*. New York: Walker and Company, 2004. Gingrich is a leading historian of astronomy. Here, he traces the fate of copies of Copernicus's masterwork in the decades after its publication in 1543 as a way of assessing its influence.

Grafton, Anthony. *Leon Battista Alberti: Master Builder of the Italian Renaissance*. New York: Hill and Wang, 2000. Grafton is an intellectual historian, and this book, like his earlier biography of Jerome Cardan, gives an appreciation of the social-cum-intellectual context of a man who was at the center of art, business, and engineering in the late 16th century. Recommended.

Grant, Edward. *Physical Science in the Middle Ages*. Cambridge: Cambridge University Press, 1977. A very good, short monograph that surveys the major ideas, people, and places. A good source of leads to reading in greater depth about medieval nature philosophy as a seedbed of modern science.

Grattan-Guinness, Ivor. *The Norton History of the Mathematical Sciences: The Rainbow of Mathematics*. New York: Norton, 1997. Grattan-Guiness is the encyclopedic historian of mathematics, and this is a rich general reference to the subject.

Greene, Brian. *The Fabric of the Cosmos*. New York: Norton, 2004. A popular treatment of late-20th-century cosmology by a Columbia University physicist. Very well written. Recommended.

———. *The Elegant Universe*. New York: Norton, 1999. All you want to know about string theory and more at the turn of the 21st century. Well and clearly written.

Grendler, Paul F. *The Universities of the Italian Renaissance*. Baltimore: Johns Hopkins University Press, 2002. A scholarly study, narrow in scope, but this is the stuff of good history writing.

Ghiselin, Michael T. *The Triumph of the Darwinian Method*. Chicago: University of Chicago Press, 1984. A prize-winning monograph on the logic of Darwin's argument in the *Origin* and his methodology. Recommended.

Hacking, Ian. *The Taming of Chance*. Cambridge: Cambridge University Press, 1991. Very good social-intellectual history of probability theory. Well written and, like all of Hacking's books, insightful. Recommended.

Hall, Marie Boas. *The Scientific Renaissance, 1450–1630*. New York: Dover, 1994. For today's historians of science, this is a dated book, but it is enjoyable to read, highly informative without being stuffy, and not wrong. A good lead-in to Westfall's *Construction* (below).

Hankins, Thomas L. *Science and the Enlightenment*. Cambridge: Cambridge University Press. An excellent, short book on science in the 18th century, with an emphasis on science as an agent of social reform through its connection to the ideas of rationality and progress. Highly recommended.

Harman, P. M. *Energy, Force and Matter: The Conceptual Development of Nineteenth-Century Physics*. Cambridge: Cambridge University Press, 1982. A very good, tightly focused book. Highly recommended.

Harris, William V. *Ancient Literacy*. Cambridge, MA: Harvard University Press, 1989. A valuable, detailed study of literacy in ancient Greece and Rome; the spread of writing in law, politics, and daily life; and the emergence of a commercial book trade. Recommended.

Harvey, William. *On the Motion of the Blood in Man and Animals*. New York: Prometheus, 1993. This remains one of the most readable of all primary source works in early modern science, arguing in 1628 for the circulation of the blood driven by the heart. Recommended.

Haskins, Charles Homer. *The Renaissance of the Twelfth Century*. Cambridge, MA: Harvard University Press, 2005. A classic essay, now reissued, that remains a joy to read as a general introduction to a field now dominated by specialists. Highly recommended.

———. *The Rise of Universities*. New York: Transactions, 2001. Again, a reissued early study. Recommended.

Hero of Alexandria. *Pneumatica*. New York: American Elsevier, 1971. Always in print, this little book, written in the 2nd century, is a collection of ideas for machines. A fascinating insight into one facet of Graeco-Roman technology, but note that the illustrations are not original. Recommended.

Hesse, Mary. *Forces and Fields: The Concept of Action at a Distance in the History of Physics*. New York: Dover, 2005. A valuable and insightful historical study of recourse by natural philosophers and modern scientists to forces acting at a distance, as opposed to mechanical contact forces, in order to explain natural phenomena without invoking magic or spiritualism. Highly recommended.

Hodges, Andrew. *Alan Turing: The Enigma*. New York: Simon and Schuster, 1983. An excellent biography of Alan Turing and a clear treatment of the intellectual context out of which the idea of the computer emerged. Recommended.

Holland, John H. *Hidden Order: How Adaptation Builds Complexity*. Boston: Addison-Wesley, 1996. Short monograph on self-organization by a pioneer of complexity theory and creator of the computer program Life. Highly recommended.

———. *Emergence: From Chaos to Order*. New York: Perseus Books, 1999. Holland gives scientific content to the cliché that the whole is greater than the sum of its parts. Recommended.

Hughes, Thomas P. *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970*. Chicago: University of Chicago Press, 2004. Very good, very readable analysis of the relationships among technology, politics, and social values from the mid-19th through the mid-20th centuries. Recommended.

———. *Networks of Power*. Baltimore: Johns Hopkins University Press, 1983. Hughes is a dean of American historians of technology and this book shows why. It traces the relationships among invention,

innovation, commerce, politics, science, and society in the creation of America's electrical networks. Recommended.

Johns, Adrian. *The Nature of the Book*. Chicago: University of Chicago Press, 1998. Johns argues at length in this big book, with lots of supporting detail, that print technology enabled authoritative, uniform versions of a text only after an extended social struggle to create institutions that protected profit and reduced pirated editions and plagiarism. Recommended.

Jones, Richard A. L. *Soft Machines: Nanotechnology and Life*. Oxford: Oxford University Press, 2004. The commercial exploitation of nanotechnology and that of molecular biology in the early 21st century are converging; this popular account of the convergence is timely.

Kelley, Donald. *Renaissance Humanism*. New York: Twayne, 1991. A good introduction to the Humanist movement by a major scholar. Recommended.

Klein, Jacob. *Greek Mathematical Thought and the Origin of Algebra*. New York: Dover, 1992. An original analysis and survey of Greek mathematics, which was, after all, a decisive influence on modern science.

Kramer, Samuel Noah. *Sumerian Mythology*. Philadelphia: University of Pennsylvania Press, 1972. Kramer was one of the pioneers of the study of Sumerian texts. This book presents deciphered Sumerian religious texts.

Kuhn, Thomas. *The Copernican Revolution: Planetary Astronomy in the History of Western Thought*. Cambridge, MA: Harvard University Press, 1992. An excellent, important analysis of the intellectual legacy of Copernicus's astronomical ideas. Highly recommended.

Lamarck, Jean-Baptiste. *Zoological Philosophy*. Chicago: University of Chicago Press, 1976. Lamarck was a far more important figure than most 20th-century biologists are willing to allow. Read this for yourself and see that Lamarck is more than just the inheritance of acquired characteristics!

Landels, J. G. *Engineering in the Ancient World*. London: Chatto and Windus, 1978. Easier to find than Drachmann's book (above), though also out of print. Both are the real thing: Engineering-knowledgeable authors use surviving texts and artifacts to reveal what the Graeco-Romans knew how to do with machinery. Sounds stuffy, but it's fascinating detective work.

Lefevre, Wolfgang. *Picturing Machines, 1400–1700*. Cambridge, MA: MIT Press 2004. A collection of essays that survey the evolution of machine drawing during the Renaissance and its implications for machine design and construction and, more broadly, for technological innovation as a social force. Recommended.

Levere, Trevor. *Transforming Matter*. Baltimore: Johns Hopkins University Press, 2001. Histories of chemistry are rare, and readable ones (to non-chemists), rarer still; thus, Levere's book is recommended.

Lewontin, Richard. *The Triple Helix*. Cambridge, MA: Harvard University Press, 2000. Lewontin is a major figure in evolutionary biology, and in these four lectures, he describes what he thinks is wrong with the current linkage of evolution to molecular biology and genetics. Recommended (but be prepared for its relentless negativism!).

Lindberg, David C. *The Beginnings of Western Science*. Chicago: University of Chicago Press, 1992. A fine example of history-of-science writing and scholarship, surveying the Greek, Roman, Islamic, medieval, and early Renaissance antecedents of modern science. Recommended.

Lindley, David. *Boltzmann's Atom*. New York: Free Press, 2001. Where Cercignani's book focuses on Boltzmann and his scientific accomplishments, Lindley focuses on the idea of the atom in the 19th century and the context within which Boltzmann championed its reality.

Lloyd, Seth. *Programming the Universe*. New York: Knopf, 2006. Lloyd is a pioneer of the quantum computer and here describes, in nontechnical terms, his conception of the Universe as a quantum computational information structure. Recommended.

Lucretius. *On the Nature of the Universe*. London: Penguin, 1994. An important and, from the Renaissance on, influential statement of Epicurus's atomism that made the armature of a philosophy of nature and of man.

Mandelbrot, Benoit. *The Fractal Geometry of Nature*. San Francisco: W.H. Freeman, 1983. Mandelbrot pioneered the field of fractional dimensionality. This is a stimulating, accessible description of what fractals are and why they matter. Subsequently, they have become important tools in applied mathematics. Recommended.

Mann, Charles C. *1491: New Revelations of the Americas Before Columbus*. New York: Knopf, 2005. Mann is a journalist, synthesizing primary source material, and his claims are controversial, but they reflect the opinions of a growing number of scholars that the inhabitants of the Americas before 1492 were far more numerous and far more sophisticated than we have been taught.

Marenbon, John. *Later Medieval Philosophy*. London: Routledge, 1991. A good introduction to the knowledge issues in medieval philosophy, but this source also describes the rise of the universities and the translation of Greek and Roman texts from Arabic into Latin. Recommended.

Mayr, Ernst. *The Growth of Biological Thought*. Cambridge, MA: Harvard University Press, 1982. Mayr was one of the great evolutionary biologists of the 20th century and was still publishing as he approached 100! This is an excellent history of the great 19th-century ideas in biology. Recommended.

McClellan, James E., III, and Harold Dorn. *Science and Technology in World History: An Introduction*. Baltimore: Johns Hopkins University Press, 2006. Excellent social-historical interpretation of how technology and, later, science-through-technology have changed the world. Recommended.

Melsen, A. G. van. *From Atomos to Atom: The History of the Concept Atom* New York: Harper, 1952. A dated but charmingly literate monograph on the atomic idea from the Greeks to the 20th century. Out of print but available used. See Pullman below.

Misa, Thomas J. *A Nation Transformed by Steel*. Baltimore: Johns Hopkins University Press, 1995. An excellent example of the placement of history of technology in its social context. The displacement of iron by steel implicated science, technology, finance, industry, government, and society, and Misa does justice to them all. Highly recommended.

Morange, Michel. *A History of Molecular Biology*. Cambridge, MA: Harvard University Press, 1998. If you're going to read just one book about molecular biology, make it this one. Morange is a biologist, not a historian, so the focus is on the science, but the writing makes it very accessible.

———. *The Misunderstood Gene*. Cambridge, MA: Harvard University Press, 2001. Highly recommended critique of the still-prevalent view that genes do it all. What genes are and how they act is still being discovered.

Newton, Isaac. *The Principia*. I. Bernard Cohen and Anne Whitman, trans. Berkeley: University of California Press, 1999. This is one of the most influential science texts ever published, and in this new translation with extensive commentary, the general reader can learn directly from Newton! Highly recommended.

Nisbet, Robert. *A History of the Idea of Progress*. Piscataway, NJ: Transaction, 1994. Intellectuals have been critical of the idea of progress for most of the 20th century, but it remains a core public value and central to science and technology. Nisbet's book takes a positive view of progress and is a successor to J. B. Bury's classic *The Idea of Progress*. Recommended.

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*. New York: Twayne, 1996. A good short history of physical science as it became a driver of social change. Highly recommended.

Overbye, Dennis. *Lonely Hearts of the Cosmos*. Boston: Little, Brown and Co., 1999. A wonderful book that uses people, their ideas, and relationships as a means of describing the development of ideas about

the origin of the Universe since the 1950s. Highly recommended. (Read the revised 1999 edition or a later one.)

Parsons, William Barclay. *Engineers and Engineering in the Renaissance.* Cambridge, MA: MIT Press, 1968. A classic study of what the title promises. Still good enough after its original publication in the late 1930s to remain in print for decades, and now available used at reasonable prices. A big book.

Pesic, Peter. *Abel's Proof*. Cambridge, MA: MIT Press, 2003. Very short, very good (and nontechnical) account of how Niels Abel's proof of a negative about algebraic equations led to major innovations in 19^{th}-century mathematics and in late-20^{th}-century symmetry-based physics.

Plato. *Plato: The Collected Dialogues*. Edith Hamilton and Huntington Cairns, eds. Princeton: Bollingen, 1978. The dialogue *Phaedrus* contains Socrates's argument against writing; the dialogues *Thaeatetus* and *Timaeus* relate to knowledge of nature.

Porter, Roy. *The Rise of Statistical Thinking, 1820–1900*. Princeton: Princeton University Press, 1986. An excellent book; nicely complements Hacking (above), with a narrower focus.

Prager, Frank D., and Gustina Scaglia. *Brunelleschi: Studies of His Technology and Inventions.* New York: Dover, 2004. Brunelleschi not only reintroduced perspective drawing, but his dome for the cathedral in Florence was an epochal technological achievement, and he invented numerous machines to enable its construction. Recommended.

Prigogine, Ilya. *Order Out of Chaos*. New York: Bantam, 1984. A philosophical reflection on the challenge of process thinking to atomistic thinking. Highly recommended. (His later *From Being to Becoming* is more challenging technically.)

Provine, William. *The Origins of Theoretical Population Genetics*. Oxford: Oxford University Press, 2003. Ignore the forbidding title: This is an excellent book that exposes how Darwinian evolutionary theory was resurrected in the 1920s. Highly recommended.

Pugsley, Alfred, ed. *The Works of Isambard Kingdom Brunel*. Cambridge: Cambridge University Press, 1976. Brunel, typically for engineers, is unknown in spite of being one of a small community of men (including his father, Marc) responsible for making the world "modern." This is a collection of short essays (search for it used online) that reveal how much one of these men accomplished while knowing so little theory!

Pullman, Bernard. *The Atom in the History of Human Thought*. Alex Reisinger, trans. Oxford: Oxford University Press, 2001. A history of the atom from the Greeks to the 20^{th} century. Given that the author was a professor of chemistry at the Sorbonne, this is a scientist's view of the history of a core scientific idea.

Raby, Peter. *Alfred Russel Wallace: A Life*. Princeton: Princeton University Press, 2001. A good biography of Wallace, who is still damned with faint praise by biologists. A leading scientist, a social reformer, and a spiritualist, Wallace deserves our attention. Recommended.

Randall, Lisa. *Warped Passages*. New York: Harper, 2005. If you're interested in learning about string theory, this is one breezily written option by a string theory researcher. I prefer Brian Greene's *The Elegant Universe* on this subject.

Ratner, Mark, and Daniel Ratner. *Nanotechnology: A Gentle Introduction to the Next Big Idea*. Upper Saddle River, NJ: Prentice Hall, 2002. Nanotechnology research, development, and commercialization, along with safety and health issues, are evolving at a breakneck pace, so consider this a good introduction to the underlying ideas and read the newspaper.

Robb, Christina. *This Changes Everything: The Relational Revolution in Psychology*. New York: Farrar, Straus and Giroux, 2006. Robb is a Pulitzer Prize–sharing journalist; this book describes how acknowledging the reality and causal efficacy of relationships affected clinical and theoretical psychology.

Rocke, Alan J. *Chemical Atomism in the 19th Century: From Dalton to Cannizaro.* Columbus: Ohio State University Press, 1984. An in-depth study of the early history of the atomic theory of matter, when it was mostly a theory for chemists.

Rudwick, Martin J. S. *The Meaning of Fossils*. Chicago: University of Chicago Press, 1985. All of Rudwick's books are excellent, and his most recent, *Bursting the Limits of Time,* is most relevant to the reconceptualization of time in the 19th century, but it is massive. This book is a gentler yet still highly informative study of the same subject. Highly recommended.

Scaglia, Gustina. *Mariano Taccola and His Book* De Ingeneis. Cambridge, MA: MIT Press, 1972. This is a very good edition, with scholarly commentary, of a Renaissance-era machine design book, symptomatic of the emergence of modern engineering. See Prager and Scaglia (above) and Scaglia's *Francesco di Giorgio*, a beautiful collection of Renaissance machine drawings with extensive commentary by Scaglia. Recommended.

Seife, Charles. *Decoding the Universe*. New York: Viking, 2006. A very readable account by a science journalist of how information has become physically real for many scientists. Recommended.

Shapin, Steven and Simon Schaffer. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life*. Princeton, New Jersey: Princeton University Press, 1985. A modern classic that exposes the equivocal character of experimental research using newly devised instruments by way of Thomas Hobbes' criticism of Robert Boyle's "discoveries" and the Royal Society as an institution. Recommended.

Singleton, Charles. *Art, Science, and History in the Renaissance*. Baltimore: Johns Hopkins University Press, 1968. An alternative to Edgerton (above); also out of print but available used at more reasonable prices.

Smolin, Lee. *The Trouble with Physics: The Rise of String Theory, the Fall of Science, and What Comes Next*. Boston: Houghton Mifflin, 2006. One of several recent attacks on string theory by physicists who claim that it is a dead end and bad science. I admire Smolin's earlier books, especially *Three Roads to Quantum Gravity*, and his criticisms are legitimate, but the book's primary value is as one skirmish in a "war" within physics.

Sorabji, Richard. *Matter, Space and Motion: Theories in Antiquity and Their Sequel*. Ithaca: Cornell University Press, 1988. A survey by a philosopher of materialist theories of nature from the earliest Greek philosophers through the 6th century. This complements Lindberg's book, above.

Stachel, John. *Einstein's Miraculous Year*. Princeton: Princeton University Press, 1998. Stachel is the editor of the Einstein papers and here offers the historic 1905 articles in translation with enough commentary for anyone to follow their arguments. Highly recommended.

Stephenson, Bruce. *The Music of the Heavens: Kepler's Harmonic Astronomy*. Princeton: Princeton University Press, 1994. Here, you can see the authority given to the Pythagorean idea that mathematical form was the indwelling order of nature underlying its expression in matter and that this order was fundamentally musical. Recommended.

Strogatz, Steven. *SYNC: The Emerging Science of Spontaneous Order*. New York: Hyperion, 2003. A readable book for a general audience on self-organization, bringing Prigogine's early ideas up-to-date. Strogatz is himself a researcher in this field.

Susskind, Leonard. *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design*. Boston: Little, Brown and Co., 2006. As if to counter Smolin's rant against string theory, one of its architects describes the theory as if its triumphant completion and confirmation were imminent! Stranger than science fiction. Recommended.

Swade, Dorn. *The Difference Engine*. London: Penguin, 2002. An excellent book that makes reading about Charles Babbage's failed quest to build a computer in the mid-19th century fun. The effort and its failure reveal much about the science-technology-society relationship. Highly recommended.

Taylor, George Rogers. *The Transportation Revolution*. New York: Harper, 1968. A solid history of the 19th-century transportation technology innovations that literally changed the world.

Travis, Anthony. *The Rainbow Makers*. Bethlehem, PA: Lehigh University Press, 1983. The fascinating story of how a teenager discovered the first synthetic dye and triggered the first "Silicon Valley" phenomenon, in which chemical science, industry, and government created enormous wealth and power. Recommended.

Uglow, Jenny. *The Lunar Men: Five Friends Whose Curiosity Changed the World*. New York: Farrar, Straus and Giroux, 2002. Wonderful account of the interactions of a group of thinkers and doers at the turn of the 19th century whose members included James Watt and Mathew Boulton, Erasmus Darwin and Josiah Wedgwood (both of them Charles Darwin's grandfathers!), and Joseph Priestley. Highly recommended.

Vitruvius. *The Ten Books on Architecture*. New York: Dover, 1960. More than 2000 years old, still in print, and still worth reading!

Watson, James D. *The Double Helix*. New York: Signet, 1968. No scientist had written such a tell-it-all account of how his research was done before this book. Highly recommended.

———. *DNA*. New York: Knopf, 2003. Now an honored senior, Watson describes the state of our understanding of how DNA works for a general audience. Recommended.

Webster, Charles. *The Great Instauration*. London: Peter Lang, 2002. Webster describes the social context of 17th-century England—especially the religious, political, social reform, and medical contexts—in which early modern science took root.

Weinberg, Steven. *Dreams of a Final Theory*. New York: Pantheon, 1992. Weinberg shared a Nobel for the first step in the unification of the four fundamental forces of nature and here anticipates the implications of full unification. Not dated because there has been little progress since 1992!

Westfall, Richard S. *Never at Rest: A Biography of Isaac Newton*. Cambridge: Cambridge University Press, 1980. The definitive personal and intellectual biography of Newton. Highly recommended.

———. *The Construction of Modern Science*. Cambridge: Cambridge University Press, 1989. Short, excellent introduction to the ideas at the heart of 17th-century science and its accomplishments. Highly recommended, as are all the monographs in the Cambridge History of Science series.

White, Lynn. *Medieval Technology and Social Change*. Oxford: Oxford University Press, 1966. White describes the social impact of the stirrup, wind power, and agricultural innovations, overstating the case but calling attention to technology as a force driving social change when most historians ignored it.

Williams, Trevor. *A History of Invention*. New York: Checkmark Books, 1987. It looks like a coffee table book, but Williams is a scholar and the book is filled with lots of valuable information without reading like an encyclopedia.

Wilson, Catherine. *The Invisible World: Early Modern Philosophy and the Invention of the Microscope*. Princeton: Princeton University Press, 1995. An important study of the interaction of ideas and instruments, theories of nature and observations. Recommended.

Worboys, Michael. *Spreading Germs: Disease Theories and Medical Practice in Britain, 1865–1900*. Cambridge: Cambridge University Press, 2000. An account of the response of the British medical community to the germ theory of disease as that theory evolved. Recommended.

Zachary, G. Pascal. *Endless Frontier: Vannevar Bush, Engineer of the American Century*. Cambridge, MA: MIT Press, 1999. A good biography of the man who was the "czar" of harnessing science and technology to the World War II effort and who promoted the postwar policy of federal support for scientific research.

Zagorin, Perez. *Francis Bacon*. Princeton: Princeton University Press, 1998. A very good biography of Bacon, doing justice to him as a social reformer, political opportunist, and philosopher of nature. Recommended.

Internet Resources:

Stanford Encyclopedia of Philosophy. A superb resource for the history of philosophy, of uniformly high quality, guaranteed to illuminate and please. Includes outstanding entries on many science topics—try advanced search. http://plato.stanford.edu.

University of Delaware Library. *Internet Resources for History of Science and Technology*. A "super" site for exploring the history of technology and of science from antiquity to the present. www2.lib.udel.edu/subj/hsci/internet.html.

Ancient Languages and Scripts. An informative site on the history of writing. www.plu.edu/~ryandp/texts.html.

The Labyrinth: Recourses for Medieval Studies. A "super" site listing resources for exploring Medieval culture. http://labyrinth.georgetown.edu.

The Art of Renaissance Science. A rich, multi-disciplinary site created by Joseph Dauben on the relationships among art, mathematics and science in the Renaissance. www.mcm.edu/academic/galileo/ars/arshtml/arstoc.html.

The Galileo Project. An excellent resource site for everything to do with Galileo's life, works and ideas. http://galileo.rice.edu.

The Newton Project. A similar, and similarly excellent resource, for the life, works and ideas of Isaac Newton. www.newtonproject.ic.ac.uk.

University of St. Andrews School of Mathematics and Statistics, *The MacTutor History of Mathematics Archive*. A very good resource for the history of mathematics; the Biographies on the site offer a comprehensive history of mathematicians and their accomplishments. www-history.mcs.st-and.ac.uk/.

Selected Classic Papers from the History of Chemistry. An outstanding collection of the full text of classic papers in the history of chemistry. http://web.lemoyne.edu/~giunta/papers.html.

The Nobel Foundation. Official web site offering access to all Nobel Prize winners, their biographies and accomplishments, and their acceptance addresses; a rich and fascinating history of science resource. http://nobelprize.org.

The History of Computing. An excellent collection of materials and links for exploring the history of computers and computing. http://ei.cs.vt.edu/~history/.

NASA History Division. A central site for aerospace history. http://history.nasa.gov.

The Official String Theory Website. The "home page" for accessible accounts of string theory. http://superstringtheory.com.

Sunny Y. Auyang. “Scientific convergence in the birth of molecular biology.” Very good essay on the history of molecular biology. Other articles available on this idiosyncratic yet interesting website by a respected scientist address engineering, including a useful history of engineering, biomedicine, and physics. www.creatingtechnology.org/biomed/dna.htm.

National Nanotechnology Initiative. The official Web site for federally funded nanotechnology research and development. www.nano.gov.

Great Scientific Ideas That Changed the World
Part III

Professor Steven L. Goldman

THE TEACHING COMPANY ®

PUBLISHED BY:

THE TEACHING COMPANY
4151 Lafayette Center Drive, Suite 100
Chantilly, Virginia 20151-1232
1-800-TEACH-12
Fax—703-378-3819
www.teach12.com

Printed in the United States of America

ISBN 978-1-59803-305-2

Steven L. Goldman, Ph.D.

Departments of Philosophy and History, Lehigh University

Steven Goldman has degrees in physics (B.Sc., Polytechnic University of New York) and philosophy (M.A., Ph.D., Boston University) and, since 1977, has been the Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University. He has a joint appointment in the departments of philosophy and history because his teaching and research focus on the history, philosophy, and social relations of modern science and technology. Professor Goldman came to Lehigh from the philosophy department at the State College campus of Pennsylvania State University, where he was a co-founder of one of the first U.S. academic programs in science, technology, and society (STS) studies. For 11 years (1977–1988), he served as director of Lehigh's STS program and was a co-founder of the National Association of Science, Technology and Society Studies. Professor Goldman has received the Lindback Distinguished Teaching Award from Lehigh University and a Book-of-the-Year Award for a book he co-authored (another book was a finalist and translated into 10 languages). He has been a national lecturer for Sigma Xi—the scientific research society—and a national program consultant for the National Endowment for the Humanities. He has served as a board member or as editor/advisory editor for a number of professional organizations and journals and was a co-founder of Lehigh University Press and, for many years, co-editor of its Research in Technology Studies series.

Since the early 1960s, Professor Goldman has studied the historical development of the conceptual framework of modern science in relation to its Western cultural context, tracing its emergence from medieval and Renaissance approaches to the study of nature through its transformation in the 20th century. He has published numerous scholarly articles on his social-historical approach to medieval and Renaissance nature philosophy and to modern science from the 17th to the 20th centuries and has lectured on these subjects at conferences and universities across the United States, in Europe, and in Asia. In the late 1970s, the professor began a similar social-historical study of technology and technological innovation since the Industrial Revolution. In the 1980s, he published a series of articles on innovation as a socially driven process and on the role played in that process by the knowledge created by scientists and engineers. These articles led to participation in science and technology policy initiatives of the federal government, which in turn led to extensive research and numerous article and book publications through the 1990s on emerging synergies that were transforming relationships among knowledge, innovation, and global commerce.

Professor Goldman is the author of two previous courses for The Teaching Company, *Science in the Twentieth Century: A Social Intellectual Survey* (2004) and *Science Wars: What Scientists Know and How They Know It* (2006).

Table of Contents
Great Scientific Ideas That Changed the World
Part III

Great Scientific Ideas That Changed the World

Scope:

It is easy to fall into one of two traps in dealing with ideas: either to dismiss them as abstractions and, thus, of less consequence than concrete things, such as swords, plowshares, and factories, or to glorify them *as* abstractions, as creative inventions of the mind, and thus, praiseworthy independent of any practical consequences whatsoever. Ideas are, nevertheless, as concrete as swords and plowshares because they are always tied to a concrete context of values, actions, beliefs, artifacts, and institutions out of which they arise and on which they *may* act. The concreteness of ideas derives from their being produced not only *within* a particular cultural context but *out* of that context, and it is because ideas are produced out of a particular context that ideas are able to influence and even to reshape that context. Treating ideas out of context, then, treating them as if their existence were, in principle, independent of any particular context, deeply distorts the reality of ideas and obscures their power to affect the world.

Ideas and their contexts interact in complex, *mutually* influential ways such that the resultant effect on society of introducing a new idea is unpredictable. The evolution of the Internet from a modest computer networking project funded by the U.S. Department of Defense to a global technology transforming commerce, industry, politics, warfare, communication, education, entertainment, and research illustrates the unpredictability of the idea-social context interaction. The still-unfolding consequences of a small number of innovative ideas introduced to solve technical problems posed by enabling different kinds of computers in different locations to share information in real time continue to surprise, confound, and disturb us!

Unpredictable though it may be, however, for 200 years now, the interaction of science and technology with society has been the primary driver of social and cultural change, first in the West, then globally and at an accelerating rate. During this period, social and personal values and relationships; social, political, and economic institutions; and cultural values and activities have changed and continue to change almost beyond recognition by our great-grandparents. What is it that has enabled such deep transformations of ways of life that have been entrenched for centuries and even millennia?

Certainly, we can identify artifacts—the telephone, the automobile, airplanes, television, the computer—that *appear* to be causes of social change. But identifying artifacts does not reach down to the *causes* of innovation itself, nor does it expose those features of the sociocultural infrastructure that enable innovations to be causes of social change. Artifacts, in spite of their high visibility, are symptoms of causes at work; they are not themselves causes. It is not television or automobiles or the Internet that have changed society. Instead, forces at work within the network of relationships that we call society are causing television and automobiles and the Internet to take the changing forms that they take. One of these forces is ideas, explicitly in the case of new scientific ideas and implicitly in the case of ideas in the past that have been internalized selectively by society, thereby shaping both the sociocultural infrastructure and the lines along which it is vulnerable to change.

The objective of this course is to explore scientific ideas that have played a formative role in determining the infrastructure of modern life through a process of sociocultural selection. But we shall interpret the term *scientific idea* broadly. There is, after all, no sharp distinction between ideas that are classified as scientific and those that are classified as philosophical or mathematical or even between scientific ideas and political, religious, or aesthetic ideas. Alfred North Whitehead, for example, famously linked the emergence of modern science in the Christian West to Judaeo-Christian monotheism: to the belief in a single, law-observing creator of the Universe.

The idea that there are laws of nature at least *seems* to reflect a political idea, while there can be no doubt that mathematical and aesthetic ideas were central to the 17th-century Scientific Revolution. Furthermore, distinguishing science and technology is fuzzy, too, especially since the second half of the 19th century,

when scientific knowledge and technological innovation were systematically coupled in industrial, academic, and government research laboratories.

With this in mind, we will begin our discussion of influential scientific ideas with the invention of writing, which may not seem a scientific idea at all. There is, nevertheless, a profound idea underlying the invention of writing, and a controversial one, as reflected in Socrates's argument *against* writing in Plato's dialogue *Phaedrus*. Writing is also a technology, of course, and thus, serves as an initial example of how technologies embody ideas that we tend to ignore because our attention is almost always drawn to *what* technologies do, to *how* they do it, and to what the consequences are of what they do.

By the time of the earliest written records that have been discovered so far, humans already had embodied, through their invention of a breathtaking range of physical, social, and cultural "technologies," an equally breathtaking range of ideas implicit in those technologies. Lecture One looks back at what humans had accomplished in the way of know-how by the 4th millennium B.C.E., while Lecture Two discusses the invention of writing and the spread of writing systems and texts from about 3500 B.C.E. to the beginning of classical antiquity, circa 500 B.C.E.

Between approximately 500 B.C.E. and 300 B.C.E., Greek philosophers developed highly specific concepts of knowledge, reason, truth, nature, mathematics, knowledge of nature, and the mathematical basis of knowledge of nature in ways that continue to inform the practice of science to the present day. Lectures Three through Five are devoted to these ideas and their legacy. Lecture Six discusses the first appearance in Western history, perhaps in world history, of the idea of techno-science, that is, of technology derived from theoretical knowledge rather than from practical know-how. This was largely a Greek idea that was applied in the context of the rising Roman Empire, and the lecture describes selected Roman-era technologies that had an influence on the rise of modern science and engineering.

Bridging the ancient and early modern eras, Lectures Seven through Eleven explore the idea of the university and its role as a progenitor of modern science; medieval machinery and Europe's first "industrial revolution"; and the Renaissance ideas of progress, of the printed book, and of mathematics as the language of nature. All these ideas are obviously seminal for science as we know it, but they are also, if less obviously, seminal for the rise of modern engineering and the form of modern technological innovation.

Lecture Twelve discusses Copernicus's idea of a moving Earth, the cultural consequences of that idea, and its subsequent evolution as a modern scientific astronomical theory. This serves as a lead-in to Lectures Thirteen through Seventeen, which explore foundational ideas of modern science, among them, the idea of method; new mathematical ideas, such as algebra and the calculus; ideas of conservation and symmetry; and the invention of new instruments that extended the mind rather than the senses and forced a new conception of knowledge.

Lectures Eighteen through Twenty-Eight explore 19th-century scientific ideas that remain profound social, cultural, and intellectual, as well as scientific, influences. These include the idea of time as an active dimension of reality, not merely a passive measure of change; the chemical atom as an expression of a generic idea of fundamental units with fixed properties, out of which nature as we experience it is composed; the ideas of the cell theory of life, the germ theory of disease, and the gene theory of inheritance, all conceptually allied to the atom idea; the ideas of energy, immaterial force fields, and structure and, thus, of relationships as elementary features of reality; the idea of systematically coupling science to technology, of coupling knowing to doing, and of using knowledge to synthesize a new world; the idea of evolution and its extension from biology to scientific thinking generally; and the idea that natural phenomena have a fundamentally probable and statistical character.

Lectures Twenty-Nine through Thirty-Five discuss central 20th-century scientific ideas, including the gene, relativity and quantum theories, the expanding Universe, computer science, information theory,

molecular biology, and the idea of systems, especially self-organizing systems and the allied ideas of ecology and self-maintaining systems.

Appropriately, Lecture Thirty-Six concludes the course by reviewing the ideas that are distinctive of modern science and technology today and anticipating ideas likely to be drivers of change tomorrow, focusing in particular on cognitive neuroscience, biotechnology and nanotechnology, and physicists' search for a theory of everything.

Lecture Twenty-Five
Evolution as Process Science

Scope:

Like Copernicus's moving-Earth theory before it and Einstein's theories of relativity after, the idea of evolution has not tangibly changed our daily lives and has led to no new technologies, but it has had a profound impact on our self-understanding. From the early 17th century to the mid-19th century, the scope of modern science expanded, naturalizing the Earth, the Solar System, the Universe as a whole, life processes within organisms, and with the advent of organic chemistry and the cell theory, life itself. The Darwin-Wallace idea of evolution by natural selection, reinforced by the contemporaneous discovery of ancestral human forms, enfolded humanity within the natural, a move completed by the naturalization of the nervous system and consciousness. Evolution has proved a powerful, innovative, and widely applicable cross-disciplinary idea, bringing contingency into scientific explanation, naturalizing apparent purposiveness, making time the dimension of novelty, and showing how novelty can emerge from the introduction of minute discontinuities into an underlying continuity.

Outline

I. The idea of evolution as formulated by Charles Darwin and Alfred Russel Wallace was a powerful and fertile intellectual innovation.

- **A.** Although famous as a theory of the "transmutation" of species, Darwin-Wallace evolution incorporates a transformed idea of time.
  1. We have already seen that the reigning idea of time—first incorporated into the deduction-based idea of knowledge from antiquity, and then into modern science—was that time *is not* a feature of reality.
  2. Time matters to us, of course, but not, in this view, to the absolute reality that is the ultimate source of experience.
  3. However, thermodynamics implied that time in physics was irreversible and a feature of reality, not merely an "illusion."
  4. Concurrently, Darwin and Wallace proposed that time in the biological world was irreversible.
  5. The evolution of species was the evolution *in time* of novel life forms.
- **B.** Evolution attributes explanatory power to a process, the process by which life forms are transformed.
  1. The process is *natural selection*, acting on continuous variability between parents and offspring under environmental pressure caused by overpopulation.
  2. There's a hierarchy of processes at work here, from the molecular processes underlying inheritance and cell division to survival of organisms in continually changing environmental challenges.
  3. Variability plays a key role, interacting with the struggle for survival and natural selection: Without variability, there is no evolution.
  4. Evolution is a complex process, in which the properties of the participants continually change over time, contrary to the fixed properties of literal and metaphorical atoms.

II. That species transform into new species was at the heart of a bitter controversy millennia before Darwin.

- **A.** Taxonomy may seem prosaic, but it is central both to the relationship between knowledge and reality and to the theory of evolution.

1. The taxonomy problem is intimately related to the problem for which evolution is proposed as a solution.
2. If species are constant because they are natural categories, then the problem of the origin of species takes one form.
3. If species are conventional, then the problem takes a very different form.
4. For example, the platypus, which combines mammalian features with non-mammalian features, challenges the category "mammal."
5. The status of the names we use for grouping together individual objects reflects Plato's exhortation to "carve nature at its joints."

B. With the European voyages of discovery, European naturalists were overwhelmed with thousands of new kinds of plants and animals.

1. Classifying a massive influx of individual objects amounts to an exercise in naming grouping features.
2. For some, the challenge is to name grouping features that are "real," that express the way nature is; for others, the challenge is to name features that are effective for botanists and zoologists.
3. The most compelling claim to a natural system was made by Carl Linnaeus, based on the sexual organs of plants, but in the end, he had to concede defeat.

III. If species names are conventional, then the constancy of species is an illusion.

A. Darwin and Wallace were among those for whom species names were conventional.

1. Species categories are really names for stable, but not permanent, groupings of continually (but slowly) changing varieties.
2. Individual living things continually vary from their parents and from one another in one feature or another, while also sharing most of their features with their parents and some other living things.
3. Over long periods of time, this variation may result in differences that lead to grouping individuals into different categories than their ancestors were grouped into.
4. In the second half of the 19th century, biologists began to identify features of the processes of cell division and sexual reproduction that were causes of the variation at the molecular level.

B. Artificial breeding is a familiar example of how new varieties are systematically created by people.

1. For Darwin, but not for Wallace, this was analogous to the process underlying change in nature.
2. For both, though, species names are names for varieties that are stable over what seem like long periods of time to human beings.
3. Individual variability is, thus, the cornerstone of the idea of evolution, but note that the individual does not evolve!

C. The question of what does evolve, if not the individual, leads to a deeper appreciation of the nature of evolution as a process theory.

1. Evolution by natural selection became dominant after the 1920s with the rise of population genetics.
2. Using newly developed statistics-based mathematical models, geneticists could calculate how gene changes would spread in a population over time as a function of the survival advantage or disadvantage they conferred.

D. Populations change their character over time as the distribution of genes changes, until the population looks very different from the way it had looked.

1. Combining Mendelian genetics, mutation theory, natural selection, and since 1953, a growing understanding of how DNA functions in the cell leads to a “picture” of how life forms radiate and adapt in time.
2. This is a “motion picture,” but the rate of its motion is such that to us, each frame looks like a single photograph projected onto the screen and held there.
3. Run backwards, we would see a common origin for all life forms, but Darwin was initially cautious about this.
4. In the 18^{th} century, Lamarck and Charles’s grandfather Erasmus had argued for a single original life form and for processes that produced the incredible multifariousness of life forms that we observe.
5. Lamarck’s theory involved a process of inheritance affected by the use/disuse of individual organs in the course of struggling to survive.
6. The origin-of-life question fits into the quest of the Romantic philosophy of nature to discover the ultimate unity of all nature, whether life forms or physical forces.

IV. In context, then, an evolutionary theory of life seems “natural.”

A. If only from Darwin’s critics, we know that the Darwin-Wallace theory of evolution did not suddenly pop up out of nowhere.

1. William Wells published an essay in 1813 suggesting a theory that we would recognize as evolution by natural selection.
2. This essay was described at length in a book by John Herschel that we know Darwin owned and had read.
3. In 1831, Patrick Mathew published a book on Royal Navy uses of trees that contained a theory of evolution based on the struggle for survival and selection.
4. In the 1840s, Robert Chambers published (initially anonymously) a British bestseller, *The Vestiges of the Natural History of Creation*, that presented a neo-Lamarckian theory of evolution.

B. The Darwin-Wallace theory became public in 1858.

1. Darwin had been working out his theory since 1835, filling notebook after notebook with data, ideas, and arguments for species as types that change over time.
2. Fortunately for him, he shared these ideas and access to some of his notebooks with leading British biologists.
3. In 1858, Wallace sent Darwin the draft of a short essay, asking Darwin’s opinion of his theory, based on biogeography, of the origin of species in terms almost identical to Darwin’s.
4. Darwin quickly wrote up a short paper of his own, and both papers were presented in 1858, followed by publication of *The Origin of Species* in 1859.

C. Evolution is a process theory, but it has two other important consequences.

1. Evolution entails making time a fundamental feature of reality and irreversible, too, moving in one direction only.
2. Individual variation is pivotal to evolution, and Darwin referred to the causative process as “spontaneous” but not “chance,” meaning not random.
3. Darwin’s physicist contemporaries, however, saw his theory as implying that individual variation *was* a chance/random phenomenon.
4. Evolutionary theory thus promoted yet another new scientific idea: that chance is a fundamental feature of nature, and thus, probability and lawfulness/rationality must be

compatible.

Essential Reading:

Charles Darwin, *On the Origin of Species*.

Loren Eiseley, *Darwin's Century*.

Questions to Consider:

1. If human beings are wholly natural in all respects, how can human existence be more meaningful than the existence of any other organism?
2. Is it life that evolves or the whole system of which life is a part, and what are the boundaries of that system: the Earth, the Solar System, the Milky Way, the Universe?

Lecture Twenty-Five

Evolution as Process Science

In the preceding three lectures we've looked at the ideas of energy, fields, and relationships as challenging the atomistic style of thinking, which is not just atomistic in the sense of attributing explanatory power to things with fixed properties, but also fits into the broader determinism of substance metaphysics, the materialistic determinism of modern science, which sort of reached a peak in the 19th century. And then these process-style forms of thought associated with the attribution of physical reality because of their causal efficacy—the fact that they act as causal agents—to energy fields and relationships.

In this lecture we're going to look at another facet of this challenge to the atomistic deterministic style of thinking, and that is the idea of evolution. The idea of evolution that is most famous, of course, is the Charles Darwin, or Charles Darwin–Alfred Russel Wallace, theory of biological evolution by means of natural selection.

The idea of evolution is an extremely powerful idea, and it is a major intellectual innovation in the context of 19th century science with its materialistic determinism, one of whose corollaries, as we have seen, was that time is in some ultimate sense unreal. Time doesn't really make a difference because the present is embedded in the past the way the conclusion of the deductive argument is already implicit in its premises. The idea that evolution entails is that time does make a difference; that time is the dimension in which novelty appears in history; that while evolution is a lawful phenomenon, it is not predictable because chance plays a critical role in the process called evolution.

So at one level the idea of evolution is a powerful intellectual conceptual innovation because it requires us to take time seriously, and it is hardly a coincidence that the idea of evolution is emerging concurrently with the idea in thermodynamics. We discussed how in the early 1850s Rudolf Clausius, through introducing the concept of entropy, was really indicating, as we see in the second law of thermodynamics, that there is such a thing as the arrow of time; an inference that William Thomson, Lord Kelvin explicitly drew a year or two after Clausius published his paper in which he identified this concept of entropy, which is the name for a number associated with all processes in which energy is transformed. The fact that entropy increases in all such processes—reflected in the second law of thermodynamics, that heat can only flow from a hotter body to a colder body—required us to accept, according to Kelvin, that there is now an arrow of time, that time does make a difference.

As I said, concurrently in the Darwin–Wallace theory of evolution, time also makes a difference. At one level the idea of evolution is innovative in forcing us to take time more seriously than we had done so, and also because it turns out (although Darwin himself waffled on this point) that chance is a fundamental feature of biological evolution (we'll be talking about that in some more detail). And that, of course, challenges the notion of determinism, that the future is precisely implicit in the present, as the present was in the past—it's a kind of preformationism.

I think that, in a really pretty way, the real challenge to the atomistic style of thinking from the idea of evolution is that the idea of evolution attributes explanatory power to a process rather than to things with fixed properties. Instead of claiming that the way to explain chemical reactions is by identifying elements of matter with specific fixed properties that cause them to combine with other elements in specific fixed proportions, the idea of evolution is that the problem to be explained—namely, the origin of species, the reason why life takes the forms that it does, with relative stability in the short run between parents and offspring, but this multifarious divergence of many different forms of life and their relationships with one another—the problem of the origin of the species, is much broader than merely the problem of the origin of the species. It's really the problem of the multifariousness of the forms of life that we find on the planet. The explanation derives from a process. It is the process that is called natural selection, acting on continuous variability between parents and offspring under selection pressure—the pressure coming from overpopulation as a fundamental principle of nature, that all organisms produce more offspring than can ultimately be provided for in their environmental niche (as we would now call it), and since this generates a struggle for survival, that forces a kind of adaptation process to take place.

There is, in fact, a hierarchy of processes associated with the idea of evolution: the process of natural selection acting on and entailing the process of adaptation to continually changing environmental circumstances. They may be changing very slowly, but they're always changing. And underneath that the processes of sexual reproduction and cell division, which neither Darwin nor Wallace were familiar with in the 1850s and 1860s. (That was only in the last decades of the 19th century, as we saw in the lecture of the cell theory of life and the gene theory of inheritance.)

Because the variability that all evolutionists recognize as a fundamental feature of life—that individuals always vary to some degree from their parents—this variability creates a pool that struggles for survival and natural selection acts on, so to speak, causing this continual adaptation to changing environmental circumstances, which leads to the multifariousness of the life forms on the planet. These are all processes.

There is a process of sexual reproduction, which we now understand to a considerable degree (certainly a heck of a lot better than Darwin and Wallace did) through DNA, that the process of sexual reproduction generates variability inevitably. Also on a random basis, the process of cell division introduces possibilities for variability, so that there is always going to be variability because of the process of cell division, and then the processes of adaptation and natural selection. So this is another sense—the sense of process is manifested in this explanation. It is a fundamentally process-based theory or idea for explaining a very complex natural phenomenon.

I referred earlier to the problem that Darwin was addressing, and so was Wallace, and that was a problem of the origin of species. It was a problem that biologists had been concerned with. Certainly from the closing decades of the 18th century, the whole question of the constancy of species and the problem of the origin of species reflects again, as we've seen in a number of lectures, the taxonomy problem—the whole question of whether there is a way of describing nature that is natural, that maps onto distinctions in nature that, so to speak, go beyond direct experience.

For example, you can't see a mammal. Mammal is the name that we give to a particular subset of living forms. Those living forms that have certain characteristics, we call mammals. But you can't see a mammal. You can't see "mammal-hood" as a category in nature. The question is, is that a real category in nature, or is it the case that we have simply organized creatures that seem to us to possess a certain set of properties and we have given that the name mammal, but that in fact does not distinguish those creatures from other creatures who are otherwise very similar to them?

That is why the platypus, when it was discovered in Australia, was so puzzling: because it seemed to combine mammalian features with non-mammalian features. In fact, initially biologists in Europe who received these carcasses thought that they were a hoax and that the various body parts had been stitched together cleverly in order to fool them, because it violated the category "mammal" by having the fundamental characteristics of a mammal, but then some characteristics that were not possessed by a mammal. That challenges the category "mammal," and challenging a fundamental category like that challenges the whole process of giving names to natural phenomena.

You may remember that I referred earlier to Plato's charge to natural philosophers that their job was to "carve nature at its joints"—to make distinctions, to give names to those phenomena that are really there, that map onto absolute characteristics of reality. It wasn't a question of just making up useful categories, categories that work, categories that help us organize material, but to carve nature at its joints, so to speak. Let us call that the realist or naturalist view of the taxonomy problem as opposed to the conventionalist view, which is that the names are useful to us, but they're not absolute, and I've referred to this in a number of different ways.

The taxonomy problem became an insistent and highly controversial one already in the late 16th century as European botanists and zoologists were overwhelmed by thousands and thousands of new species and genera of plants and animals that the European voyages of discovery and exploration were bringing back to Europe. Now all of a sudden we need to organize them, and I've referred before to the fact that this posed this challenge. Is there a natural system of classification that we need to discover, uncover, so we can categorize, we can identify genus and species, for example, based on natural characteristics, or are there only conventional ways of dealing with this?

If there are only conventional ways, then there is no such thing as a species, and so the transmutation of species is not a traumatic thing. It's not a violation of the natural order. It is only if you think that species are natural, that that is a natural classification, that changing one species into another seems like a fundamentally impossible thing to do, because that is a natural distinction. One species and another species are fundamentally distinct. There is a gulf between them that cannot be bridged by any kind of breeding experiment.

In the 18th century, I mentioned that Carl Linnaeus represented in some sense the epitome of the naturalist view of classification based on organizing plants and later animals by sexual characteristics, but plants especially was his forte. But I had mentioned that at the end of his life he had to acknowledge that his system of classification was really not natural, it was not unique, it did not map onto the way plants really were, but that it was ultimately and sadly only conventional.

This view is Darwin's view, because for Darwin, for Wallace, and for all of the other people who we will be shortly mentioning who addressed this question of the origin of species, it was obvious that there really is no such thing as a species. All of the categories that we call species categories are really varieties, that life forms are continually changing under this process, this family of co-related processes of sexual reproduction, cell division (speaking now a little anachronistically in the middle of the 19th century), natural selection. All of these processes are continually changing each generation of living thing in small, sometimes (almost always) subtle ways, but over vast periods of time, it leads to a radiation of life forms, each life form reflecting adaptation to a particular environment in which it is able to flourish, or at least to survive.

The origin of species question is solved by saying that there is no such thing as a species, that there are only varieties; but some varieties are more stable than others. Ordinary varieties—the varieties of dogs and pigeons that we see around us, for example—display tremendous variety and instability. They easily, so to speak, reproduce in ways that show reversions back to characteristics of previous generations of dogs and pigeons. So varieties as we ordinarily experience them by animal breeders and plant breeders, for example, are rich with variability; but what Darwin and Wallace were pointing out is that there is a form of variety that is stable over long periods of time, and so we think that it's eternal. There are people who think that species are eternal, and this is a misconception. The process by which life reproduces itself in response to continually changing environmental circumstances is a process that guarantees variability, and that has a time structure to it that is so long compared to human consciousness that changes that take place over millions of years, hundreds of thousands of years, tens of thousands of years, even, for individuals, are just so slow that we assume that what we're seeing is constant.

What we have in the theory of evolution is a theory that strangely requires taking very seriously individual variability, the degree to which each individual varies to some degree from their parent. But the individual does not evolve. The individual is different from its parent; it's different from its siblings; it's different from other animals or plants of its kind, so to speak, but the individual is exactly what it is. What is it that evolves?

Again you have to step back and take a process view. Ultimately what emerged in the 1920s and '30s was a need to take a population-based view of the process of evolution. What we see over time is that the distribution of genes—not available to Darwin—but in the 1920s we had a mathematical description, we had formulae that showed how a particular distribution of genes would spread through a population if any of those genes gave any survival advantage at all to the individuals that possessed them, and the rate at which those genes would spread. So if there was a mutation in a gene we can calculate how rapidly it would spread through a population given their reproduction rate, and given some understanding of the environmental pressures that they were acting under. And if a gene was harmful, we can calculate how quickly the individuals that possess it will die out of the population.

So the population changes its character over time. The distribution of genes and the expression of those genes change over long periods of time. It's really a situation that's somewhat analogous to a motion picture. When you're watching a motion picture nothing is changing—no thing is changing—in the way that you see. The process by which we see, which makes us insensitive to image changes that are less than approximately a tenth of a second apart, makes us respond to a series of slides. A motion picture film is really a series of stills, of slides, each one of which is only minutely different from the preceding one, but when they're shown quickly enough, then we experience motion.

Evolution is saying that because the picture of life and its reproduction is so slow, we see constancy; whereas, if we could see a time-lapse photograph of the emergence of life on earth even over the last billion years (instead of three and a half billion) then we would see this transmutation of species. We would see the radiation of life forms. We would see how multifariousness emerged from a single original life form, at least from the point of view of the later development of the Darwin–Wallace theory of evolution. Darwin was very careful, saying that he thought there were maybe four or five initial forms of animals, and maybe three or four initial forms of plants. Possibly there was only one initial life form, but he didn't press that point. I think if you read between the lines you see that's what he was getting at, but he was being very cautious in his first major publication, *On the Origin of Species*, in 1859.

But others had preceded him in this, because they saw the origin of species question as just one example of a deeper question of the origin of life. That question became a scientific question—as we referred to it in the cell theory of life lecture—in the middle of the 18th century. It is associated with the names of Georges Buffon in France, Lamarck in France, Charles Darwin's grandfather Erasmus Darwin, among others, who argued that there was initially one life form that then became diverse in the form of its expression because of, in the case of Lamarck and Erasmus Darwin certainly, because of strictly mechanical processes going on in nature without any need to refer to divine creation, to any providential intervention. That an initial life form, however that arose, then generated all of the different forms of plants and animals, insects, birds, etc., that we see on the earth through strictly mechanical processes. This is most famous in the case of Lamarck—based on the use and disuse of its organs by its own struggle for survival to acquire characteristics that would help it to survive to the age of reproduction, and the inheritance of acquired characteristics, which is a fundamental feature of Lamarck's theory of evolution.

This notion that the origin of life is the basis for the origin of species, once we have a theory of the origin of life of the Lamarckian/Erasmian/Buffonian sort, then we see already that there is an internal dynamism to nature at the level of living creatures that makes it the case that there is constant change going on here. But it is the inverse of what happens when we see a motion picture; there we are fooled into seeing motion when there really is no motion. In the case of the evolution of life forms, we are seeing stability when there is really motion, because we're just not around here long enough in order to see the slow flow. Think in terms of, for example—you've all heard this at some point and maybe found it believable or not—the fact that glass is really a super fluid, that glass is a fluid and it flows, but it flows very slowly. You can't look at a window and see how gravity is causing the material in the window—the glass—to flow down the window. But if you look back at medieval stained glass windows from 700–800 years ago, then we see very clearly that the top of the glass is much thinner than the bottom of the glass. The glass over 800 years has measurably flowed, thickened at the bottom, which makes it very delicate to repair or to replace those windows.

So the origin of life question, the whole idea: where did this come from, that life is unified? Well, we've already got the ingredients for the answer to this question. I mentioned that at the end of the 18th, beginning of the 19th century, this notion of the unity of nature became part of (so to speak) scientific thinking, in part through the Romantic nature-philosophers, predominantly German and to some extent French at the time, who argued that there was a unity to all the forces in nature. That was one of the threads that was woven into the concept of energy, but they also held that there was a unity to all the life forces in nature, and all life forms. That there was originally one life form, that everything that is, is an expression of a fundamental underlying life force, just as all forms of energy are specific expressions of a generic form of energy, which does not exist in its generic character, only in its specific character. The same thing is true of life forms.

So the Romantic nature-philosophers, among them the German poet, intellectual, and dramatist, Goethe—Goethe wrote a book on what we call the evolution of plants in which he identified the Urpflanze, the primordial plant form that then radiated into all the different forms of plants that we see on the planet by a series of natural processes. In this context, when we look at the origin of life question from roughly speaking 1750, 1760 on, it is not surprising that the origin of species question acquired the kind of answer that we identify with Charles Darwin (and a little unfairly, not giving full enough credit to Alfred Russel Wallace).

For example we know, and Darwin was eventually forced to confront it by his critics, that an American naturalist who lived in England named William Wells, in 1813 had published an essay on what we would call "evolution by natural selection," that was referred to at length in a book by John Herschel that we know that Darwin owned and Darwin had read carefully. He was good friends with Herschel, so we know that he read that book, and he did acknowledge that he had read that book.

In 1831 a British arboriculturalist—somebody who cultures trees and is an expert on trees—named Patrick Matthews wrote a book on arboriculture, especially trees adapted to use for the navy, in a time when the navy was still using wooden ships and had lots of masts to carry the sails that they carried. Matthews had a very explicit theory of evolution, which is very Darwinian in the sense that it refers to struggle for survival and something like natural selection. There is no question that Matthews's idea, as Darwin himself acknowledged, prefigures Darwin's thinking.

In the 1840s a bestseller in Britain, initially anonymous but the author was subsequently identified as Robert Chambers, called *The Vestiges of Creation*, gave a kind of updated Lamarckian theory of evolution. And thousands and thousands of copies of this book were sold, primarily because religious leaders opposed it and denounced it as scandalous, perhaps.

Then in 1858, Darwin and Wallace both announced their theory of evolution by natural selection. Darwin, after 24 years—he came back from his five-year voyage with the *Beagle* in 1835 (he left just about the same time that Matthews published his monograph on tree culture)—24 years, 1835 to 1859, between that and *The Origin of Species*, and the entire *Origin of Species* is a small fraction of the total amount of notes he had accumulated. There is no comparison between the speculations of people like Wells and Matthews—insightful speculations—and the arguments that Darwin presented in *The Origin of Species* for the claim that species are really varieties, and that there is no constancy in nature. Over long enough periods of time, life forms are continually adapting to changing environmental circumstances, changing competition for survival, and they're able to do this because of the continual chance variability that each organism possesses vis-à-vis its parents.

Alfred Russel Wallace, who was in the South Pacific, in Malaya as it was then called, sent a short letter to Darwin (only about 8 or 10 pages long) in which all of the elements of this theory are equally present without the enormous backing of data that Darwin had assembled over the preceding 24 years. But from Wallace's point of view that data was irrelevant anyway, because Darwin, as Matthews before him, focused very specifically on an analogy between artificial breeding and natural selection, whereas Wallace rejected that on the grounds that artificial breeders manipulate the struggle for survival. They eliminate the natural struggle for survival, and so he thought you could not make a useful analogy between artificial breeding and the natural selection basis for evolution. His argument was, so to speak, a purer version based on the distribution of plants and animals—biogeography, as it's called—as he observed it from the years that he spent first in the Brazilian jungle and then in Malaya, collecting specimens for rich British collectors of rare plants and animals.

The theory of evolution contains within it a number of startling conceptual features, not least of which is the idea that chance plays an important role, a fundamental role in the process that explains the origin of species. Darwin, as I said before, waffled on this. Darwin tried to avoid claiming explicitly that chance was behind the spontaneous variations—what we would call mutations—and he never used the expression "random mutations."

But by the 1860s and '70s physicists recognized that the theory of evolution required assuming that chance plays a fundamental role. This is a deep challenge to the embedded determinism of modern science, of what science considers rationality itself. We are going to be looking at how this was reflected in the rise of probabilistic theories in science in the next lecture.

Lecture Twenty-Six
Statistical Laws Challenge Determinism

Scope:

Modern science was based on a deterministic conception of nature and natural explanation. With deduction the paradigm of reasoning about natural phenomena, it followed that every natural phenomenon is a necessary effect of a unique cause operating in accordance with universal laws. This was proclaimed by Laplace at the turn of the 19th century as a foundational principle of science. But in the course of that century, this principle was undermined by the introduction of statistics into scientific explanation and by the claim that certain processes, from the behavior of atoms to the behavior of human beings, obeyed statistical laws. The discovery of radioactivity led to the idea that radioactive "decay" was a stochastic process, and this was reinforced by mutation theory in genetics and the development of quantum mechanics. Earlier, however, a compelling case for statistical laws was made by social scientists and by physicists formulating the kinetic theory of gases and statistical mechanics and thermodynamics.

Outline

I. Over the last three lectures, we have seen the rise of a process style of thinking about nature challenge the dominant atomistic style.

- **A.** Concurrently, there was a challenge to a much deeper principle of modern science than atomism, namely, determinism.
  - **1.** As we have seen, determinism is a corollary of the deduction-based conception of knowledge on which modern science rests.
  - **2.** Effects flow from causes in nature as conclusions flow from premises in deductive arguments: necessarily.
  - **3.** Determinism, whether strictly materialistic or incorporating energy, fields, and non-contact forces, is inescapable.
- **B.** To claim that natural phenomena have an intrinsically stochastic character has far-reaching implications.
  - **1.** If nature is stochastic, then the same must be true of theories that claim to describe nature.
  - **2.** It follows that knowledge of nature cannot be universal, necessary, and certain, and neither can (all) laws of nature.
  - **3.** In fact, if nature is stochastic, we need to redefine what we mean by the terms *knowledge*, *truth*, *law*, and *reality*.
  - **4.** Yet Galileo's *Dialogue* reveals the depth of the commitment to knowledge as deductive and, hence, universal, necessary, and certain.
- **C.** Probability theory emerged first in mathematics in the 16th century.
  - **1.** Cardan concerned himself with gambling probabilities, and in the 17th century, others developed mathematical theories of games of chance.
  - **2.** A turning point was Jacob Bernoulli's *Art of Conjecturing*, which claimed that probability theory could be applied to real-world decision-making.
  - **3.** That is, acting on the basis of probabilistic reasoning could be rational, alongside deductive reasoning.
- **D.** Laplace was famous for defending the determinism of science, but he was also a contributor to probability theory.
  - **1.** Laplace saw probabilities as a reflection of human ignorance.

2. Faced with a situation *that has strictly deterministic causes* but about which we lack information, probability theory allows us to estimate the relative likelihood of outcomes given the information that we do possess.
3. This does not imply that *nature* is stochastic.

II. In the course of the 19th century, scientists had to consider the possibility that there was an irreducibly random character to at least some natural phenomena.

A. The Darwin-Wallace theory of evolution was one theory forcing this consideration.

1. Random mutations are an essential part of evolutionary theory today, and numerous physicists and philosophers thought the theory required that individual variation be random.
2. This is revolutionary in intellectual terms, but neither physics nor biology was leading the way.
3. In 1835, Adolphe Quetelet published a treatise on human behavior that introduced the then-radical idea of *statistical* laws.

B. Quetelet came to social science from the "hard" science of astronomy.

1. He began his career in astronomy and learned the mathematical techniques of observational error correction that astronomers used, including the so-called "normal" distribution of values.
2. His innovation was to apply these techniques to the growing body of statistical data about people that governments were collecting, a legacy of Bernoulli's idea that probability theory could lead to rational social decision-making.
3. Quetelet saw that there were regular patterns of behavior among large numbers of people, for example, the number of suicides per year, or even per season or week, in a country or large city.
4. These patterns, he claimed, allowed accurate predictions about groups of people quite independently of which individuals would do what or why.

C. This led Quetelet and, after him, Henry Buckle in England to proclaim the existence of statistical laws.

1. On the one hand, this idea, on the face of it self-contradictory, reinforced the collection of social statistics by governments and by individual researchers.
2. On the other hand, the idea of statistical laws made a deep impression on several physicists, among them, James Clerk Maxwell, who thought this idea could rescue human free will from the determinism of natural science.

D. At this very time, Maxwell and others were developing statistical theories in physics.

1. Maxwell and Ludwig Boltzmann played lead roles in formulating the kinetic theory of gases, which describes the behavior of gases as a statistical process involving the behaviors of vast numbers of atoms/molecules.
2. Both were also involved in a statistical interpretation of the second law of thermodynamics, which implies the irreversibility of time.
3. On their interpretation, this is only a probabilistic law, not a necessary one; thus, the reversibility of time in mechanics is preserved, at least in principle.
4. The mathematics they developed subsequently was applied to mechanics itself, leading to the field of statistical mechanics near the end of the century.

III. These developments were just consistent with determinism, but the discovery of radioactivity led to the attribution of irreducible randomness to nature.

A. Radioactivity was discovered in 1896, the same year that the electron and X-rays were discovered, and all three became intertwined.

1. Radioactivity was discovered accidentally by Henri Becquerel.
2. Becquerel attended a lecture announcing the discovery of X-rays, repeated Röntgen's experiment, then decided to see if phosphorescent substances gave off these rays naturally.
3. Fifteen years earlier, Becquerel had prepared a uranium compound for his famous physicist father's research on phosphorescence, and he decided to retrieve that specimen and conduct an investigation.
4. He stored the uranium, wrapped in a thick black cloth, with a photographic plate and a copper cross; when he developed the plate, the image of the cross was quite clear.
5. The uranium was emitting rays of some kind but not X-rays.

B. Becquerel's discovery didn't attract much attention until Marie and Pierre Curie entered the picture.

1. Marie took up the study of Becquerel's rays in 1897, using an instrument of Pierre's design, and was immediately successful.
2. In 1898, she established the reality of the phenomenon, named it *radioactivity*, and ranked substances according to their radioactive "power," focusing first on uranium and thorium, then on pitchblende.
3. Pitchblende led to the discovery of a new radioactive element that Marie named polonium, then to the most powerfully radioactive substance of all, radium, which she isolated in 1902.

C. The Curies were awarded the Nobel Prize for chemistry in 1903, but by then, radioactivity research had become a very "hot" topic indeed.

1. One important question was: Where did the energy of these radioactive rays come from?
2. Under the influence of the traditional solid concept of the atom, Pierre urged that it came from outside the atom, but in 1899, Marie noted the possibility that it came from a disintegration within the atom involving a loss of mass.
3. Ernest Rutherford, a student of J. J. Thomson's, inclined to an intra-atomic view of radioactivity and became the Curies' greatest research rival.
4. Rutherford and Frederick Soddy discovered that radioactivity is composed of multiple types of rays.
5. They named two of these, alpha and beta, identifying the former as possibly helium nuclei and the latter as electrons; in 1900, Paul Villard identified X-ray-like gamma rays.
6. In 1903, Rutherford and Soddy established that radioactivity was a process internal to the atom, that each radioactive element had a distinctive half-life, that the process was random, and that it involved the transmutation of atoms.
7. Note well: Radioactive decay is a random process, but it is strictly lawful in large populations of atoms, as reflected in the precise, unique half-life assignable to each radioactive element.

D. Rutherford led the way in seeing radioactivity as a "tool" for probing the interior of the atom.

1. He used a beam of alpha rays to arrive at the *Solar System model* of the atom in 1910, which led Niels Bohr to lay the foundations of quantum mechanics in 1912.
2. By 1917, Bohr and Einstein showed that the orbital changes of electrons bound to nuclei in the new quantum theory were random, as were the emission and radiation of photons that accompanied these changes.
3. As we will see, the development of quantum mechanics so anchored the stochastic character of nature that we really did need to rethink what we meant by *knowledge*, *truth*, *law*, and *reality*.

Essential Reading:

Ian Hacking, *The Taming of Chance*.

Theodore M. Porter, *The Rise of Statistical Thinking, 1820–1900*.

Questions to Consider:

1. Does a statistical explanation truly explain, or is it merely descriptive of a state of affairs?
2. How is it that behaviors within large groups are highly predictable even if the behavior of individuals composing the group is random/free?

Lecture Twenty-Six
Statistical Laws Challenge Determinism

This lecture rounds out our presentation or exploration of the process style of thinking as an alternative to (I really prefer an enhancement and complement to) the atomistic style of thinking.

In the last lecture I ended by noting that the idea of evolution opened a particular door (well, I didn't use exactly that language). The idea of evolution opened up multiple doors, but the one that I focused on at the very end of the lecture was that it opened the door to attaching probabilities to fundamental natural processes. This is another major idea innovation in the 19th century that is fundamental to 21st century science, and that flies in the face of, so to speak, the heritage of modern science, which is rooted in, as we saw in multiple early lectures, the idea that deductive reasoning is the basis of reasoning to truth.

Theories that claim to describe reality, to give us knowledge of reality, must have this deductive character, which means that the description of nature that our theories incorporate has to be deterministic in character. The relationship of causes to effects is, as I mentioned in the last lecture, the same as the relationship between premise and conclusion. Events in the natural and the social and the human world must be related to earlier events as causes are to effects in, for example, the treatment in physics of moving material particles. And those reflect the relationship between premises and conclusion.

So this is a fundamental theme of modern science. This determinism is a fundamental theme of modern science, which means that if you claim that probability, that natural and social phenomena and human phenomena—our decision making, for example—that they are fundamentally stochastic (a nice word which refers to statistical in character, probabilistic), then you have to redefine what the words knowledge, law, truth, reality mean. It's not a matter of adjustment.

You have to redefine what you mean by knowledge if knowledge is no longer universal, necessary, and certain, because if nature has a fundamentally stochastic character, if elementary natural processes have a stochastic character, then the knowledge must also have a stochastic character. The theories must be stochastic theories. Then we cannot have universal, necessary, and certain knowledge of nature. We cannot have a strictly deterministic theory of nature.

What does law mean if it is not deterministic? What does it mean to say that there is such a thing as a statistical or stochastic law? It sounds like an oxymoron, a contradiction in terms. Law already incorporates this notion of rigidity, that given a certain set of circumstances, the law means that what follows, follows necessarily.

There is a really wonderful comment—it is an insight into a way of thinking that, when it occurs, is a kind of a delicious gem—in Galileo's *Dialogue Concerning the Two Great World Systems,* the book that got him into so much trouble in the 1630s with the Inquisition. His hero character, the one who embodies the Copernican theory, and who is, so to speak, Galileo's mouthpiece, says that while God's knowledge is infinite quantitatively, so to speak, qualitatively when we know anything, we know it the same way God knows it. That is because knowledge, for Galileo, as for almost all of his peers among the founders of modern science, knowledge was deductive. Deductive knowledge is universal, necessary, and certain. You can't be any more certain than that.

If we know, if we have knowledge of a phenomenon—for example, knowledge of a phenomenon in nature—then that knowledge is as pure and as perfect as God's knowledge of that event. Galileo acknowledges that God knows infinitely more than we do, but intensively speaking, qualitatively speaking, knowledge has this absolute character. But now, that attitude towards knowledge, that understanding of what we mean by the term knowledge is completely transformed if we start associating probability with knowledge, that knowledge can only have a probabilistic character.

I mentioned in an earlier lecture that probability theory begins in the 16th century, although it really only becomes developed in a more sophisticated mathematical form at the close of the 17th, the beginning of the 18th century, and I particularly highlighted Jakob Bernoulli's *Art of Conjecturing*. But earlier, in the 16th century, Jerome Cardano had published a work on probability theory applied to gambling, to games—and was not published for over 100 years, so the impact of that publication was lost. But in the course of the 17th century probability theory began to be developed, earlier in the century by Pascal and Fermat, I think I had mentioned in that lecture, and then most sophisticatedly at the turn of the 18th century by Bernoulli, and Abraham de Moivre, and others.

What happened through the early 1800s, including the seminal essays on probability of Pierre-Simon Laplace, who was this great spokesperson, as I've mentioned several times, for determinism, for the deterministic view of science, that probability was associated with ignorance on our part. We used probability because we did not know the underlying causes of events or we did not know the relevant information in order to deduce the outcome of some event or some phenomenon. So probability was a measure of our ignorance.

What I've been talking about in the 19th century is the beginning of a recognition that probability is a feature of natural and social phenomena. In the previous lecture I said that the door was opened by Darwin, the Darwin–Wallace theory of evolution by natural selection, acting on what we call random mutations, and what they called chance variations, spontaneous variations. And as I said, there were a growing number of physicists who were very interested in the theory of evolution, and philosophers who recognized that while Darwin was being too cautious, that the theory of evolution required recognizing that chance is a fundamental feature of the processes by which life reproduces.

This is a startling innovation, and it comes at a time when there was a kind of a cascade of attribution of stochastic features to fundamental processes. While we ordinarily think sometimes that the intellectual way in science is led by the hard sciences, especially physics, in fact it was in the middle of the 19th century and even earlier than that (1835) when the Belgian sociologist, mathematician, astronomer, Adolphe Quetelet published his *Treatise on Man and the Development of His Faculties*, in which he really introduced this idea of statistical laws.

Quetelet had studied astronomy, and in the course of studying astronomy and working as an astronomer, had learned the error theory that astronomers use to correct for the ways that different observers (unconsciously, of course) subtly make small errors in observation. Then a mathematical technique (what we now call the normal curve) was developed for correcting these errors mathematically—without knowing the right answer, looking at the distribution of the data, figuring out, so to speak, what the correct measured value is likely to be within a certain range.

What Quetelet did was he took this error-correcting mathematical technique and he applied it to social phenomena. He took the data that people were beginning to collect, the social-statistical data that people were beginning to collect in response to 18th century probability theorists who claimed that better political decisions could be made if we had more information about human affairs, and he started showing how there were statistical correlations among things like crime and its distribution as a function of age, gender, poverty.

He started collecting data on suicides, for example, and one of the things that he startled people with, we're not startled with it today because we've become inured to this, but in the 19th century people were startled at the claim that he could predict within a fairly narrow range how many suicides there would be in Paris the next year, or in Brussels or in London. There was something like a statistical law, he said—and he used that language of a statistical law, which is a startling notion—the idea that you can have a lawful phenomenon that is only statistical.

Now I don't want to apply the term random to this particular phenomenon. We don't think that people commit suicide randomly. But the distribution of suicides (who commits suicide is not predictable), but that in a given population, based on statistical patterns that we have observed, we can predict how many suicides there will be over Christmas week in New York City within some relatively narrow limits. And if you include things like the weather, whether it's sunny or has been raining for 17 consecutive days, and the temperature, and what the economic situation is, you can probably get even closer than that.

So Quetelet and in England the historian Henry Buckle, both popularized in the middle of the 19th century, roughly speaking from the 1830s—Quetelet's book was published in French in 1835; it was translated into English only in 1842—so from 1840s on, there was a growing sense that there were such things as statistical laws for social phenomena.

It is interesting that this led to a tremendous obsession with collecting statistics all over Europe and then in the United States, in which just about every government set up a bureau of statistics to collect more and more complex information about the population. We need to know in any given area how many people there are by ethnic distribution: how many Catholics; how many Protestants; how many Jews; how many Muslims? Once you collect that, you want to know what are their health statistics? What are their mortality statistics? What are their financial statistics? What professions are they in? Because all of this is supposed to lead to better government.

But initially what it led to, at any rate, was the accumulation of huge amounts of data, and the question was, what do you then do with this data and how do you organize that data? Well, we will be hearing very soon in a lecture on the computer that a seminal moment in the history of the computer was when Herman Hollerith got a contract from the U.S. Census Bureau for the 1890 Census, which now included by congressional mandate a wide range of information about Americans, not just counting them. Then the question was, how are we going to collate and organize this information? He got a contract to develop a tabulating machine that would automatically tabulate, collate, and organize the information that the Census Bureau collected. We will be talking about how that ramified into IBM, as I said, in a subsequent lecture. So here we have, in the 1850s and '60s, this notion of statistical law in social phenomena. We have a statistical character associated with the process of evolution, with the origin and certainly with the reproduction of life, explaining the multifariousness of life.

We also have James Clerk Maxwell, who was very sensitive to the work of Buckle in England, and through him of Quetelet, to the idea that he thought that one could rescue free will by accepting this idea that statistical laws governed human affairs, but there was no necessity on any given individual. Whether that solves the problem philosophically, I think philosophers would say not, but Maxwell was very involved with this, and that is why he was interested in the theory of evolution and the role that chance played in the theory of evolution.

Maxwell, at the same time as Ludwig Boltzmann, the Austrian physicist, developed a kinetic theory of gasses, in which the behavior of gasses, especially the characteristics that we call temperature and pressure of a gas, are fundamentally statistical phenomena. The kinetic theory of gasses successfully explained the pressure–volume relationships by assuming that matter was atomic, and that the motions of matter, the kinetic energy of these molecules or atoms, generates heat, is what we mean by heat—they have a temperature—and the pressure that a gas exerts is derived from these equations which have a fundamentally probabilistic or statistical character. So the kinetic theory of gasses from 1860s on became a very important theory in physics, and it assumed that pressure and temperature characteristics were essentially statistical in nature.

They were also involved in the statistical interpretation of thermodynamics, as I mentioned in an earlier lecture, in an attempt to undo the arrow of time. They attributed a statistical character to the fundamental processes by which energy is measured in thermodynamics, so it's the same as the kinetic theory of heat, really, that heat is a statistical quantity having to do with the motion of the atoms and molecules that make up a substance, let's say a gas. When the second law of thermodynamics says that heat can only flow from a hotter body to a colder body, initially that was understood to be a deterministic phenomena, that there is no possibility of it going back the other way, of heat flowing from a colder body to hotter body.

Boltzmann and Maxwell argued that that was merely a statistical claim, that statistically there always is some likelihood of heat flowing from a colder body to a hotter body. Maxwell invented a thought experiment. It involved something that he called a demon, and everybody subsequently called it Maxwell's demon, who could sort of open the door when the faster molecules in the colder body—which may be moving more rapidly than the slower molecules in the hotter body, because it's a statistical distribution of motion, of kinetic energy in any particular gas; that's what we mean when we talk about a statistical theory of motion—and so the demon could open up the door whenever the faster molecules on the cold side were moving and let only the slowest molecules from the hot side go through. What would then happen would be that the hot side would get hotter and the cold side would get colder, because we were taking the fastest molecules out of the cold side, taking the slowest molecules out of the hot side.

This in effect allows for the reversibility of time, but is an extremely improbable event. That claim, though, means that there is a fundamentally statistical character to the processes that underlie even such a fundamental concept as time. The statistical interpretation of what had been deterministic scientific equations continued at the end of the 19th century with the development of statistical mechanics, especially by J. Willard Gibbs here in the United States at Yale University. Statistical mechanics became a fundamental tool for physicists and continues to be so today. Again, looking at a phenomenon that from the 17th century on had been deterministic—the behavior of the motion of material particles—and treating it statistically.

Now there is a really interesting and epical event, which is the discovering of radioactivity in 1896, that went beyond attributing a statistical character to explicitly attributing a random character to fundamental natural processes. This randomness expanded, so to speak, conceptually into quantum theory in the 20th century, and has become deeply embedded in 20th century physics. It is not merely a statistical character, but it is that natural and social phenomena—but especially here natural phenomena—have a statistical character because they have a fundamentally random character.

Let's take a look at this in a little more detail, and I think you will get a feeling of what I mean. In 1896 a French physicist named Henri Becquerel, himself the son of a French physicist, went to a lecture on the newly discovered X-rays, then still called Röntgen rays after their discoverer, and he went home and decided to see if phosphorescent substances also emitted rays. This was in 1896.

It so happened that his father's career as a physicist was based on the study of phosphorescence, and 15 years before, he remembered that he had prepared a series of specimens for his father to study, and one of these was a collection of uranium salts, a block of a uranium salt that was stored in the laboratory. So he went and he got the specimen, wrapped it in a thick black cloth, and put it in a drawer where there was also a photographic plate, waiting for a sunny day because through his father he, like others, believed that phosphorescent substances phosphoresced more strongly after they were exposed to sunlight. If you exposed the phosphorescent substance to sunlight, that stimulates them in some way, and then you take them away from the sunlight and then they give off this phosphorescence. Now, does the phosphorescent substance give off rays like X-rays, because phosphorescent rays can't go through stuff?

It turned out, accidentally, that it rained day after day after day, so the stuff was sitting in the drawer day after day after day. Finally the sun came out. He takes the uranium compound out. He's got the photographic plate. Something about the plate looks off, so he develops it, and he discovers that the photographic plate, even though it has been in a drawer, and that the phosphorescent stuff has been wrapped in a thick black cloth to make sure that whatever weak phosphorescence it has can't get out, that the photographic plate is cloudy. That means that the uranium salt was giving off some kind of rays that were not phosphorescent. But he was able to establish quickly that it was also not X-rays.

So this is a new kind of radiation and by the end of that year—1896, still within the same year—he reported to the Paris Academy of Sciences on this observation, and in 1897 he published a short note about it. It did not initially get a lot of attention, but coincidentally Marie Curie was looking for a doctoral dissertation research subject and her husband Pierre Curie suggested that she study this weird phenomenon that Becquerel had come up with. He had a hunch that it would be important.

In order to help her, because she needed to have a detector in order to prove that there was really some kind of rays coming out of this compound, he invented an extremely supple electroscope, a device that can detect electric charge. It was a very fragile instrument, very complicated to use correctly, and Marie Curie mastered it. Actually, it goes back to the whole question of how do you know when you're using a new instrument that's measuring something that you don't know anything about, how do you know you're using it correctly? But we'll let that go for the moment.

In 1898 Marie Curie gave the name radioactivity to what was going on in Becquerel's sample, and she started studying different substances and ranking them in terms of their radioactive power, and studied uranium, thorium, and an ore called pitchblende, which really turned out to have powerful radioactivity in it. She isolated from a tremendous amount of pitchblende a minute quantity of a brand new element that she named polonium (after her native Poland), and that left a residue which contained something even more radioactive, but which required processing tons and tons of ore for a minute fraction of a gram of radium.

She and her husband Pierre Curie in 1903 shared the Nobel Prize in physics with Becquerel, who one could argue had an original good idea but didn't do much with it, but she shared the Nobel Prize with them. Marie Curie got her own Nobel Prize in 1911 in chemistry for her subsequent work in radioactivity. Now this made radioactivity, if you'll forgive the expression, a very hot research topic, and into this topic moved Ernest Rutherford, one of the most influential physicists of the first third of the 20th century, although obviously not nearly as well known as people like Einstein and Max Planck and Niels Bohr. Rutherford's own work (Nobel Prize–winning), as well as the work of the many generations of students that he trained, was extremely influential. Rutherford, initially alone starting in 1900, and then with a chemist named Frederick Soddy, developed a much deeper understanding of radioactivity.

Pierre Curie, in 1899, when his wife started publishing and announcing the discovery of these new elements, believed that the atom was solid. Two years before, J. J. Thomson had announced the discovery of the electron as an internal feature of the atom, so the atom had an internal structure; but Pierre Curie didn't buy that, and believed that the atom was solid. Marie Curie went along with that, at least superficially, but in 1899 speculated, just threw out a hint, that maybe this incredible energy from radioactive substances comes from an internal disintegration, a disintegration of something inside the atom, and that this radiation of energy may be correlated with a loss of mass (that would become famous as $E = mc^2$ when Einstein gets on the scene in 1905). But this was a hint.

Rutherford, who was a student of J. J. Thomson, immediately bought into the idea that atoms have an internal structure. His research was all based from the beginning (he and Soddy) on the idea that atoms have an internal structure, and that radioactivity is the result of a disintegration process (which we now call typically a decay process) of the nucleus within (that was not a term that would have been used in 1902, 1903). A disintegration process within the atom, because the atom has an internal structure.

Rutherford and Soddy identified that there are at least two kinds of rays associated with radioactivity. Alpha rays, which act just like, and then were identified as, helium nuclei (helium was an element that had only recently been discovered). And that there are helium nuclei (two protons and two neutrons, to use our language, not available in 1902), and that beta rays were in fact electrons. So what's happening is that these radioactive elements are releasing helium nuclei (helium atoms stripped of their electrons) and electrons are coming from inside the atom.

What is really important to us is that Rutherford and Soddy announced that radioactivity was a fundamentally random process—and they used that language—that it was a strictly random process in which you could not predict any given uranium nucleus disintegrating in this way. But they claimed they could measure with precision the distinctive what we call half-life for every radioactive element—that every radioactive element has a distinctive half-life, the way human beings are supposed to have distinctive fingerprints—that half of any large sample will decay in a particular period of time (10,000 years, 100,000 years, 11 days, 6 hours, 2 minutes; whatever it happens to be).

This is a fundamental development because it gives body to the idea that a phenomenon can be random and lawful. There is only a statistical probability to be attached to whether any given atom of radioactivity will disintegrate, but give me a large enough sample and I will predict with precision how much energy will be released in any given unit of time once I know the half-life associated with that particular element. And that is what Rutherford and Soddy got their Nobel Prize for.

That was a really powerful development, but now radioactivity was taken by Rutherford and was used as a probe, as a tool, as a new scientific instrument given his new understanding of radioactivity, and especially that what we get is helium nuclei—which are relatively heavy, weighing thousands of times more than an electron—helium nuclei come out of a radioactive specimen; let's say, uranium. If you put it inside a box with a little hole, then out of that hole is going to come a stream of helium nuclei. He put some of his graduate students to work to see how we could explore the interior of the atom by means of bombardment with these helium nuclei—the alpha rays. In 1900 a physicist named Paul Villard identified that there is another ray associated with radioactivity—gamma rays—and that those rays are very similar to X-rays. That completes that particular picture.

In 1909, 1910, Rutherford and his graduate students came up with data that strongly supported the idea that an atom was largely empty space with a tiny solid nucleus surrounded by orbiting electrons. As we will see more specifically in the lecture on quantum theory, two years later Niels Bohr founded quantum theory on the basis of rescuing Rutherford's solar system model of the atom.

Between 1913, when the publication first came out, and 1917, Bohr and Einstein, sort of separately but also together, showed that the change of orbits of electrons, which is the source of all absorption and emission of electromagnetic energy, is a random process. Nevertheless it can be described with statistical precision. In fact, the work that Einstein did in 1917 and up through 1919 in this particular area (and Einstein did fundamental work in statistical mechanics) is really the basis for lasers, although it was about 40 years later when the first lasers were actually built.

But the idea that lasers are built on, that you can get a precise physical phenomenon—you can get a laser beam that you can use for eye surgery, that you can use to read music CDs and DVDs—out of this random statistical process, is another illustration of the idea that randomness and lawfulness, statistical stochastic character and lawfulness are not exclusive of one another. That means that we really do need to go back to the drawing boards and see what we're going to mean by the terms knowledge, law, truth, reality in science. It is a small irony that Einstein and Bohr disagreed about this for decades.

Lecture Twenty-Seven
Techno-Science Comes of Age

Scope:

Although the idea of techno-science originated in the Graeco-Roman period, and technological innovation was a major factor in social change in the 12th century and the Renaissance, it was in the 19th century that techno-science erupted onto the world scene as an omnivorous and relentless driver of social change. Such technologies as the electric telegraph, the transatlantic telegraph, electricity and its host of applications in industry and the home, synthetic dyes and fibers, plastics, artificial fertilizer and hybrid seeds, high-energy explosives, long-distance telephony, radio, and television were made possible by science-informed engineering. And these are merely the tip of the iceberg. By the early 20th century, science, engineering, and innovation had become so intimately intertwined that their respective contributions could not be distinguished. Transportation, communication, construction, production, and information *systems* were all products of this alliance, and all were characterized by continual innovation at an accelerating pace.

Outline

I. In the 19th century, techno-science erupted onto the world scene as a relentless driver of social change.

- **A.** That theoretical knowledge of nature and craft know-how could be integrated fruitfully was already recognized in the Graeco-Roman period.
  - **1.** The idea of techno-science is clearly articulated in Vitruvius's *Ten Books on Architecture*, and textual and artifactual evidence shows that mathematical physics was employed technologically to a limited extent from the 3rd century B.C.E. through the 3rd century C.E.
  - **2.** The industrial revolution of the 12th and 13th centuries was know-how–driven, thus not an instance of techno-science, but during the Renaissance, mathematical knowledge was made the basis of a wide range of technological innovations.
  - **3.** Furthermore, technological innovation was explicitly identified with progress.
- **B.** Techno-science was implicit in the creation of modern science.
  - **1.** In the 17th century, Francis Bacon and René Descartes, however different their conceptions concerning knowledge of nature and how to get it, agreed that knowledge of nature would give us power over nature.
  - **2.** It was only in the 19th century, though, concurrent with the creation of new scientific theories of nature, that techno-science went from promise to driver of social change.

II. We tend to deprecate "tinkering," but the first phase of the Industrial Revolution was initiated not by scientists but by tinkerers, gifted with know-how but possessing little or no formal education or knowledge.

- **A.** Mass production of iron and of textiles, the factory system, and the steam engine were 18th-century inventions that launched the 19th-century Industrial Revolution.
  - **1.** Iron was produced in antiquity, and water-powered blast furnaces were in operation in Europe by the 15th century at the latest, but the scale of iron production skyrocketed beginning in the early 18th century.
  - **2.** Abraham Darby was apprenticed as a teenager to a bronze-smelting master and became a bronze master himself.
  - **3.** He then invented a coke-based process for smelting iron ore in place of the increasingly

expensive charcoal-based process then in use.

4. In 1709, Darby adapted the process to the blast furnace and began commercial production, lowering iron production costs dramatically and increasing production volume many-fold—and at an expanding rate.
5. Darby also patented a technique for casting iron in molds that enabled mass production of nearly identical pieces, and he incorporated a metallurgy laboratory into his operations, arguably the first industrial research laboratory.
6. His firm, led by his grandson, built the first iron bridge in 1779, launching iron's use as a structural material.

B. James Hargreaves and Richard Arkwright, both from desperately poor families, made mass production possible.

1. Hargreaves was a barely literate textile worker whose first *spinning jenny*, developed in 1764, had eight spindles driven by a single operator.
2. By 1777, some 20,000 jennies with up to 80 spindles per wheel were in operation in England alone.
3. Richard Arkwright, taught to read by an older sister, introduced a water-powered *spinning frame* in 1771.
4. In 1775, he patented an improved carding engine to feed the frame; soon, automatic looms were invented to weave the vast output of the growing number of frames into cloth.
5. Unlike Hargreaves, Arkwright became extremely wealthy, largely through his vision of a factory-based system of mass production enabled by the new machinery.
6. As happened with Darby's iron innovations, unit cost (of cotton thread and cloth) collapsed as volume increased a hundredfold and more—but the new factory-based system of production was brutally exploitative of workers, creating wealth for a few from what the Romantic poet William Blake called "dark Satanic mills."

C. James Watt's improved steam engine offered an alternative to water-powered mills, freeing factories from river sites only.

1. Watt was a mechanic/instrument maker who, between 1765 and 1774, developed a much improved version of the original Newcomen steam pump.
2. In 1774, Matthew Boulton bought out Watt's bankrupt backer, immediately adapted Watt's prototype for commercial production, and put Watt to work inventing a string of improved versions.
3. Boulton and Watt steam engines accelerated the Industrial Revolution begun by water-powered mass production, but steam engines soon moved from stationary applications powering mills to mobile applications.
4. The first steam-powered railroads began operation in the 1820s, pioneered by George and Robert Stephenson, then Marc and Isambard Brunel, both father-son teams, with only the last having some formal schooling.
5. Robert Fulton had no technical training at all, but using off-the-shelf engines and hardware and simple arithmetic calculations and with the support of the politically savvy Robert Livingston, he succeeded in converting his vision of steam-powered boats into commercial reality.

III. In the 19th century, a qualitative change in the nature of technological innovation took place as science became coupled to engineering and entrepreneurship.

A. Increasingly, invention became one element in a complex process of innovation that was dependent on scientific knowledge, formal engineering training, and supportive business acumen.

1. The electric telegraph was invented and demonstrated by physicists—Joseph Henry in America and Charles Wheatstone in England—prior to Samuel Morse's efforts, which failed until Joseph Henry was consulted by an associate of Morse and used his physics knowledge to repair the flaw in the design.
2. Similarly, the first "amateur"-designed undersea telegraph cable, financed by Cyrus Field, failed ignominiously, but its successor, redesigned by the physicist William Thomson, became a global triumph.
3. Michael Faraday's dynamo of 1830, together with the body of electrical and electromagnetic theory that had grown up in the interim, underlay the emergence of commercial electricity generators from about 1870.
4. Thomas Edison was a classic know-how genius, but behind his bluster of disrespect for theory, he employed mathematicians, chemists, and physicists to make his inventions commercially successful.
5. A great deal of scientific and science-based engineering knowledge underlies Edison's scheme for the central generation and distribution of electricity.
6. Radio technology is directly based on Maxwell's mathematical theory of the electromagnetic field: tinkering without knowledge of electrical theory would not get you very far.
7. Alexander Graham Bell's telephone worked locally and on a small scale, but more physics was needed to make long-distance work.
8. In the last decades of the 19th century, the germ theory of disease led to practical applications in vaccination and antisepsis.

B. A particularly good example of the realization of the idea of techno- science is the creation of the synthetic dye industry.

1. William Perkin made the first synthetic dye, mauve, in 1856 while "tinkering" with coal tar as a course project.
2. Enormous wealth and power were subsequently created out of chemical knowledge as an engine of technological innovation.
3. Perkin made a modest fortune, but German chemists generated whole new industries in dyes, synthetic materials, pharmaceuticals, artificial fertilizers, explosives, and more.
4. All of a sudden, the idea of techno-science became a compelling reality for entrepreneurs, industrialists, financiers, and politicians.

Essential Reading:

Anthony Travis, *The Rainbow Makers*.

Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm*.

Questions to Consider:

1. What is it that drives the pace of innovation—knowledge or desire?
2. Did the very nature of technology change in the 19th century by comparison with the technologies deployed until then?

Lecture Twenty-Seven
Techno-Science Comes of Age

In the very first lecture in this course I called attention to the fact that scientific ideas overwhelmingly changed the world through technological applications, and I introduced the term techno-science to refer to those technological applications that are explicitly dependent on and derived from scientific knowledge.

The idea of techno-science first manifested itself, you'll recall, in the Graeco-Roman period. I cited the *Ten Books on Architecture* by Vitruvius, who specifically spoke to the superior kind of know-how that an architect/engineer would possess if it were based on knowledge rather than sort of the craft know-how that had been accumulating for thousands of years and that was omnipresent in the Graeco-Roman world through the very considerable technology infrastructure that existed at the time.

The idea of techno-science is therefore easily attributable to, let's say, the last 200 years before the beginning of the Christian era, so roughly speaking from the time of Archimedes and maybe some of his immediate predecessors through Vitruvius and into the Roman world. But there was no scientific knowledge that could be used to generate technological applications of a considerable sort.

There was a certain amount of mathematical physics that was available that was used in the design of weapons, for example, ballistas and catapults, but overwhelmingly the idea of techno-science was an idea, and it's fascinating that that idea could have been part of the Graeco-Roman mindset. It tells us a lot about the power of the idea of scientific knowledge, which was at that time a relatively new idea, and from our perspective did not have a great deal of accomplishment behind it.

In the 12th century Renascence (as I called it), the industrial revolution of the 12th and 13th centuries in which there was an explosion of technological innovation, there was nothing that I would call techno-science. It was, again, an industrial revolution based on know-how. It was craftsmanly, it was superb, it was innovative, it was creative, it was clever, it was powerful; but it was not based on knowledge.

In the Renaissance we had an interesting intellectual development in that the idea of progress in the 16th and 17th centuries was explicitly linked to technological innovation and scientific knowledge as a source of technological innovation. But the only technological innovations in the Renaissance period that one could point to as based on knowledge were those that were based on mathematical knowledge. The applications of mathematics as in central vanishing point perspective drawing, and in mathematical cartography, navigation, engineering drawing, etc., were the examples that I pointed to in that lecture.

We have been, for 300 years in effect, on a roll of talking about the emergence of increasingly powerful scientific ideas, with a clear focus on the 19th century as the time when scientific ideas began to reach degrees of maturity and explanatory power that we recognize as predecessors of the scientific theories that are in use today. Now is the time when we need to look at not just the idea of techno-science, but the emergence in the 19th century, collateral with the emergence of this new generation of increasingly powerful scientific theories, the rise of techno-science not just as an idea but as a force relentlessly transforming society.

In this lecture and the next lecture I want to look at the emergence of techno-science as a force in society, its transition from an idea, a promise—as Francis Bacon and René Descartes promised—that scientific knowledge of nature would give us power over nature. That promise is delivered beginning in the mid-19th century.

But by then, the Industrial Revolution was already in place. And what is interesting, the industrial revolution that we associate with steam power in the end of the 18th and the early 19th century, what is interesting is again, and right from the beginning I've tried to do justice to this, that know-how was really the basis of the innovations that initiated the Industrial Revolution. The Industrial Revolution was not dependent on techno-science. Techno-science piggybacked on an industrial revolution that had been precipitated by people who possessed know-how and often had little or no formal education, or had been apprenticed and had considerable craftsmanly know-how, but again were not formally educated. They did not possess what we have seen scientists of the modern stripe require in order to qualify as having knowledge, as being scientists, having the kind of theoretical understanding that we associate with science as distinct from craftsmanship, know-how, etc.

The Industrial Revolution is full of fascinating characters; the origins of the Industrial Revolution are rich in fascinating characters. The man Abraham Darby, born to a Quaker family, and apprenticed out as a teenager, becoming knowledgeable about the business of machining bronze, of smelting bronze, of casting bronze, and becoming a very successful businessman in bronze, but showing considerable creativity in discovering how to smelt iron ore using coke instead of charcoal.

This is in the early 18th century (1709 for example) in which his iron works was in production. At that time, wood was becoming increasingly scarce, and it takes an enormous amount of wood to be burned down to charcoal to be used as fuel in an iron forge, in a blast furnace. Darby figured out how to use coal, not directly, but by first converting coal to coke by burning it in a closed vessel and getting coke out of it, and then using coke as the fuel. This required modifying the iron forge in order to be able to use coke, and it was a trick that he and his colleagues in England managed to keep secret, so to speak (it was an open secret), keep away from competitors for over 100 years. It was really illegal to export that kind of knowledge, especially to America, but eventually a Welshman named David Thomas in the 19th century did come to America, settled in the Lehigh Valley, and started building iron forges that used coal rather than charcoal as a fuel. That dramatically reduced the cost of iron and the volume of iron that could be produced.

So Darby in some sense, a self-educated but nevertheless highly intelligent individual, really pioneered or opened the way to iron becoming a commodity. And it became increasingly a commodity throughout the next two hundred years as the production processes increased in volume, and the cost per pound of iron decreased. So Darby really opened this way, and his family business flourished for over a century in which successive generations of Darbys further pushed the production of iron, eventually building the first iron bridge, for example, and initiating major changes in construction. Darby is one example of how a critical piece of the infrastructure that erupted as the Industrial Revolution at the end of the 18th, beginning of the 19th century, emerged out of know-how.

Even more startling is the story of James Hargreaves, who invented the spinning jenny, or who built the spinning jenny based on an idea that he heard of (I'm not exactly clear). But Hargreaves was basically illiterate, and he built a working spinning jenny in which a single operator turned one wheel which spun eight spindles on which thread was spun. This was obviously a tremendous labor-saver, and so his early machinery was sometimes attacked and destroyed by workers who felt that they were going to be losing their jobs.

He built his first model in 1764, and it had eight spindles. Within 10 years there were tens of thousands of spinning jennies in England, with up to 80 spindles per worker, where a single wheel operated up to 80 spindles, a tremendous increase in the volume of thread and yarn that was available, and a tremendous collapse in the price of that thread and yarn, which eventually filters through to a tremendous decrease in the price of the finished cloth. The beginnings of mass production come from an effectively illiterate workman who had an idea, who translated it into a device which was immediately picked up and copied on an enormous scale. I mean tens of thousands of spinning jennies in England alone, as I said, within 10 years.

By the time Hargreaves got around to patenting it (somebody told him that you had better patent this) they wouldn't grant him a patent because it was already being used all over the place, and so he died poor.

By contrast, Richard Arkwright, who is credited with having developed, but probably did not invent, a water-powered version of the spinning jenny called the water frame or the spinning frame, in which a waterwheel powered a much larger version of the spinning machine, again tremendously increasing the volume of thread that could be produced, and then developing an automatic carding machine, because they needed to feed the spindles. We needed much more raw material from the wool or the cotton in order to provide the materials to be spun into thread. And then after that somebody had to invent, and did invent, automatic weaving machines in order to make fabric out of the cotton thread and the wool yarn, because otherwise the stuff just piles up, and how are you going to sell it? You sell it to people who make their own clothes, but you can also now, instead of human weavers weaving by hand at a loom, you can have automated weaving powered by water machinery. And again we have a tremendous increase in volume, and decrease in price of the finished goods, which is good in some respects.

But Arkwright was a much better businessman than Hargreaves, and died very rich. He patented from the beginning. He was an early adopter of the steam engine. But unlike Hargreaves, Arkwright understood that in order to really benefit from this machine, it needed to be embedded in a systematic framework, and so he developed a factory-based system of production that integrated the skills necessary for the water power translated into machine power, the machines, the operators of the machines, labor policies—brutal labor policies, exploiting child labor and discarding workers at a relatively young age because he found that they no longer possessed the nimbleness in their fingers in order to operate and to produce the finished work that he needed.

He was one of the brutal examples of what William Blake, the poet, at that time called the "dark satanic mills," seeing in the first phase of the Industrial Revolution a terrible, terrible impact on the working-class in England. Arkwright's wealth is directly correlated with pressing down the wages that workers earned by finding in a sense the minimum labor cost that you could have in order to get people to work in these factories.

Interestingly, Samuel Slater, a young Englishman, worked as an apprentice with one of Arkwright's partners and collaborators. He escaped to America and at the end of the 18th century arrived in Pawtucket, Rhode Island (around 1790). It was illegal for workers in these industries to immigrate because of the knowledge that they carried in their heads, and without any drawings whatsoever, because that would have been a serious criminal offence, Slater arrived in Pawtucket and convinced local businessmen that he could build versions of the machines that the Arkwright factories used. He was given the resources to do that, and within several years had started what became a very large spinning industry here in the United States.

Again, Arkwright came from a very poor background. He was taught to read by one of his sisters. Very poor education, but tremendous talent in the area of know-how.

James Watt improved an existing steam engine. Watt himself was a mechanic. He was a musical instrument-maker as well as a scientific instrument-maker. He was apprenticed to learn that, but he had a very fragile constitution so he only served as an apprentice for one year, then he moved back from England to Scotland, settled in Glasgow, and got a job at the university repairing scientific instruments.

One of the things he was given was not a scientific instrument, but was an old Newcomen engine, which was an early form of a steam engine (really a steam pump). Extremely inefficient, and Watt realized that this could be made much more efficient if the cylinder was kept hot all the time instead of cooling it off in every cycle in order to get the piston to fall down. The steam pressure pushed the piston up, and then they cooled the cylinder wall in order for the steam to condense, and then the piston dropped down, and the cycle started over again. It was an incredibly inefficient device, and only made sense if you were using it to pump water out of a coal mine where the coal was basically free in order to fuel the engine.

Watt quickly saw how the efficiency could be at least tripled, and in fact eventually increased by a factor of 10, and that is what really launched the steam-power based Industrial Revolution. But Watt himself had very little formal training except as he became more and more knowledgeable through self-education;

he was a good example of know-how. One of the pillars of the Industrial Revolution was, of course, the Watt steam engine.

He worked on it for eight or nine years, initially supported by a physician who had a number of entrepreneurial interests (he owned coal mines, for example) named John Roebuck. Roebuck went bankrupt in 1773 and his interests were bought up by a friend of his, and someone who was acquainted with Watt, named Matthew Boulton. Boulton, together with Watt, created the first commercial steam engine company using increasingly sophisticated versions of Watt's improved steam engine.

The first railroads were created by the father-son team of George and Robert Stephenson, also workmen (in the case of the father especially) with almost no schooling and no formal education. I think that the father only learned to read as a teenager, for example. The father and son team Marc and Isambard Kingdom Brunel were responsible for fundamental developments in construction technology, building the first tunnel under the Thames River, for example, building bridges, tunnels, and railroads all over England. The son, Isambard Kingdom, had some formal schooling, but nothing like what we would consider a college- or university-level education, and did not possess scientific knowledge, but a tremendous amount of sophisticated know-how, systematic know-how that used mathematics, that quantified relationships. This is a very typical phenomenon at the time, in which people were responsible for major technologies in a sense without being indebted to anything that we would recognize as scientific knowledge.

Robert Fulton's steamboat for example, the first steam-powered boat, was basically an off-the-shelf engine put on a boat. Fulton calculated how big the boat would have to be in order for a steam engine to be able to turn the paddles fast enough to paddle upstream. He was able to get backing and win the support of Robert Livingston, an extremely politically well-connected American sort of "aristocrat," who had the political connections to get the contracts from the government to do a prototype and prove that they could go up the Hudson River and back down much faster than existing watercraft. And that started the whole steamboat industry.

Fulton was not the only person making steam engines for the boat, but what is fascinating is that he had no special training whatsoever in engineering, but he got this idea, and the idea was translated into reality by exploiting other people's know-how and by accumulating the know-how to do what he wanted to do. As if somebody decided that they were going to build their own custom-made sports car, but they bought a kit and they put it together, along the way having to do lots of cutting and trimming in order to get it to work correctly. So they bought an engine here and a used car that they used the chassis and the suspension from, etc. That is sort of what Fulton did, although he did it for the first time, and he had to come up with the right calculations so that he could convince people that this thing would work.

This is a very familiar story. In the early decades of the Industrial Revolution the key ingredients came from know-how; but things changed. Things clearly changed when we come to the electric telegraph, which we associate with Samuel F. B. Morse, an artist who went to England in order to try to sell the monumental paintings that he was making that he could not sell here in the United States. He got the idea of an electric telegraph to replace the mechanical telegraph that had been built starting in the 1790s in France, and then spread throughout Europe by Claude Chappe and his brother.

Morse got this idea that you could have a series of semaphores, and the arms of the semaphores at different positions would stand for different signals, words or letters, and using a telescope a person could look at a semaphore miles away, read the positions of the arm, and then transmit the message to the next semaphore station down the line. By the 1820s or '30s there were thousands of miles of this kind of mechanical optical telegraph in Western Europe. Of course there were problems in bad weather, and you can't do it at night, but it did allow the transfer of information over long distances much more rapidly than sending somebody on a horse or on a boat. No comparison.

But Morse got the idea for an electric telegraph. Now while he was in England the physicist Charles Wheatstone developed an electric telegraph which was actually built in England, but it was a much more complicated and cumbersome device that Morse's, so Morse sort of succeeds in getting the credit for the first practical commercial electric telegraph. But Morse didn't know any science, and Morse's telegraph would not work until, through a young physicist that he was introduced to who knew Joseph Henry at Princeton—that Joseph Henry the physicist at Princeton had already built an electric telegraph based on Faraday's researches on electromagnetism. He had seen the possibility of an electric telegraph, built a one-mile line between his laboratory at Princeton and his home so he could let his wife know when he was coming home for lunch, and then took the thing apart. He had no interest in commercializing it.

Morse needed the physics knowledge that Henry possessed in order to make his electric telegraph work. That knowledge needed to be built into Morse's idea, which refused to work because he didn't understand the physics of the situation. We can see in this an instance of techno-science now beginning to emerge, but it now erupts on a scale that is, of course, colossal.

In the 1850s the American entrepreneur Cyrus Field decided the time had come to build an underwater telegraph cable connecting America and Europe, and what a wonderful boon that would be in terms of business and the transfer of information; particularly relevant to business, but later, of course, for newspapers as well (even at the time, the mass circulation newspaper was just beginning to come into its own). Field engaged an amateur telegraph enthusiast who thought that he knew how to do this, and they actually got the money together and built the cable, which lasted approximately a month and then collapsed totally and irretrievably.

The successful transatlantic cable needed to be based on physics, and William Thomson, Lord Kelvin, who has appeared numerous times in recent lectures, was called in as an authority and he was put in charge of what became the first transatlantic cable in the 1860s, the transatlantic telegraph cable linking the United States and Europe. Within several years that same knowledge was used to lay telegraph cables that connected effectively all of the continents—Japan, Southern Asia, Europe and the United States, and Australia eventually. The same knowledge, the knowledge based in physics.

Of course, Faraday's work has already been mentioned. Faraday, I mentioned, invented the dynamo somewhere around 1830, 1831. The dynamo was the basis of all electrical generating machinery. All of the technology associated with the generation of electricity is based on the dynamo principle until you get to the 20th century and such things as photovoltaic devices. That technology, when it became commercialized, especially from approximately the 1870s on, and you could actually go into a shop and buy or order an electric generator, then that technology was based on the physics of electromagnetism, and it was necessary to have that knowledge in order to build successful machines and to use them.

As Thomas Edison discovered—because he was a know-how guy if ever there was one—but as his inventions needed to be translated into commercial products, Edison became increasingly dependent on physicists, chemists, and mathematicians (who publicly he mocked all the time) in order to have access to the knowledge that was necessary for his products to actually work.

A good example of that, of course, is his introduction of the commercial central generation of electricity and its distribution, the Pearl Street Plant in Lower Manhattan that was the first example of centrally generated electricity that was used commercially in order to support his invention of the incandescent light bulb. That unleashed the whole electrical appliance industry, so that within 20 years you had electric ovens and electric refrigerators and electric irons and electric toasters and electric hairdryers. Almost all the appliances that we think of today as modern were laid down in the closing decades of the 19th century, the first decades of the 20th century, in response to the availability of electricity.

This industry was clearly based on the physics of electromagnetism and people who worked in this area—engineers—needed to know that in order to design these devices, especially the whole network associated with generating electric power, transmitting it a non-trivial distance, and then distributing it to, for example, households and stores and offices. The systemic character of Edison's electric business is very important. Just like with the book, there is an infrastructure of subsystems that are necessary in order to create, generate, and distribute electricity.

The technology associated with radio was developed by Guglielmo Marconi, first commercialized by him, and explicitly based on Maxwell's electromagnetic field theory and the prediction that there were such things as free electromagnetic waves that traveled through space with the speed of light. So there is another example where physics is critical to a technology that has been very powerful in changing people's lives, subsequently television of course.

The American Telephone & Telegraph business in the 1890s needed to turn to physics in order to solve problems in long distance telephony that were making it impractical for telephone lines to essentially cross the country.

We saw in the lectures on the germ theory of disease that biology, the science of biology and especially biochemistry, constituted a body of knowledge that was translated into new technologies. A beautiful example of this is the invention of the first synthetic dye by William Perkin, an 18-year-old English boy who was studying with a German chemist named A. W. Hofmann who was teaching in London at the time. He had been a student of Justus Liebig, who rejected the whole structure business that we had talked about in the lecture on the importance of structure to the properties of molecules.

Perkin studied under Hofmann, and was given the problem of looking into the chemistry of coal tar, which is what is left over when you burn coal in a way that generates a gas that is flammable, and was distributed as illuminating gas, or what we call gaslight, before there was electric light; and then there is this mess that's left over called coal tar. Perkin discovered the first synthetic dye—mauve—and triggered not just a tremendous change in the fashion industry, but triggered a kind of a Silicon Valley of chemical knowledge, generating new materials in synthetic dyes, pharmaceuticals, plastics, artificial fertilizer, explosives, propellants for artillery shells, that generated an enormous amount of power and prosperity—physical power, military power, but also economic and political power and a tremendous amount of wealth.

Initially William Perkin benefited. He and his family benefited. He, like Steve Jobs and Steve Wozniak, dropped out of college in order to build this business and was quite successful at it. But Hofmann went back to Germany, and Germany snatched this proto-Silicon Valley away from England, and Germany from the 1860s and '70s until, I would say until today, but certainly up to World War II, was the dominant factor in world affairs in the application of chemical knowledge to important commercial products.

So we see here that the idea of techno-science is now not just an idea. It is, in fact all of a sudden, scientific knowledge is being used to change the world quite literally. And I want you to leave with the impression that something fundamental about technology has changed in the 19th century, that what we mean by technology, what we mean by innovation has changed qualitatively. In the next lecture I want to describe how this new aspect of technology, this new kind of innovation was deliberately channeled into society by creating new social institutions to enable techno-science to be the driver of social change that it has been ever since.

Lecture Twenty-Eight
Institutions Empower Innovation

Scope:

The coupling of newly powerful scientific theories to invention changed the very nature of technological innovation, opening the door to world- and life-transforming technologies. To enter that door, Western societies created institutions explicitly designed to promote innovation, to "capture" it, and to channel it into society. It was this institutionalization of innovation, doubtless provoked by the power of new inventions and the prospect of unprecedented profitability, that made the social impact of technology since 1800 different from its impact in the Graeco-Roman and medieval periods. It also explains why the pace of innovation since 1800 has been so great: These institutions demand continuous innovation. The enablers of modern techno-science as an agent of change include science-based engineering education serving innovation-driven industrial corporations, the university as a generator of new knowledge, commercial institutions keyed to innovation-driven economic growth, and governmental policies linking security and prosperity to continuous innovation.

Outline

I. The institutionalization of innovation was the key to the social impact of modern technology.

- **A.** By the early 19th century, all the pieces were in place for transforming the scale and scope of technological innovation.
  1. All technologies may be artificial, but they are not all equal from a societal perspective.
  2. In the course of the 19th century, technological innovation changed its character and acquired new social power.
  3. Instead of building on or enhancing existing capabilities, techno-scientific innovations introduced capabilities that never existed before.
- **B.** How this transformation took place such that it has been sustained for 200 years is not self-evident.
  1. Invention by itself cannot explain the transformation because it is episodic, while 19th-century techno-science became a stable, almost continuous source of repetitive innovation.
  2. Entrepreneurialism cannot explain the transformation because it is too narrowly motivated to be the driver of social change that techno-science became.
- **C.** One important factor was a growing perception—which appeared just as the Industrial Revolution was getting underway—that invention and scientific knowledge could be coupled to create a true engine of economic growth.
  1. The perception appears in Adam Smith's *The Wealth of Nations* [with its chapters on how division of labor can maximize the efficiency of factory-based mass production].
  2. It appears in Alexander Hamilton's *Report on Manufactures* to the new American Congress, in which he championed industrialization over Jeffersonian gentleman farming as the basis for the new republic's future.
  3. This debate raged throughout the 19th century in the United States in different sectors of the still expanding Union, but recognition grew that institutions can be created and reformed so as to encourage technological, knowledge-based innovation that can be channeled into society.

II. The key to unleashing the power of techno-science in the 19th century was institutionalization.

- **A.** A deliberate effort was made to create new institutions—educational, business, and governmental—that would systematically couple science and engineering to create a sustained engine of growth based on technological innovation.

1. One globally influential outcome of the French Revolution was the creation of the École Polytechnique, the first modern engineering school.
2. It is modern in the sense that it was the first school in which the engineering curriculum was based on rigorous training in mathematics and physical science and in the laboratory.
3. The curriculum was, in fact, intended to train engineers in techno-science.
4. The École continues to exist, and an astonishing number of influential French figures continue to be among its graduates.
5. Henri Becquerel, for example, was a fourth-generation École alumnus.

B. The École curriculum was a major international influence, but it also precipitated bitter controversies in educational circles that lasted for decades.

1. That engineering education should be based on science, math, and laboratory work rather than machine shop and field experience was highly controversial in many circles.
2. That engineering education should be considered "higher" education at all was highly controversial, especially at elite universities that were suspicious of teaching science, let alone engineering.
3. Ironically, the British, whose inventive "tinkerers" and deep pool of mechanics gifted with creative know-how had started the Industrial Revolution, strongly resisted reforming engineering education as a college/university curriculum.
4. This reluctance came in spite of the fact that by 1850, Parliament was warned that Germany and America would overtake England as an industrial power if engineering education were not reformed.
5. Late in the century, engineering training in England still required an apprenticeship, as if engineering were a craft guild.
6. An ironic consequence of this was that J. J. Thomson, who would win a Nobel Prize in physics and whose students, Ernest Rutherford and Francis Aston, also won Nobel Prizes, went to college only because his family could not afford the engineering apprenticeship fees!

C. Engineering education in the United States also struggled mightily to establish itself as a science-math-lab–based university-level curriculum.

1. West Point Military Academy adopted the École curriculum from its inception, and that curriculum evolved into the most generally used curriculum in the United States, though it was supplemented by a good deal of machine shop and field work.
2. Until 1862, there were literally only a handful of engineering colleges in the United States, but passage of the Morrill Land Grant Act that year created very substantial financial incentives for states to establish engineering colleges.
3. After the Civil War, U.S. engineering colleges grew explosively, as did the engineering student population.
4. The number of U.S. engineers doubled every decade from 1880 to 1960, reaching some 2 million by 1980.

D. This explosive growth is a social phenomenon, not an educational one.

1. Institutions needed to be created to educate the growing numbers of students who wanted to study engineering.
2. Not only is creating such a foundation capital intensive, but given an École-style curriculum, it also requires a massive increase in the number of physicists, chemists, and mathematicians, as well engineering faculty.
3. This is perhaps the single most important cause of the existence of a U.S. community of research-oriented physicists, chemists, and mathematicians in the 20^{th} century.
4. The increasing number of engineering students was itself the effect of a transformed U.S. industry that required science-trained engineers to ride the techno-science bandwagon.

E. The positive feedback relationship between engineering and industry made people aware of the social consequences of riding this bandwagon.

1. The creation of the Georgia Institute of Technology in the 1890s became a battleground within southern society over the expanded industrialization implicit in preparing so many engineers for jobs that required techno-science training.
2. The battle was over the nature of the curriculum, and initially, approval to build Georgia Tech was contingent on a machine shop-based curriculum, a startling contrast from MIT and Cal Tech, for example.
3. By the 1890s, the character of U.S. science and engineering education had been enriched by the German research model and reflected the latest developments in physics, chemistry, and mathematics and their industrial applications.

III. Demand for such educational reforms came from new business and governmental institutions that made technological innovation fundamental to commercial success and national power.

A. Francis Lowell's creation of an integrated textile factory put U.S. industry on the path to the modern industrial corporation.

1. Lowell's idea led to a host of innovations in production machinery, in water-power generation and transportation technologies, and in business organization and workforce management.
2. The competitive advantage of the integrated enterprise was a reduction in transaction costs and time, and as the value of time increased, so did the value of integrating firms to reduce transaction costs.
3. The social impact of aggressively competitive integrated firms was profound, and sustained competitive success demanded continuous growth through repeated innovation.

B. The Swift Meat Packing Company illustrates the technology-intensive character of the integrated modern industrial corporation and the vast social "ripples" it generated.

1. Swift created a competitive juggernaut and only by copying him could his competitors survive.
2. The complexity of Swift's business model is not widely appreciated, but it should be.
3. Those competitors who emulated his model, such as Armour, joined with Swift to form a national "meat trust" that in 1905 was declared by the Supreme Court to be in violation of antitrust laws created to protect society against unfair competitive advantage.
4. But Swift's institutional model was a universal competitive machine, and entrepreneurs across all industries saw the competitive advantage of emulating that machine.
5. Standard Oil, General Electric, U.S. Steel, Westinghouse, Ford, DuPont, and General Motors, among many others, were all organized along these lines.

C. New government institutions that were keyed to techno-science also needed to be created.

1. Except for a contentious alliance during World War I, the U.S. government kept direct-support scientific research to a minimum and provided barely indirect support for technological innovation.
2. World War II changed all that with the creation and extraordinary success of the Office of Scientific Research and Development, headed by Vannevar Bush.
3. At the end of the war, Bush presented President Truman with a report, *Science: The Endless Frontier*, that, together with the Cold War, created a mandate for large-scale federal support of scientific and technological research and development.
4. It launched a raft of government institutional reforms that have woven science and technology more deeply into the fabric of modern life.

Essential Reading:

Thomas P. Hughes, *Networks of Power*.

G. Pascal Zachary, *Endless Frontier*.

Questions to Consider:

1. Since the rise of modern techno-science, science and science-based engineering certainly have *changed* the conditions of human life, but is life *better* for those changes? For whom and at what cost?
2. Where does responsibility for the social and physical impacts of innovations lie: in knowledge, in technologies, in society?

Lecture Twenty-Eight

Institutions Empower Innovation

What we're trying to shed light on here is the emergence of techno-science, especially in the second half of the 19th century, and increasingly in the 20th century, as a force in society. In particular a force that has changed our lives by selectively channeling scientific knowledge into society through technological innovations.

The American polymath, Herbert Simon, who was sometimes described as an economist in part because he won the Nobel Memorial Award in Economics, but was more an organizational theorist and contributed significantly to the mathematical theory of decision making and also to artificial intelligence research. Herbert Simon, in one of his books called *The Science of the Artificial*, makes the comment that "a plowed field is as artificial as a highway." That's correct, and it's a very powerful and interesting insight, especially in the context of sometimes extreme environmental criticism of technology. A plowed field is as unnatural as a highway is, as a computer is, for that matter; but nevertheless I have tried in the previous lecture to suggest that something qualitative happened to technology in the 19th century, that technology became qualitatively different. It became decisively more artificial.

Innovations were not now improving what existed already, not now enhancing natural power, such as water power and wind power, but were introducing things that never existed and never could exist except through the insights that knowledge gave us into ways that nature could be manipulated. I think that there is a profound qualitative difference between the Chappe mechanical or optical telegraph and Marconi's radio waves. It is true that both of them are artificial, but I think that that can blur a very important distinction.

What I want to do in this lecture is focus on how it came to be that techno-science has become such a powerful force in driving social change.

Invention is episodic. You cannot, so to speak, rely on invention if you are responding to invention as a source of power and prosperity. Invention is episodic and individual entrepreneurship is much too opportunistic and self-centered to be an engine of social change, of growth in wealth and in physical, political, and military power that we associate with techno-science.

What happened in the 19th century was not just that there were lots of inventions at the last half of the 18th century and throughout the 19th century, not just that knowledge had reached a point where we could use that knowledge to control nature in ways that had not been imagined in the preceding centuries. What happened was that suddenly there was a perception that invention and knowledge could be coupled in ways that would provide a true engine of growth—economic growth, for example; let's just focus on that.

This perception is perhaps more important than the individual inventions that provoked it. I'm thinking, for example, of Adam Smith's *The Wealth of Nations*, published in 1776, which in effect makes the argument seem almost obvious that economic prosperity is keyed to the most efficient implementation of the new technologies of production that are being introduced initially in England and then spread throughout the world.

There was for decades in this country an ongoing debate, which began between Thomas Jefferson and Alexander Hamilton, on whether America should be industrialized or whether it should be a fundamentally agricultural society. Jefferson distrusted urbanization and industry, whereas Hamilton championed what were called manufactures, and that the government needed to implement policies in order to encourage the growth of manufacturing industry here in the United States.

For obvious reasons, the British wanted to maintain a monopoly on these new technologies, and to use the United States even after independence as a source of raw material. Import cotton, for example, from the United States, and then do all of the work on the cotton that added value to it in England, and then sell it as high-priced finished goods back to the United States and to everybody else that they could get to buy British cotton goods; and the same thing with woolen goods.

What Hamilton argued was that the United States government needed to introduce policies—obviously tariff is one of the first things you think of in this connection—that encouraged people to develop industry here in the United States. Now, this debate lasted much longer than Jefferson and Hamilton's personal lives lasted, and in fact the southern part of the United States through the Civil War era, right through the 19th century, resisted the idea that its economy ought to be based on industry rather than on agriculture, and especially being keyed to cotton and tobacco. In fact it was, according to many historians, the disproportionate industrialization of the North versus the South that made the outcome of the Civil War almost inevitable, extraordinarily tragic and painful, but almost inevitable.

The idea that your economy should be based on technology and industry is not an obvious one, and it's not a no-brainer. You do have to make a deliberate decision to do that. What made techno-science powerful was the recognition that we already see reflected in Adam Smith's book *Wealth of Nations*, that we see reflected in Alexander Hamilton's *Report on Manufactures* to the U.S. Congress early in the life of the republic, and throughout the 19th century, ongoing recognition that something new was happening in society. That in order to be able to get the maximum benefit out of it, we have to create institutions that would encourage technological innovation, that would encourage knowledge-based innovation, and channel that into society.

We needed to reform educational institutions; we needed to reform business institutions; we needed to reform government institutions; and in particular the relationship between government and business and educational institutions—which sounds like low on the totem pole, but it turns out that reforming educational institutions to make them congenial homes, so to speak, to techno-science is a critical factor in making techno-science the kind of force that it became in the 19th century and continues to be today.

The French Revolution, among its many destructive activities, one of a number of constructive things that they did was the creation of the École Polytechnique, which is the first modern engineering school—that is to say, it is the first engineering school that continues to exist—and very, very prominent in French civil affairs. An extraordinary number of politically influential individuals have been graduates of the École Polytechnique. I mentioned Henri Becquerel in the last lecture. He graduated the École as his father did before him, and as his grandfather did before his father.

The École Polytechnique was created in the 1790s to be the first engineering school in which the curriculum was based on mathematics and physics, and secondarily chemistry, but especially mathematics and physics, and the laboratory and experimentation. As opposed to what? As opposed to basing engineering education on machine shop, apprenticeship, and field experience—"seat of the pants," learning how to be a civil engineer by working on canals and building bridges and seeing how the masters worked and acquiring that knowledge.

This became a contentious debate throughout the 19th century in educational circles: whether engineering education should be based on the machine shop, apprenticeship, and field experience, or whether it should be based on book learning; whether it should be based on mathematics and physics and chemistry and laboratory work and experimentation, but virtually no practical experience. Those are not necessary exclusive of one another, but in fact that's the way it turned out.

Now, interestingly, the British, who started the Industrial Revolution, and who dominated the Industrial Revolution throughout the 19th century—beginning to lose way to Germany in the last third of the 19th century (and decisively so), and then to America—didn't buy into this educational reform, largely for social status reasons did not accept the idea that engineering could be professionalized, that it was worthy, so to speak, of being considered a university education. Technical schools, yes, but not really incorporated into the university curriculum. In fact there was great resistance in England and the United States among our most elite institutions, like Harvard and Yale, even to having degrees in science, degrees in physics, for example. For decades Harvard and Yale resisted bequests to create schools or colleges of science within the university, because it was felt that that was not consistent with what we understood a university education to be.

But Germany especially, and the United States eventually, bought into this model. In England, for example, I mentioned one of the students of J. J. Thomson, the man who discovered the electron, was Ernest Rutherford. Another one of his students was Francis Aston, who won the Nobel Prize for inventing the mass spectrometer, working under J. J. Thomson; which was a very important scientific instrument for separating elements of different molecular weight, and being able to study their properties.

Thomson was supposed to have been an engineer. But in England at the turn of the 20th century, you had to be an apprentice to become an engineer, and his parents couldn't afford the fees for him to be an apprentice to an engineer, and he got a scholarship to go to college. So he went to college and studied chemistry and physics, and eventually made physics his career, and that became the basis for his Nobel Prize.

This idea of educational reform is very important, and let me show you why it's important. In the United States before the Civil War, there was almost no engineering education to speak of. There were only a half a dozen institutions at any given time that gave degrees in engineering. Significantly, however, beginning with West Point at the very end of the 18th and beginning of the 19th century, West Point from the beginning adopted the École Polytechnique model, that military engineering would be based on mathematics and science and the laboratory. There would be fieldwork as well, but the core curriculum was mathematics, physics, and laboratory, that knowledge was the basis of engineering, and most American engineering institutions adopted this particular model.

In 1862, in the middle of the war, the United States Congress passed the Morrill Land-Grant Act, an act which had come before Congress several times in the 1850s and had been defeated largely by Southern congressmen. Now that the Southern congressmen were not there, Congress passed the Morrill Land-Grant Act, which among other things gave states who created engineering colleges very substantial financial incentives. Especially they gave them very large tracts of federally-owned land as a gift if they would create so-called "land-grant colleges." At that time there were only six institutions in the United States that gave degrees in engineering. By the end of the century there were over a hundred.

What we have to think of is that this is an extraordinary phenomena. The number of engineers in the United States in 1860 is sometimes estimated to be somewhere between 1,000 and 3,000 people who made their livings as engineers in the United States. I incline more to the lower figure, but it doesn't matter. By the end of the century, you have tens of thousands of students enrolled in engineering colleges in the United States. This is a social phenomenon. We have to ask, what's happening here? And the pressure to build more engineering colleges, which continued into the 20th century so that the number eventually doubled in the early 20th century, this is now a social phenomena. What is happening here? Why are so many people going to study engineering?

Well, two things have to happen. First of all, the institutions have to be created to allow them to study engineering. The means have to be available in order to study engineering. So if you are going to have all of those tens of thousands of students studying math and science and chemistry, and have the laboratories, you need thousands of mathematicians, physicists, and chemists in order to give those courses to those engineers. But if you do that, then you are de facto creating a community of people who make a living doing mathematics, doing physics, doing chemistry, and they have their own agendas. In others words, as physicists, they want to do physics. They have to teach engineering students, but they also have to teach the next generation of people who will teach physics to the engineering students. Inadvertently, so to speak, the community of research scientists in the United States grew in parallel with (at a slower rate) the enormous increase in the number of engineers in the United States.

The number of engineers in the United States doubled every decade from 1860 to 1960, after which the rate of increase slowed down. But by the end of the 1980s there were millions of engineers in America, and it was the single largest profession for males in the United States. That is a significant social phenomenon, and we see immediately what the answer is. The reason why there was this tremendous increase in engineering enrollment is because industry needed those people. They needed engineers who had the mathematical and the scientific and the laboratory experience in order to build the factories, to operate the factories, to produce the machinery and the innovations that would channel inventions into society, that would support the electrical appliance industry, the generation and distribution of electricity, that would support radio and the aircraft industry, and the automobile industry, etc.

It is the industrial reform, the transformation of industry, especially in the second half of the 19th century, that pulled educational reform. So it's not one thing leading to the other. There is a complex reciprocal relationship between the two. Educational institution reform and reform of business and industry institutions went hand in hand. The new kinds of technologies, especially mass-production technologies that were introduced through such people as James Hargreaves and Richard Arkwright, those technologies of mass production led to new kinds of business models in the 19th century. Those new kinds of business models increased the scale of industry tremendously, but made industry's new scale critically dependent on new technologies, especially for example of steam power and electricity. Those new technologies required different kinds of skills and knowledge than water and wind power technologies required.

So there is a positive feedback relationship between educational institution reform and business reform. I had referred earlier to the resistance of the American South to industrialization as the key to their economy because, after all, as the economy goes, so goes the society. You can't change the economic basis of a society without changing the social relationships as well. If you shift from an agricultural society based on tobacco and cotton, primarily, to an industrial society, you change the nature of society. The people who are big in one era may not be big in the other era. They may not be prominent. They may not be successful in the industrial era, especially if they had inherited the plantations that they operated.

Now, an example of this Southern resistance is the creation of the Georgia Institute of Technology at the end of the 19th century, where there were advocates for creating it based on the École Polytechnique model as it had evolved throughout the 19th century (so, based on math, physics, etc.) and then others were saying, no. If you do this you're going to sneak in a kind of a Trojan horse into Southern culture, of individuals who are going to be reinforcing industry in the South, and we prefer the machine shop, apprenticeship, and fieldwork model.

This actually was a social and political battle that was fought over the creation of the Georgia Institute of Technology, which initially was based on a modified version of the machine shop model, and then eventually flipped over to the scientific basis for engineering education in the early 20th century. Schools like MIT—the Massachusetts Institute of Technology—and the California Institute of Technology—which was the new name for the Throop College of Technology earlier in the 20th century—were from the beginning based on intense science training for engineers, and along the way developing scientific research departments of physics, chemistry, and mathematics, in which research was the order of the day.

This idea that the goal of the university is to generate new knowledge is a 19th century idea. The medieval university transmitted ancient knowledge. But in the 19th century, especially at the end of the 19th century, beginning I believe with École Polytechnique, then developed very strongly by the German institutions—especially after unification in 1865, and the creation of government-funded research institutions—and then at the end of the 19th century in America, the expectation that faculty at a university will create new knowledge, and that that's what, so to speak, their jobs are dependent on. The whole concept of publish or perish goes back in some simplistic sense to the 1890s with the creation of the University of Chicago, where the expectation was that faculty will do research, publish new knowledge, and that will be the basis of their professional evaluation.

Now the new business models that pulled educational reform in this area, creating whole new communities of scientists, mathematicians, and engineers, began to manifest themselves very early in the 19th century. Francis Lowell, somewhere in the period 1810–1815, got the idea of building an integrated factory in which raw material would come in one end, for example, raw cotton would come in one end and finished calico cloth would go out the other end. All of the operations necessary for transforming the raw material into finished goods would take place within the factory. He saw this as having tremendous advantages over the existing system, the so-called "putting-out system" in which the raw cotton went to one group of workers who cleaned it, and another group of workers somewhere else it was moved to who did the carding, and another group of workers who did the spinning, and another group of workers who did the weaving, and others who did the dyeing, etc. All of that would be done within the factory and there would be tremendous efficiencies, Lowell thought.

Now, he died before the full realization of his vision—and he did not have any technical knowledge, but he was gifted in the know-how area—led to the transformation of the Merrimack River Valley in the United States into a major center of textile production and technological innovation; which became increasingly scientific as the factories needed to compete, and they had to push their costs down.

Now the genius of the integrated factory is not immediately obvious. Common sense suggests oh, of course. What a wonderful idea. Why didn't anyone think of this before? As a matter of fact, the British, using the old-fashioned putting-out system, which seems hopelessly inefficient and time-consuming, were able to sell calico cloth in the United States with transformation for less than the Lowell mill cost with the integrated factory. So the United States government yielded to political pressure, lobbying, and put a tariff on the British cloth in order to give the American industry a chance to develop.

The real genius of the integrated factory, as was pointed out by the Anglo-American economist Ronald Coase—and he got the Nobel Prize in part for this—an economic law theorist and economist, Coase pointed out that the genius of the integrated firm is that it reduces transaction costs. All of the costs associated with each different task that needs to be performed is a transaction. When time is valuable then the transaction costs become critical. If time is valuable then reducing transaction costs consistent with reducing time becomes a justification for the integrated firm.

The integrated firm has a whole different character. It changed the economy dramatically. Instead of having lots of workers working primarily in their home doing specific kinds of tasks on a piecework basis, overwhelmingly the economy shifted to people being employees in factories of larger and larger size, because as these larger businesses competed with one another, costs needed to be driven down in order to retain profitability. And again, in order to do that, new inventions were necessary. Technological innovation became increasingly incorporated into the fabric of the economy. We became increasingly dependent on innovation in order for businesses to be able to succeed, in order to create new businesses with the profits from the old businesses; and this represents a kind of an economic addiction. No growth, a society collapses. The source of growth is embedded in this process of technological innovation, increasingly keyed to scientific knowledge: the ability to use scientific knowledge and inventions to create innovations, to create new kinds of products and services.

The next stage of development of the Lowell vision of an integrated factory was the Swift Meat Packing Company, which pioneered the modern industrial corporation as a whole new kind of business that was vertically integrated, centrally administered, and hierarchically organized; something that was only possible because the telegraph and the telephone were available. Managers who were in a central headquarters could control what was going on in the various divisions, which had presidents, and underneath the divisions there were subdivisions, all the way down to the factory floor where there was a foreman.

You had this military-style managerial hierarchy, and these factories (the meat packing company) became vertically integrated. In order to protect himself against competitors, Swift got this initial idea, which was relatively simple. You have all of these herds of beef out in the West, and they're collected in a couple of cities, like Sioux City and Chicago; but most of the population lives on the East Coast, so if you ship these animals to the East Coast to be slaughtered by local butcher shops, that is a major expense. Wouldn't it be nice if we could slaughter the animals right there where the animals are collected? For example, Chicago, major rail terminus; we slaughter them there, and then we ship the finished beef to the butchers. We will be able to benefit because we're shipping a finished good, not a raw material.

Well, how can you do that? The meat will spoil. Well, we can refrigerate it. The whole concept of a refrigerated railroad car made sense after the Civil War because now, for one thing, we have a national transcontinental railroad, which was completed in 1869; and Swift got the idea of getting a boxcar that was refrigerated that would keep the meat fresh until it reached the butcher shops of the East Coast.

This turned out to be more complicated than he thought, but eventually he did subsidize the construction of a small group, I think his initial order was for six railcars that were mechanically refrigerated. They started off with ice—that turned out to be a real problem—but then fortunately for him mechanical refrigeration was invented, and the boxcars became mechanically refrigerated, and he started slaughtering animals in Chicago and shipping the dressed meat to the East Coast. But once you've invested so much in railcars, you've got to have a scale of business to get that investment back. You can't just slaughter 10 cows or 100 cows a day. You have to slaughter large numbers of cows. Your competitors, in order to compete against you, may try to interfere with your supply of cows; so he bought up whole herds of cows and slaughtered them. So now he's got to sell huge quantities of beef in order to keep the thing together. (He also dealt with lambs and pigs—I don't want to single out cows.)

When he gets to the East Coast, the butchers don't want to buy his dressed beef. They make their money from slaughtering animals and selling the dressed beef at a much higher profit than they can get if they sell his already dressed beef. So he winds up having to open up his own chain of butcher stores. To open up his own chain of butcher stores he has to start using the new mass circulation newspapers to advertise, to let people know that his meat is there. And he's got to be able to prove that it's fresh, because his competitors are saying this meat is spoiled. It's traveled all the way from Chicago, or even worse from Sioux City, Iowa.

When you have whole herds being slaughtered, you have huge quantities of hides and hooves and horns and internal organs that you can't otherwise use, so you get into the dog food business, you get into the leather business, you get into the glue business. And so Swift actually pioneered—I mean, it sounds odd, "meat packing." It was, conceptually, the highest technology business of the late 19th century, and it was immediately perceived by the great entrepreneurs of the period to be the definitive model for creating a brutally competitive machine.

The model of the business was itself the machine. So we see the formation of companies like United States Steel and Dupont (Dupont was older but reorganized in the early 20th century), and Westinghouse and General Electric and Ford and General Motors. Ford, after all, in the 1920s built the River Rouge Plant, which was an extreme example of raw materials coming in the front door—raw materials like iron ore and raw rubber and materials for glass—and out comes completed Ford automobiles. It was probably the only truly fully integrated automobile plant that was ever made. They made the glass inside; they made the tires inside; and they smelted the ore inside.

This model became crucial to American business, and it meant a tremendous consolidation and increase in the size of the business. You can see how this pulls educational institution reform in order to create the millions of engineers that industry needs in order to keep this flow going.

The government gets involved increasingly in World War I and then in World War II especially, because all of a sudden it becomes inescapable, in spite of the resistance of the military, that science and technology are critical to military power. Science played a major role in World War I, but an incomparably greater role in World War II. Vannevar Bush, who had been the head of the Office of Scientific Research and Development throughout World War II, masterminding and organizing various projects that led to radar and the atomic bomb and cheap penicillin, wrote a report in 1945, and delivered it to President Truman. That became the pattern for American governmental feedback into educational system reform and industrial reform by federal subsidy of research and development to the tune of tens of billions of dollars eventually.

So these are the kinds of institutional reforms that made it possible for techno-science to become the driver of social change that it became.

Lecture Twenty-Nine
The Quantum Revolution

Scope:

Quantum physics is without question the most esoteric of all scientific theories, and the most inaccessible without advanced training in that theory. It is the most revolutionary of 20th-century theories, replacing wholesale the inherited conceptual framework of modern physics. At the same time, quantum mechanics is arguably the most important physical scientific theory of the 20th century and the most explanatorily powerful, experimentally confirmed, and predictively successful physical theory ever. In spite of this, and in spite of the wealth of its practical applications, the interpretation of the theory has been controversial since the mid-1920s, and it is inconsistent with the general theory of relativity. Quantum mechanics imputes randomness, probability, and uncertainty to elementary physical processes and to the elementary structure of physical reality. It redefines causality, space, time, matter, energy, the nature of scientific law and explanation, and the relationship between mind and world. It is exhilarating!

Outline

I. The quantum idea seems to be the most bizarre idea in modern science, but it became the cornerstone of a powerful theory of matter and energy.

- **A.** Initially, the quantum idea was that electromagnetic energy only comes "packaged" in discrete sizes.
  - **1.** In 1900, Maxwell's theory of electromagnetic energy and the electromagnetic field was at the heart of theoretical physics.
  - **2.** Some argued that electromagnetic energy was the ultimate stuff of physical reality and that matter was reducible to it.
  - **3.** The concern of physicists with a correct theory of the aether was motivated by the need to anchor the physical reality of the electromagnetic field.
  - **4.** A fundamental feature of Maxwell's theory is that electromagnetic energy is continuous.
- **B.** The story of quantum *mechanics* begins with Niels Bohr, but the quantum *idea* preceded Bohr.
  - **1.** Max Planck invented the quantum idea in late 1900 as a way of solving a gnawing problem in the physics of the day.
  - **2.** This problem required for its solution a description of how the electromagnetic energy of an ideal *black body*—one that absorbed all the radiation that fell on it—was distributed as a function of frequency.
  - **3.** This seemed a simple problem, but it resisted a comprehensive solution until December of 1900, when Planck solved it. He was displeased with the assumption his solution required, however: that radiation is emitted/absorbed in quantized units.
  - **4.** The electromagnetic field is continuous and electromagnetic waves are continuous; thus, electromagnetic energy should be continuous, but somehow the process of emission/absorption *seems* discontinuous.
- **C.** While Planck was trying to kill the quantum idea, Einstein made it real.
  - **1.** In 1905, Einstein showed that the quantum idea, if treated as real, could explain the puzzling photoelectric effect.
  - **2.** Einstein was awarded the Nobel Prize for his paper on this, but note that it overturns the wave theory of light and replaces it with an "atomic" theory of light.
  - **3.** These quanta of light, paradoxically, also have a frequency and, thus, must in some sense be wavelike, and their energy follows Planck's formula of 1900.

4. Einstein treated the quantum idea as a new fact about physical reality and, from 1906 to 1908, used it to solve other problems in physics and chemistry (though as he focused on the general theory, he abandoned atomic units of reality!).

D. In 1910, Ernest Rutherford proposed a Solar System model for the atom, but it was seriously flawed: electrons should immediately spiral into a positively charged nucleus, according to Maxwell's theory, yet atoms were stable!

E. Niels Bohr worked in Rutherford's laboratory in 1911 and rescued Rutherford's model by proposing new principles of nature at the subatomic level, as if Maxwell's theory were not allowed in there.

1. Orbital electrons do not radiate energy while orbiting; they radiate energy whenever they change orbits.
2. For each chemical element, the electrons in its atoms are strictly limited to a discrete set of "permitted" orbital radii only, each associated with a specific quantized energy level.
3. The energy radiated/absorbed when electrons change orbits is equal to the difference between the energy level of the orbit from which the electron starts and that of the orbit at which it arrives.

F. These are, on the face of it, bizarre assumptions and they violate Maxwell's theory, but there was a powerful payoff.

1. Since the mid-19th century, a mountain of data had accumulated by spectroscopists documenting distinctive frequencies of light emitted by each element without explaining this phenomenon.
2. Bohr predicted that these frequencies corresponded precisely to "permitted" orbital transitions for an atom of each element and showed that this was indeed the case for hydrogen.
3. Further, Bohr predicted that the periodic table of the elements, another unexplained "fact" about matter, was a consequence of the way atoms were built up as electrons and protons were added to the "basic" hydrogen atom.

II. Building quantum mechanics on the quantum idea took place in three distinct stages and has had profound social consequences through its applications.

A. The first stage extended from Bohr's adoption of the quantum idea in 1912 to 1925.

1. Bohr's quantum rules for orbital electrons attracted a cadre of physicists who, over the next 10 years, dramatically extended the quantum theory of the internal structure of the atom and fulfilled Bohr's vision of explaining the periodic table.
2. Ironically, the theory stimulated new and much more precise spectroscopic experimentation that, by the early 1920s, had Bohr's initial quantum theory of the atoms on the ropes!
3. The new spectroscopic data could not be explained by Bohr's original version of quantum theory.
4. This precipitated a genuine crisis, with some suggesting that the quantum idea should be abandoned entirely.
5. Concurrently, Louis de Broglie argued for extending the quantum idea from radiation to matter, in particular, the coexistence of wave and particle features Einstein had proposed for quanta of radiation.

B. The second stage extended from the resolution of the crisis in 1925 to the early 1960s.

1. Werner Heisenberg and Erwin Schrödinger independently resolved the crisis in 1925 by creating quantum mechanics, though their respective formulations were profoundly different from each other.

2. Between 1926 and 1929, Heisenberg saw that his quantum mechanics implied an *uncertainty principle*, and he and Bohr developed a statistical interpretation of quantum mechanics and a radically new interpretation of physical theory based on it.
3. In 1929, Paul Dirac published a new theory of the electron that evolved into a quantum-level analogue of Maxwell's theory, called *quantum electrodynamics* (QED).
4. Quantum physics also provided a theoretical framework for designing increasingly powerful particle accelerators from the early 1930s to the present.

C. The third stage extended from the early 1960s to the present as QED evolved into *quantum chromodynamics* (QCD).

1. By the early 1960s, particle accelerators had created some 200 "elementary" subatomic particles, which was clearly impossible!
2. In 1964, Murray Gell-Mann and George Zweig independently proposed a new theory of matter, later called QCD, which is a theory of the so-called strong force holding the nucleus together.
3. In QCD, the elementary building blocks of all nuclear particles are quarks, which are held together by massless particles called gluons, while electrons are members of a family of elementary particles called leptons.
4. As QCD developed, the number of quarks needed to build up all known particles reached six, with a matching number of leptons and three types of gluons.

III. Also in the early 1960s, physicists began the pursuit, still unachieved, of a unified theory of the four known forces in nature.

A. The four forces are: electromagnetic, weak (affecting leptons), strong (affecting quark-based particles), and gravity.

1. The first step toward unification of these forces was to unify the electromagnetic and weak forces.
2. Based on a suggestion by Sheldon Glashow for how this could be accomplished, Abdus Salam, Steven Weinberg, and Glashow succeeded in developing an electro-weak theory.
3. The theory predicted the existence of a hitherto unsuspected family of particles, and experiment soon confirmed their existence with the properties predicted by the theory.

B. The next step was unifying electro-weak theory and QCD, the theory of the strong force.

1. Actually, unification of these two theories overlapped and was accomplished by the late 1980s.
2. This so-called *standard model*, although not without some problems, has achieved impressive experimental confirmation.
3. It also works at levels ranging from the subatomic to the cosmological.
4. The final step, uniting the standard model with the gravitational force into a *theory of everything*, has so far proven elusive.

Essential Reading:

George Gamow, *Thirty Years That Shook Physics*.

Steven Weinberg, *Dreams of a Final Theory*.

Questions to Consider:

1. How could a theory as tested as quantum theory, and with so many complex technologies based on it, possibly be wrong?
2. What is energy "made of" that the Universe can be described as arising out of negative quantum vacuum energy?

Lecture Twenty-Nine
The Quantum Revolution

The subject of this lecture is the quantum idea, which evolved into quantum theory. And with quantum theory, we crossed the imaginary divide called centuries into the 20th century. One of the things that makes it imaginary, of course, is that events simply do not organize themselves in ways that respect the division into centuries that we like so much.

For example, while the quantum theory and relativity theory are clearly 20th century theories, it was in the same decade, the first decade of the 20th century, that the quantum and relativity theories were first formulated, that the theory of evolution and the intrusion of stochastic processes into nature were extremely lively subjects of debate. So while evolution could be seen as a mid-19th century theory, it was only in the first decade of the 20th century that there were vigorous debates, I would say bitter controversies, about whether Darwinian evolution was consistent with Mendelian genetics, etc., as we discussed in an earlier lecture.

But we're going to focus now on the idea of the quantum, which is simple to state, but had a very confusing birth that we're going to clarify right now. The idea of the quantum is that natural processes are quantized. They are packaged, so to speak, in discrete units.

Initially, the quantum idea was only applied to electromagnetic energy. That electromagnetic energy is quantized is to say that instead of being continuously distributed in a continuous field, which is what is explicit in Maxwell's electromagnetic theory, that electromagnetic energy is distributed in space continuously. And that is why we have ether physics, in order to try to explain how the electromagnetic field could have a substantial underpinning, how it could be carried, so to speak, through space, because the physicists of the day rejected action at a distance, or were wary, at least, of action at a distance as a kind of a mystical concept.

So in Maxwell's theory, electromagnetic energy is continuously distributed; whereas in quantum theory, the initial idea of the quantum is that electromagnetic energy only comes in discrete units, which are multiples of a fundamental unit. It would be like saying that you can buy one ounce of sugar, or two ounces of sugar, or three ounces of sugar, but you cannot buy an ounce and a half or an ounce and a quarter. In Maxwell's theory, you can buy as much electromagnetic energy as you like. A field is continuous. That means it's infinitely divisible; you can get down to smaller and smaller—there is no limit to the smallness with which the field can be divided. But the quantum idea is that there is a limit, and that all manifestations of electromagnetic energy are packages that are whole multiples of a discrete unit.

Now the credit for the original quantum idea unquestionably belongs to Max Planck, who at the end of 1900 announced his solution to a problem that had been vexing physicists for much of the previous decade. It was a relatively straightforward problem in the sense that everyone initially thought that Maxwell's theory could easily explain this problem. The problem was to describe the behavior of an idealized entity called a black body.

A black body is any body that absorbs all of the electromagnetic radiation that falls on it. So, for example, no matter what frequency the radiation is, whether it's below visibility, whether it's X-rays, whether it's gamma rays (anachronistic to speak of that in 1900), but whether it's visible light, or infrared, or ultraviolet, whatever the frequency, a black body absorbs it all. Now, actually, a thick black coated object comes pretty close to being a black body, but it's an idealization, the way physicists deal with frictionless planes and weightless strings and so on.

The idea is that Maxwell's theory should tell us how a body that absorbs all of the electromagnetic energy that falls upon it would then, as it warms up from absorbing all of this electromagnetic energy, eventually reach a temperature where it starts radiating electromagnetic energy. So, for example, you heat it up. It starts to glow. So maybe it starts getting hotter and hotter, and it gets red hot; it gets white hot; it gets blue hot. What is the distribution of the energy that is radiating among all the frequencies of electromagnetic energy? It absorbs energy of all frequencies. Does it radiate energy of all frequencies, and what's the distribution? Does it favor low frequency or high frequency?

This is called the black body radiation problem, and it resisted solution until 1900 when Planck came up with an equation that correctly described the distribution of energy radiated by such a black body. But in the course of arriving at his solution, Planck had to interpret the equation as implying that within the black body, electromagnetic energy was absorbed and radiated in discrete units that he called quanta. So he introduced the concept of quanta of energy, which at that time is electromagnetic energy in the processes of absorption and emission only.

Planck believed that in space, electromagnetic energy was continuously distributed; that it was not quantized. So electromagnetic energy was really not quantized. Light was not quantized. It's a form of electromagnetic energy, of course. But when it is absorbed and emitted, somehow the process of absorption and of radiation emission causes somehow and in some mysterious way—and he didn't like that hypothesis at all, and over the next 10 or 11 years he tried to arrive at that same equation without the assumption of the quantization of the absorption and emission of electromagnetic energy.

So Planck is the father of the quantum idea, but then he, so to speak, steps to the side of the evolution of the quantum idea into quantum theory, quantum physics, quantum mechanics, because he himself in the first decade or so was not convinced, did not believe, that electromagnetic energy really was quantized. So now in 1905, one of the seminal papers that Einstein published in 1905 was on the so-called photoelectric effect. The behavior of certain metals when exposed to light is to release electrons. And puzzlingly, while the number of electrons that are released is a function of how intense the light source is (so if you have a 50-watt bulb and you switch it to a 100-watt bulb, you'll get more electrons coming off), no matter how powerful you make the same light (if you make it from 50 watts to 100 watts to 200 watts), the energy of the electrons that come off is the same. The number increases, but the energy is the same. And it should not be that way.

If light is really a wave the way the wave theory of light in the 19th century said it was—it's an electromagnetic wave—then if you have a strong wave hitting something on the shore, it transfers a lot more energy than a small wave does. So how come when you ratchet up the power of the light bulb from 50 to 200 watts, the energy that it transfers is the same, just the number is different? However, if you change the frequency of the light, and you have higher frequency light, then while the numbers won't change—you have a 50-watt bulb, but now you've changed it so that the light that comes out is a higher frequency, let's say it's violet light instead of green light—then the number of electrons stays the same, but the energy of the electrons that come off is much greater.

Einstein explained the photoelectric effect. He gave a solution to this problem by supposing that electromagnetic energy really is quantized; that light, for example, as an instance of electromagnetic energy, travels through space as if it were a kind of an atom. If you then use Planck's equation—which Einstein derived knowing that Planck already had the equation, but he showed that it could be derived independently of some of the assumptions that Planck made that troubled Einstein—then you can explain the photoelectric effect, and then you have assumed that light really is quantized, not just in the processes of emission and absorption, but, contrary to Maxwell's theory, light is quantized. All electromagnetic energy is quantized. This postulate of Einstein's then can be used, and you can explain other phenomena.

Einstein then, in 1906 to 1908, applied this quantum hypothesis to a wider range of problems in physics and in physical chemistry beyond just the quantization of electromagnetic energy; and that really launched quantum theory, Einstein's work in this area. Although it was a modest theory that attracted modest attention until approximately 1912, when Niels Bohr, a brand new Danish Ph.D. in physics, won an award from the Carlsberg Beer Company to go to England to study in the laboratory of J. J. Thomson, who was a very famous physicist at the time: the man who discovered the electron, the director of the Cavendish Laboratory at Cambridge University.

Bohr came to England, found that his personality did not click with Thomson's personality, and found it much more congenial to spend his time in Ernest Rutherford's laboratory at the University of Manchester. He was there when Rutherford had just recently announced the solar system model of the atom. But the problem with the solar system model of the atom, which looked like a fatal problem, was that if it is the case that electrons orbit around a central nucleus, then according to Maxwell's electromagnetic theory, the atom should collapse almost instantaneously, because the electrons should spiral into the nucleus.

Maxwell's electromagnetic theory claims that an electrically charged particle moving in an electric field interacts with the field in such a way that it should spiral into the source of that field. That doesn't happen if the solar system model is correct. How can it be? Niels Bohr came up with this idea, which he published in 1913, and one can perhaps see this as the founding paper of the beginning of the maturation of quantum theory.

Bohr proposed the following: Let us suppose, contrary to Maxwell's theory, and we don't understand why or how, let us suppose that it is a fact of nature that electrons orbiting a nucleus do not radiate electromagnetic energy. They only radiate energy when they change orbits, and the amount of energy that they radiate is a function of the difference of the energy levels of orbiting far away and orbiting closer, or the other way around. When they change orbits, that is when they radiate energy, and the amount that they radiate is equal to the difference in the energy level between the two orbits. Furthermore, and here is where the quantum idea comes in, furthermore, electrons around a particular nucleus are not allowed to orbit at any old place they want to. They can only be in certain specific orbits.

What Bohr was proposing was to quantize the mechanical energy of the orbital electron. An electron orbiting at some particular radius around a nucleus has a certain mechanical energy, which is measured by its velocity, and that is determined by the strength of the electromagnetic field and its distance from the nucleus. What Bohr is claiming is that there are only certain rails, so to speak, the rails that electrons can orbit on are only located at specific places concentric with the nucleus of the atom, and as long as they are on those rails, electrons do not radiate. It is only when they jump from one rail to the next that they radiate energy, and it is the difference between the energy levels of those two orbits or those two concentric rails, metaphorically speaking.

Now these are completely ad hoc hypotheses. There is no question about that. These are completely ad hoc hypotheses, and you say, well, why would anybody pay attention to Bohr? The answer: there is a big payoff. The big payoff is that for about 50 years physicists had accumulated a tremendous amount of spectroscopic data (forbidding term), which is that they had discovered in the middle of the 19th century that all glowing specimens of matter, of elements, when they are made hot, they all radiate electromagnetic energy. They radiate light of specific frequencies.

Every element has its own light print, analogous to fingerprints. If it's sodium, if it's mercury, if it's carbon, it has its own set of frequencies that it radiates. And nobody understood why it radiated those frequencies. Bohr instantly provides an explanation by saying that when we excite atoms by adding heat to a specimen—of carbon, let's say, or sodium—then what is happening is that we are pumping thermal energy into the atoms. The electrons are absorbing photons, and they are jumping up and they are changing their energy levels, and they are radiating electromagnetic energy that is exactly the difference between the two orbits. From the spectroscopic data we can then calculate what the orbits have to be for that exact amount of energy corresponding to the different frequencies radiated. Each one of those frequencies represents an energy level in the atom, and now we can calculate what the permitted orbits are.

So Bohr coupled quantum theory to this body of spectroscopic data, which was enormous and very precise, but completely unexplained. It was the promise of explaining that data that made people look at his theory. But once they did that and they took it seriously, they can now actually start calculating what the permitted orbits are for different atoms; which led to the idea that maybe now we can make sense out of the periodic table, and explain how the elements are built up as the nucleus becomes more and more complex as you add protons, and we would now say neutrons, to the nuclei of hydrogen atoms.

So we are transforming the hydrogen into helium, into lithium, into carbon, into oxygen, etc. By adding protons to the nucleus we are also changing the configuration of electrons, and that means changing the sets of orbits that electrons can occupy. Maybe this new quantum theory can actually explain why the elements built up in the way that they did. That was an important promise of the new quantum theory between approximately 1912 and the early 1920s.

So they gathered around Bohr, and Einstein was an enthusiastic participant in this, because he was in some sense the adoptive father of quantum theory since his paper in 1905. It was in the 1910s that he and Bohr published a paper showing that it made sense to assume that these orbital transitions were completely random in the same way that radioactivity was random (lawful but random), and that it was possible to use radioactivity-like statistics to describe the jumping of electrons from one orbit to another within an atom. The randomness applied to the orbital change and to the direction in which the photon (as we now call it—the quantum of electromagnetic energy is now called a photon; it got that name in the 1920s), the direction in which it is emitted.

Here is another example in which stochastic processes (statistical processes) became attached to fundamental natural processes. Quantum theory is perhaps the most powerful example of how deeply entrenched this statistical idea became. We had a growing community of mostly young physicists who adopted the quantum hypothesis and started exploring it. And, of course, because it was coupled to spectroscopy, the natural thing to do was to use more and more sophisticated spectroscopic experiments in order to get more insight into the internal structure of the atom.

Remember, the whole point of Bohr's argument was that we can now make sense out of the spectroscopic data, why each element has the light print that it has. But the frequencies in that light print give us insight into the way that the electrons are organized around any given nucleus; the nucleus of, let's say, uranium, or whatever element you care to explore. So the spectroscopic data also gives us insight into the internal configuration of the electrons within a given element's atoms.

More sophisticated experiments, however, showed that Bohr's initial version of the theory did not work well, that it generated all kinds of inconsistencies with the data; In the early 1920s—and this is beautifully ironic in a certain sense—quantum theory encountered its first serious crisis, in which it was now no longer consistent with the growing body of much more sophisticated spectroscopic data using new kinds of instruments to analyze much more closely the light that is radiated by hot sodium, let's say, or mercury. We find that these frequencies are split in ways that are not explained by Bohr's initial version of the theory.

There was some talk about whether we now needed to look for a new theory, and maybe give up the quantum hypothesis completely. Now, a further irony is that in the early 1920s—1922, 1923—a young French physicist writing his doctoral dissertation, Louis de Broglie, applied to matter the same curious observation that Einstein had made in his 1905 paper about light. In that paper, Einstein, remember, argued that light behaves as if it were particular, which sounds like he's returning to Newton's corpuscular theory of light, where light is like a series of bullets or atoms. But for Einstein (as in fact for Newton as well, although at the time it was a very puzzling thing to Newton, and it was puzzling in the 20th century also) these little light atoms have a frequency. How can a particle have a frequency?

Well, it is clear that light has a frequency. All electromagnetic energy has a frequency and a wavelength. Nevertheless, says Einstein, it also acts as if it travels through space, as if it were packaged as some kind of an atom. So it has a dual nature. De Broglie showed that, based on his application of this quantum idea to mechanics, that particles—like electrons and protons and atoms, for that matter, also—they are particles, but they must also have a frequency and a wavelength associated with them. Matter must have a wave-like character.

In 1905 Einstein argued that wave-like stuff—electromagnetic energy—has a particulate character. De Broglie argued in his doctoral dissertation that particles must have a wave-like character. By the end of the 1920s, this was completely vindicated experimentally to show that, as a matter of fact, electrons, protons, and even whole atoms do display wave-like behavior. So this was in a sense a strong confirmation of the quantum idea, at the same time that people were beginning to seriously doubt the quantum idea.

Quantum theory was in a certain sense rescued in 1925 when Werner Heisenberg and Erwin Schrödinger in different ways, working quite independently, and using totally different approaches, founded what Max Born called quantum mechanics. Quantum mechanics was able to explain all of the new spectroscopic data. It anchored the quantum theory very powerfully, but it had a problem. The biggest problem with it was it was not clear what the theory meant physically. There were terms in the theory that did not obviously co-relate with the physical world, and that was a problem at a time when physicists believed that their theories were describing reality.

Between 1925 and 1929 a number of physicists, especially Niels Bohr and Werner Heisenberg, but others were involved as well, essentially looked at quantum mechanics philosophically. One of the important conclusions that Heisenberg reached was something called the uncertainty principle, which was that there were limits to the precision with which certain quantities could be measured.

Bohr formulated something called the principle of complementarity, which is that sometimes we have to use complementary, logically contradictory concepts in order to describe the phenomena that we experience, and that is because our concepts reflect experience. We cannot give pictures of reality, we can only provide theories that give us pictures of experience. This was very controversial and remains somewhat controversial even to this day. But it led to very interesting philosophical discussions in the 1930s and '40s and '50s about whether quantum theory finally had broken, so to speak, the stranglehold of the Platonic–Aristotelian definition of knowledge that had been part of the conceptual skeleton of modern science from its beginnings.

In 1929, Paul Dirac took the quantum mechanics of the day and made it partially consistent with the special theory of relativity, which had been ignored in the first simple (relatively speaking) form of quantum mechanics, and laid the foundation for what lasted for 35 years, until the early 1960s, as the decisive quantum theory of matter and energy, and came to have the name quantum electrodynamics. Quantum electrodynamics describes the interaction of matter and electromagnetic energy, and it does it with extraordinary precision, experimentally confirmed to a very high degree. It was what we used in the 1930s to study nuclear physics and fission. It underlies the creation of those particle accelerators, the atom smashers that let us explore the internal of the atom. It underlies the invention of the transistor, for example, and the laser. So it has direct techno-scientific applications that have changed our lives.

But by the early 1960s, the success of the atom smashers had created another problem. The problem was that we had so successfully smashed atoms to pieces that we now had over 200 particles that could be called in some sense elementary, and that was obviously impossible. That led to a new phase of quantum theory, which we are still in, and the transformation of quantum electrodynamics (generally referred to as QED) into QCD, quantum chromodynamics, or what most of us have heard of as the quark theory of matter.

Murray Gell-Mann here in the United States, and George Zweig in Switzerland, sort of semi-independently came up with the idea that we have to give up the idea that protons and neutrons are elementary particles, and we have to propose that the really elementary bits of matter are called quarks; and that protons and neutrons are compound particles made up out of combinations of quarks. Three quarks are necessary to make protons and neutrons. And we need electrons—they are truly elementary.

Then you come up with a theory called quantum chromodynamics, which explains why the nucleus stays together, why the nucleus is stable, which had been a problem ever since the 1930s when nuclear physics began to be studied seriously. Sometimes quantum chromodynamics is called the theory of the strong force, the force that holds the nucleus of atoms together; because you've got all those protons jammed together, they should repel one another.

Another curious nuclear phenomenon that we discovered in the 1930s, really, is that in radioactive atoms what happens is that a neutron inside the nucleus suddenly spits out an electron and turns into a proton. It also spits out something called an anti-neutrino. The force that controls the decay of neutrons into protons and electrons is called the weak force, although those terms are not to be taken literally. Electrons respond to the weak force. They are not affected at all by the strong force, and particles that respond to the strong force do not respond to the weak force.

Quantum chromodynamics is about the strong force, and it has been developing since the 1960s. Experiments have in fact found quarks, and we have, in 1995 especially, found what is believed to be the sixth and final quark, called the top quark, and in some sense that puts the final stamp of experimental approval on the Gell-Mann-Zweig quark theory of matter, or quantum chromodynamics.

But more happened to quantum theory starting in 1963 that used the rise of quantum chromodynamics in order to come up with a more complete theory of matter and energy. That was, early in the 1960s, it was also recognized that there really were just four fundamental forces that explained all natural phenomena at the level of physics. This was the strong force that I just referred to, the weak force, the electromagnetic force, and gravity.

And now began, in the 1960s and '70s especially, a movement towards coming up with a theory that unified these forces. The first was an attempt to unify the electromagnetic force (photons) with the weak force that electrons are sensitive to. That made a lot of sense because the electromagnetic force is about the way electrons interact with electromagnetic energy, and so it's already a theory of electrons and electromagnetic energy. The electrons are the particles that respond to the weak force, so that was a very reasonable first step.

And Glashow, Weinberg, and Abdus Salam shared a Nobel Prize for coming up with the so-called electroweak theory. This theory successfully united the electromagnetic force and the weak force, predicting the existence of a bizarre new family of particles, and they were discovered with the properties that the theory predicted that they would have.

The next step was to unite the electroweak theory with the strong force, and that was accomplished in the 1970s and 1980s especially, and what emerged is something called the Standard Model in quantum theory, which is I guess we would say today this is the status quo in quantum theory. It is our most powerful theory of matter and energy not just at the microscopic level but even at the cosmological level, and it is a theory that unites the strong force, the weak force, and the electromagnetic force. What it ignores is gravity for the moment.

The Standard Model is not only applied to matter and energy at the microscopic level, but since the 1960s it became part of cosmology, as we will be discussing in the lecture on the newly reinvented universe in the early 20th century. It became an element in cosmological theory because the theory was used to explain how atoms are built up from hydrogen to helium to provide all of the other elements that we see in the world. It has been used very powerfully to analyze black holes.

It turns out that black hole physics has turned out to be a very, very fertile area of physics, as we will be discussing especially in the very last lecture when we talk about string theory. Because the natural next step in unification is to unify the Standard Model with the force of gravity into what Weinberg and others call a theory of everything—a single theory that encompasses all of the four major forces that we think explain all natural phenomena at the level of physics.

Meanwhile, we're going to look in the next lecture at the second great theory in 20^{th} century physics, and that is the special and general theories of relativity.

Lecture Thirty
Relativity Redefines Space and Time

Scope:

Between 1905 and 1915, Einstein effectively redirected the course of modern physics. Although he is identified with the special and general theories of relativity, he was also a leading architect of quantum theory up to the formulation of quantum mechanics in 1925. The special theory solved a problem central to 19^{th}-century physics that had resisted solution for decades. In the process, it eliminated the aether (and a generation of aether physics), forced a reconceptualization of Newtonian space and time, and proclaimed the interconvertibility of matter and energy. The general theory went much further. It was a universal theory of gravity that redefined physical reality at the cosmological level. Space and time were dynamically interrelated with matter and energy, their properties determined by the evolving distribution of matter and energy. Both theories made utterly unanticipated predictions that have been confirmed, especially in the 1930s and since the 1960s.

Outline

I. Einstein's special and general theories of relativity, introduced in 1905 and 1915, respectively, have had a profound impact on our conception of reality.

- **A.** Independently of relativity theory, two other papers written by Einstein in 1905 had already altered our conception of reality.
- **B.** Einstein published a theory of Brownian motion that played a major role in convincing physicists of the reality of atoms, that matter really was discontinuously distributed in space.
- **C.** Einstein also published his theory of the photoelectric effect we discussed in the last lecture, which made quanta of radiation (photons) real, overthrew the wave theory of light, and introduced the seemingly dual nature of these quanta, later extended to matter.

II. As if that were not quite enough for one year, in 1905 Einstein also published a paper called "On the Electrodynamics of Moving Bodies."

- **A.** This is the paper that founded the special theory of relativity (STR).
  1. STR dismissed the reality of the aether, which had become central to physicists' account of reality from the 1840s, as a mistake.
  2. The mistake was not taking into account how we measure time and space, using clocks and rulers, and the role that light signals play in making these measurements.
  3. Einstein postulated as a law of nature that the speed of light is a constant for all observers regardless of their motion relative to that light.
  4. Numerous 19^{th}-century experiments suggested this, but it is a conceptually bold and somewhat bizarre idea.
- **B.** Einstein also postulated a principle of relativity that physicists had been using since Galileo and Huygens, namely, that the laws of nature are indifferent to uniform (unaccelerated and, hence, force-free) motion.
  1. Thus, two observers moving uniformly with respect to each other and doing the same experiment would "discover" the same law of nature at work in that experiment.
  2. Einstein showed that combining this long-established principle with the constancy of the speed of light and applying both systematically allows us to account for all known mechanical, electromagnetic, and optical phenomena, without any need for the aether.

3. The aether, Einstein claimed, was invented by physicists to explain a problem that disappears when one accepts the constancy of the speed of light and applies the principle of relativity in electromagnetic theory, as well as in mechanics.
4. The constant, finite velocity means that the time it takes for light signals to give observers information from rulers and clocks affects the results of those measurement operations.
5. The results of measuring spatial intervals and temporal intervals depend on the relative motion of the observer and what he or she is measuring.
6. Two observers moving relative to each other and measuring the same lengths and times will get two different answers, but these are strictly correlated by the laws of STR.
7. Each can predict the other's results once the relative motion of each is known.

C. STR implies a profound change in our definitions of space and time, matter and energy.

1. We have discussed the historic roots of the principles of the conservation of matter and the conservation of energy.
2. The equations of STR have as a logical consequence that matter and energy are not, ultimately, two different features of reality, and they are not conserved independent of each other.
3. The equation $E = mc^2$, unsought for in advance, predicts that they are interconvertible and only jointly conserved.
4. Einstein suggested that this surprising connection between matter and energy could be tested by extending Marie Curie's experiments on radioactivity.

D. Since Newton, space and time had an absolute character, as if they were things with properties of their own independent of what happens in space and time.

1. In STR, talk of space and time in physics is meaningful only as talk of measurements relative to particular frames of reference.
2. Absolute space and time are replaced by local space and local time, but all possible "locales" are strictly correlated with one another by the equations of STR.
3. This is a fundamental point about STR and the general theory of relativity: They are strictly deterministic theories!
4. What is relative in STR is not reality but the measurement of lengths and times: The results of measurements are relative to the frame of reference of the observer, but all possible observers are correlated deterministically.
5. Quantum theory, to which Einstein made fundamental contributions from 1905 to 1925, evolved into a stochastic theory of nature, and for that reason, Einstein never accepted its finality as a theory. He was irrevocably committed to determinism as the only rational account of experience.

III. The general theory of relativity (GTR) appeared in 1915, after eight years of intense work that Einstein said sometimes made him feel he was going mad.

A. GTR removes the limitation in STR of the principle of relativity to observers in uniform motion.

1. As with STR, Einstein begins by postulating as a principle of nature something physicists had known about for centuries but whose implications had been ignored.
2. This principle was the equivalence of gravitational mass (weight in a gravitational field) and inertial mass (the force required to accelerate an object, even if it is "weightless," as a satellite in orbit is).
3. This equivalence implies that there should be no difference in the laws of physics for an observer stationary in a gravitational field or experiencing a force independent of a gravitational field.

B. When the laws of physics are reformulated in a way that reflects this property of invariance, reality changes!

1. For one thing, space and time in GTR really are names of relationships, not things in their own right.
2. Further, there is no way to specify the properties of space and time independently of what happens in space and time.
3. There is, for example, no universal geometry to space, contrary to the age-old assumption that Euclidean geometry was the absolute background geometry for all of nature.
4. The geometry of space is determined by the distribution of matter and energy within space: "flat"/Euclidean where the density of matter/energy is very, very small and "curved"/non-Euclidean where the density is greater, with a radius of curvature that is a function of the density.

C. GTR as a theory of space, time and gravity is independent of quantum physics as a theory of the natures of matter and energy.

1. GTR is a theory of the Universe as a whole, a cosmological theory.
2. Einstein fine-tuned the initial version of the theory to reflect the prevailing conviction that the Universe as a whole was static.
3. From 1917 to 1923, however, physicists found that GTR was a dynamic theory that predicted an expanding Universe.
4. Einstein introduced a term into the GTR field equations that cancelled the expansion, but in 1929, Edwin Hubble announced that the Universe *was* expanding!

D. Like STR, GTR has withstood intense experimental testing and has made startling predictions that have been confirmed.

1. Most recently, astronomers have confirmed that GTR correctly predicted the observed orbits of two pulsars around each other.
2. NASA's *Gravity Probe B* confirmed the prediction that the rotational motion of the Earth twists spacetime in its immediate vicinity.
3. Apart from being used to refine the accuracy of the Global Positioning System (GPS), GTR has had no other technological implications that I know of, but GTR has wholly transformed our most fundamental scientific ideas about the Universe and its structure.
4. STR, by contrast, is familiar from its application to atomic energy (nuclear and thermonuclear technologies), and as a feature of the design of particle accelerators, but less familiar for its assimilation into explanation in physics at the deepest level.

Essential Reading:

Albert Einstein, *Relativity: The Special and General Theory*.

John Stachel, *Einstein's Miraculous Year*.

Questions to Consider:

1. What do Einstein's theories tell us about the power of the human mind to discover the truth about the world "out there" just through thinking?
2. Why was Einstein so committed to determinism?

Lecture Thirty
Relativity Redefines Space and Time

In 1905, and again in 1915, Albert Einstein decisively altered the direction of physics, which is why he has the reputation that he has. It was not just because he told good jokes. In 1905 Einstein published a paper on the Brownian motion, which I've referred to before, which is the apparently random motion of tiny particles suspended in a fluid, and used that analysis of the Brownian motion to make a case for calculating the size of molecules. This paper, which is actually is part of a series of papers on the Brownian motion, contributed significantly to the acceptance by physicists of the reality of atoms. You will recall I mentioned physicists resisted throughout the 19th and into the early 20th century, agreeing that it was a very useful hypothesis for purposes of doing such things as the kinetic theory of gasses and explaining chemical reactions, but that matter was not in fact atomic, that matter was continuously divisible. I mentioned that, for example, Michael Faraday was among many physicists in the mid-19th century who rejected the reality of the atomic theory of matter. But in the 20th century, Einstein's work was significant here in shifting the climate of opinion to one in which atoms were understood to be physically real entities.

I mentioned that when the French physicist Jean Perrin received his Nobel Prize in physics, one of the contributions to physics that he made was explicitly mentioned in his Nobel Prize award. It was mentioned that he had extended the work of Albert Einstein in doing experiments that convinced the physics community that matter was discontinuous. That is to say, it was atomic, or as we can now say, it was quantized, which is another way of saying that it's discontinuous, that matter comes in the form of discrete packages.

In that same year Einstein published the paper that I discussed in the last lecture on the photoelectric effect, which in a sense gave an atomic theory of light. Einstein was not merely saying that matter is atomic. He was saying that, in some curious way that in 1905 was still quite puzzling and unclear, and to some extent is still unclear, electromagnetic energy is atomic also; that electromagnetic energy occurs in the form of quanta. But these atoms of electromagnetic energy, which we call quanta, and then were in the 1920s called photons, that photons are atoms, but they have a frequency and a wavelength associated with them, which means that they have a dual character. And that in discussing electromagnetic energy and its interactions with matter we have to use both wave concepts (frequency and wavelength) and particle concepts (the quantization factor) as if they were sharply localized in space, and this does seem very puzzling.

How can there be something that is both a wave and a particle? And one response to this is to say, "Oh, wait a minute; we have now stumbled over the role that our concepts play in describing our experience. We used to think that our concepts were transparent, that our concepts mapped onto the reality behind experience, but maybe what we're seeing here is that our experience is caused by entities that we do not experience. Our concepts come from experience, so our concepts can't map onto what we never experience. We are driven by experience to use both wave concepts and particle concepts in order to describe really fundamental phenomena whose ultimate reality, so to speak, is beyond any possible experiences that we can have."

So that became part of the philosophical underpinnings of quantum theory. But it launched, of course as I said in the last lecture, that photoelectric effect paper really launched quantum physics, and shifted attention away from Maxwell's electromagnetic theory and the electromagnetic wave theory of light, which was one of the great triumphs of 19th century physics, to a quasi-Newtonian atomic or corpuscular theory of light, as Newton called it. Newton also recognized that there was a puzzling wave-like character to his corpuscles, and also recognized that it was conceptually illogical and puzzling for that to be the case, but nevertheless the experiments indicated that that was the case.

Again in 1905, Einstein redirected the course of physics with the paper on the electrodynamics of moving bodies that founded the special theory of relativity, and that is what we're going to be talking about now. The special theory of relativity was the theory that undid ether physics, and in a way that is startlingly cool considering the investment that the physics community had in ether physics for the previous approximately 50–60 years.

Einstein simply announces that postulating the existence of an electromagnetic ether in order to explain the phenomena of electromagnetism and electrodynamics, the way that the forces act on moving charged particles in electric and magnetic fields, that it was simply a mistake. There was no need for such an ether once you take into account the role that measurement operations play in dealing with phenomena; once you take into account the role that rulers, clocks, and light signals play in measuring spatial intervals and temporal intervals in determining what we mean when we say that two events happen at the same time, or two events happen 10 seconds apart, or 10 days apart.

Whenever we talk about measuring spatial intervals (a length), and temporal intervals (a time), and you have to do that in order to measure motion, we tend to ignore the physical operation of using a ruler, using a clock, and looking at the clock and seeing what time it is, which means that a light signal has to travel from the clock to our eyes. Now of course, ordinarily, it is totally irrelevant. Light travels so rapidly that it is effectively instantaneous. But when you're doing physics, effectively instantaneous has to be qualified. Well, it is in effect instantaneous. Light travels at a fixed speed, and in fact that is one of the principles of the theory of relativity.

Einstein postulates that it is a law of nature, so to speak, that light travels at the same speed for all observers regardless of their motion, and therefore it is the only, so to speak, constant in the background of doing physics. The speed of light does not seem to be different depending on whether you are moving toward or away from a source of light, which is contrary to all our other experiences of relative motion. But he says if you make that assumption, which is experimentally strongly suggested, then there is no longer any need for the ether.

I'd like to read a paragraph from Einstein's 1905 paper on the *Electrodynamics of Moving Bodies*, which is called that because what Einstein argues in this paper is that we can unite mechanics and electrodynamics. We have to apply the same rules that apply to the motions of material objects, that even in the 17th century physicists recognized that there was a principle of relativity of uniform motion that when, for example, if you're doing an experiment in your laboratory which is on dry land, and somebody is doing the same experiment in a railroad train that is moving uniformly (it's not slowing down or speeding up or going around a turn), then you're going to get the same results that the person in the laboratory gets. The laws of physics that you discover will be the same if two individuals are moving uniformly with respect to one another.

Galileo and especially Christian Huygens had made this point explicitly in the 17th century, and this is built into the fabric of modern science. But what Einstein pointed out was that in the case of electromagnetic theory, people have not been careful to apply the principle of relativity to that as well, and they have not paid attention to the measurement operations. As a result, they felt they needed an aether in order to explain the behavior of electrically charged objects in electromagnetic fields and optical phenomena. Whereas, he shows in this paper that all of the phenomena of mechanics, electrodynamics, and optics can be explained by making some simple assumptions, and there is no need for an aether whatsoever.

Einstein notes that because of not applying the principle of relativity to electromagnetic theory, certain problems have arisen. One of the things that we discover experimentally is that no one can find the speed of the earth relative to the aether, and this suggests that there is nothing in nature that corresponds to the idea of absolute rest. "These problems suggest, rather, that as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good." The equations of mechanics are bound by the rule that the equations stay the same for all observers in uniform motion with respect to one another. That has to apply to electrodynamics and optics as well. We will raise this conjecture, that the principle of relativity applies to electrodynamics and optics and not just mechanics:

> The purport of which will hereafter be called 'The Principle of Relativity' to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely that light is always propagated in empty space with a definite velocity which is independent of the state of motion of the emitting body.

It seems contradictory, because first you tell me that the principle of relativity of motion has to be applied not just in mechanics but to light and to optics and to electromagnetic phenomena generally, and then you tell me that the speed of light is not subject to the principle of uniform motion; it is the same for everybody:

> These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a luminiferous aether [the electromagnetic aether] will prove to be superfluous inasmuch as the view here to be developed will not require an absolutely stationary space provided with special properties, nor assign a velocity vector to a point of the empty space in which electromagnetic processes take place.

Without having to assign what he calls a velocity vector to every point in space, you don't need a field that is essentially some kind of materialization of those abstract mathematical vector points, but since those points exert a force, we don't want abstract mathematical points to exert a force on matter. That sounds mystical. So the field was invented to explain how at every point in space a charged object in an electric field or a magnetic field can experience a force. Einstein says you don't need that. Get rid of all of those vector points. All you have to do is pay attention to the operations that we perform, of what it means to say that we measure—given the finite velocity of light—that two events happen at the same time.

When we measure a length—when I am in my laboratory and I try to measure the length of an object that is moving away from me—I will find that that object seems to be shorter than when that object was in my laboratory. And that is only puzzling if I don't realize that it took time for light to get from the tip of that object to me, and a different time for it to get from the tail of that object to me. Now, of course, if it's moving 10 miles an hour, 100 miles an hour, 1,000 miles an hour, it's not going to show up. But if it's moving a hundred million miles an hour, then it is going to show up.

The speed of light, after all, is 186,000 miles a second, but once experiments become increasingly precise, then you can start seeing, as in the case of Michelson and Morley's experiments to find the motion of the earth relative to the ether, motion of the earth relative to absolute space, absolute rest, as Einstein just called it, then the machine that Michelson invented (the interferometer) to make that measurement was capable of exquisitely sensitive measurements. As a result of not finding the motion, you remember Lorenz and FitzGerald came up with this idea that matter contracts in the direction along which it moves, because all matter is electrically charged internally, and it interacts with the electromagnetic ether, because all electrically charged matter moving in an electromagnetic field interacts with the field, so the interaction causes the matter to shrink.

Einstein says it is not shrinking. Forget that ether. All you have to do is remember that light has a finite velocity, and if you make the assumption that that velocity is the same regardless of the state of motion of the observer, then it turns out that the measurement will be smaller exactly to the degree that the Lorenz-FitzGerald contraction predicted the thing would shrink. It's not really shrinking. It's the same length it was, but the measurement is different.

At the very end of the paper Einstein points out that there is something puzzling, however, which is that while measuring the spatial interval only appears the length of a moving object, moving relative to a stationary frame of reference (I'm making the measurement in my laboratory, but the object I'm measuring is moving with respect to me), then the length only apparently changes. But if I have a clock on that object, and I synchronized it with a clock in my laboratory before that object started moving away from me, and that object comes back to me, the two clocks will no longer be synchronized. I don't just measure that time is moving more slowly on the moving object relative to the stationary object; it really has moved more slowly, as reflected in the fact that while it's just as long when it comes back as when it left, the time is different. Time has apparently moved more slowly on the moving object.

Again, this is a minute effect in ordinary experience, but has been verified over and over again experimentally, so that it's quite true, as far as we can say that anything that is experimentally confirmed is true.

Now what emerges out of the special theory of relativity is a very important reconceptualization of what we mean by space, time, matter, and energy. Because by what Einstein called a happy circumstance, out of his now modified equations for the behavior of moving bodies, what falls out is the equation $E = mc^2$, which implies that energy and matter are interconvertible, and that is interesting, but it also implies that energy has inertia. Since matter has inertia, and energy and matter are equivalent, they are interconvertible one to the other, then energy must also have inertia just the way matter does. He suggested that this can be tested by Marie Curie's experimental work on radium, just published in the previous couple of years before 1905, and suggests that he expects that this will be confirmed, that energy will turn out to have inertia.

In the general theory of relativity, published in 1915, it turns out that just as matter becomes the source of a gravitational field, energy is the source of a gravitational field, and that turns out to be important in the general theory. But here in the special theory of relativity, one of the logical consequences of the theory is that space and time no longer have the absolute character that Newton defined them to have at the beginning, so to speak, of modern mechanics. In Newton's *Principia* of 1687, you remember I read to you his definitions of space and time. They are the absolute backdrops of natural events. And Einstein says there is no absolute space; there is no absolute time; there are only local spaces and local times, which are coordinated by strictly deterministic absolute laws.

The equations of the special theory of relativity, as with the general theory of relativity, are deterministic equations. It's kind of misleading to call them the theory of relativity, because the term "relativity of motion," or as Einstein used, "the principle of relativity," really, it's the measurement that's relative, but all the laws of physics are strictly deterministic. And Einstein was a deterministic kind of guy. Einstein, to the end of his life, resisted the completeness of quantum mechanics because it turned out to have a fundamentally statistical interpretation, according to Bohr and Heisenberg and just about everybody else using the theory.

Quantum theory is a stochastic theory at the most fundamental level. What is going on has a probabilistic character. Now, Einstein says that can't be, because you can't have statistical laws. He did not accept what we had discussed in an earlier lecture, that there were such things as statistical laws of nature. He was a determinist. These are deterministic theories that make for one problem with respect to reconciling the general theory of relativity—which is a gravitational theory, a theory of the gravitational force—with the three forces that have been united in the Standard Model of quantum theory. One problem is that that's a deterministic theory, the other is stochastic; we would have to come up with a statistical theory of gravity also. There are some more serious problems that we'll get to in a moment when we talk about the general theory of relativity—which we might just as well make the transition to, because the general theory of relativity essentially drops the restriction that the equations of motion of physics are the same for all observers in uniform motion with respect to one another. Uniform means they're not accelerating; they're not decelerating; they're either at rest with respect to each other or they are moving uniformly.

Uniform motion means no forces are acting on the system. And that makes a lot of sense, because if you're doing an experiment and there are no forces acting on you that are not acting on someone else, you expect the results to be the same. But if it turns out that someone else is doing this experiment while they are falling freely from an airplane before they open their parachute, then you do expect that there will be a difference in the outcome of the experiment because one is being subjected to a different set of forces than the other one is (if nothing else, the force of the air that is rushing past you).

So what Einstein says in the general theory of relativity is—and Einstein says he worked on this for eight years, from roughly speaking 1907 to 1915, eight years that almost drove him mad because of the abstractness and the complexity of the ideas underlying the general theory of relativity. It was triggered by an insight that is strictly analogous to what Einstein just did in the special theory of relativity—making a postulate out of something that was experimentally recognized but had not been erected to the status of a principle of nature, and then seeing what follows from that. What can we explain? What can we predict? What can we test experimentally?

In the general theory of relativity, Einstein says everybody knows that empirically some gravitational mass (weight) is equivalent to inertial mass, and that is built into Newtonian mechanics, also. But no one has asked the question, why are these two equivalent? And what Einstein concludes is this is a principle of nature. Gravitational mass and inertial mass. Inertial mass is the resistance of matter to acceleration. Gravitational mass is familiar to us as weight, and inertial mass is more general, so to speak. In order to move a material object you have to apply a force to it, and the force that you would have to apply in order to move it is a function of its inertial mass. It's measured by the Newton's famous equation $F = ma$, that the force you need to apply in order to get any particular acceleration is equal to the inertial mass of an object times its acceleration. You can calculate what the inertial mass is by seeing how much does any given force cause an object to accelerate (to move), and how rapidly it moves over some period of time. That gives you force over acceleration, and then that's the inertial mass.

Einstein says we make those equivalent, then what we really have discovered is that there is no difference between an object that is stationary in a gravitational field or an object that is accelerating independently of a gravitational field. The laws of physics will be the same whether you're in a spaceship that is accelerating or whether you're stationary in an area of space where there is a strong gravitational field that, so to speak, mimics the acceleration of your spaceship. This is why you can sort of have artificial weight in an accelerating spaceship even if it's far away from any object that's exerting a gravitational force. The acceleration itself exerts a force that is indistinguishable from a gravitational force.

Now the general theory of relativity is conceptually even more revolutionary than the special theory of relativity, in part because it removes the restriction on uniform motion and means that the laws of physics have a much more general character than they have in the special theory of relativity. It also means that space and time really are relationships whose reality is a function of matter and energy; that matter and energy shape space and time, influence space and time, and there's no way that you can separate space and time, matter and energy. Newton thought that you could. It had been tacitly assumed that space and time were sort of the absolute backdrop of events. The special theory of relativity challenged that, but the general theory of relativity dismisses that.

There is no background geometry to space. And this can give you vertigo. We can understand what Einstein meant when he said that this was driving him mad. The general theory of relativity says that the geometry of space is a function of matter and energy that's in space. If there were no matter and energy, there would be no space. The curvature of space, as we have come to call it, is a function of how much matter, and how much energy, because matter generates the gravitational field which shapes space.

Space, time, matter, and energy are now reciprocally co-related in the general theory of relativity in ways that they never were before. The general theory of relativity is a universal theory of gravity that co-relates space, time, matter, and energy. It is a theory, therefore, of the universe in the same sense that Newton's universal theory of gravity was a theory of the universe; but in a much more sophisticated and substantial way. Because now Einstein is saying that the very shape of space, the character of time, the flow of time are functions of the distribution of matter and energy.

So the general theory of relativity has cosmological implications. Not in terms of an infinite backdrop of space that Newton thought; on the contrary, the general theory of relativity implies that space is finite, that the universe is finite spatially. Newton thought that it was infinite spatially, whereas the general theory of relativity says that the universe is finite spatially and that it is the basic set of equations, the equations of the general theory of relativity give us equations for a gravitational field that describes the shape of space and the flow of time and the distribution of matter and energy in a way that's coordinated. So it's a really complicated set of reciprocal, mutually dependent relationships.

Einstein formulated the field equations and, accepting from his contemporary astronomers that the universe was stationary, which is what they thought at the time—and the assumption at the time too was that the long-term stability of anything implies equilibrium, so Einstein wanted the universe to be an equilibrium—and he formulated the field equations, the gravitational field equations from the general theory of relativity, so that they would generate a stable universe that was in equilibrium. Given the force of gravity which pulls matter together, Einstein had to stick in a term in the equation which counteracted the force of gravity in order for the universe to be stable. This was in 1915 and shortly thereafter.

Between 1917 and 1919 other physicists started playing with the general theory of relativity—a Dutch physicist named Willem de Sitter in particular, and a German physicist named Schwarzchild, and in Russia in the early 1920s Alexander Friedman in 1922, 1923—and they pointed out to Einstein that the solutions to these equations were very tricky, that the way the equations were set up it looked as though the universe would expand. That seemed quite incorrect, so Einstein was, in that period of time, playing with the cosmological constant (as this fudge factor came to be called) in order to somehow keep the universe stable and not allow there to be solutions to the equations which would generate a universe which didn't look like what the astronomers said the universe was like.

Ironically, of course, he was preventing the equations from predicting the expansion of the universe exactly when the universe was discovered to be expanding; which in fact Willem de Sitter, even in the late 1910s, recognized. There was some data that was accumulating called the redshift of light, that we'll be discussing in the next lecture, that strongly suggested that the universe was not in equilibrium, that it was not stationary, that it was changing, that star positions were changing relative to one another, and that we needed dynamic solutions to the equations of the general theory of relativity.

Friedman made this much more the case, that the general theory is an intrinsically dynamic theory of the universe. Of course once the expansion of the universe was discovered, Einstein sort of hit himself in the head and said it was the stupidest thing I ever did—playing around with my own theory because I thought that I needed to make it match what the astronomers told us about the universe, as if they knew what the nature of the universe was.

In fact, the general theory of relativity, like the special theory of relativity, has had extensive and intensive experimental confirmation, and it has passed every such test, including most recently correctly predicting the behavior of a pair of pulsars that orbit one another, and the claim from the theory that space and time in the immediate vicinity of the earth are in a certain sense warped or dragged by the rotational motion of the earth. There's a satellite called Gravity Probe B which has tested this and the prediction is confirmed, as was the prediction of black holes and galactic lenses and the curvature of rays of light passing near a gravitationally dense body like the sun. The only practical application of the general theory of relativity that I can think of is the global positioning system, which is now so precise that it has to take the general theory of relativity into account in order to track the satellites that the global positioning system uses in order to determine locations on the earth. That is very interesting all by itself.

The special theory has had a number of practical applications, not necessarily in consumer technology, but this is something of a contrast between the relativity theory and quantum theory. Many practical applications in the case of the quantum theory are semi-conductive physics, the transistor, the laser, to mention just a few. In the case of the special theory, we've got all the things associated with atomic energy, and particle accelerators need to use the special theory, that's built into their design. But from the point of view of consumer and industrial techno-science, the general theory of relativity is conceptually revolutionary, intellectually radical and revolutionary, but has not yet been translated into techno-science for the consumer, at least not until atomic energy becomes a consumer product.

Lecture Thirty-One
Reconceiving the Universe, Again

Scope:

The Newtonian Universe was spatially infinite and materially finite. The consensus view, although it was not unanimous, was that the material Universe was identical with the Milky Way, whose size was first determined during World War I. In the 1920s, the scale of the Universe changed dramatically with the discovery of thousands of galaxies extending to the limits of observability. Then, Edwin Hubble announced that the Universe was expanding. Together with the general theory of relativity, cosmological speculation became a branch of science and made a scientific problem out of the origin of the Universe. After World War II, the Big Bang and Steady-State theories were offered as rival explanations, even as astronomers were discovering a rich, complex, invisible Universe behind the visible. In the 1980s, the scale and the nature of the Universe changed again, the vastness now beyond imagination, and the detectable Universe, visible and invisible, a mere footnote to a newly conceived whole.

Outline

I. The Universe was reinvented in the aftermath of Copernicus's theory of the heavens and refined in the 18th century, then reinvented again in the 20th.

- **A.** Copernicus opened a door and philosophers and scientists streamed through it.
    1. The Universe as Copernicus himself conceived it was superficially similar to the medieval Universe.
    2. Both were spherical and, hence, had a well-defined center and periphery, though Copernicus's was much larger.
    3. Copernicus's Universe was heliocentric, not geocentric, and this stripped it of all explicit symbolic meaning.
    4. De-centering the Earth naturalized and secularized the Universe.
- **B.** The naturalistic implications of Copernicus's idea were quickly extended by others.
    1. Thomas Digges adopted Copernicus's idea but made the Universe infinite in space, populated by an endless number of stars.
    2. Copernicus and the infinity of the Universe were championed by Giordano Bruno in his *Infinite Universe and Worlds*.
- **C.** By the end of the 18th century, Copernicus's ideas, amended by Kepler and Newton, were triumphant: The Universe was wholly natural and infinite.
    1. Consider the title of Thomas Wright's 1750 book: *An Original Theory or New Hypothesis of the Universe, Founded upon the Laws of Nature, and Solving by Mathematical Principles the General Phenomena of the Visible Creation*….
    2. Immanuel Kant was inspired by a review of Wright's book to formulate a Newtonian cosmological theory of his own in his *Universal Natural History and Theory of the Heavens*.
    3. Kant's Universe is a boundless, gravitationally ordered hierarchy of systems of galaxies composed of solar systems like our own, continually forming, collapsing, and reforming out of gaseous nebulae, according to Newtonian laws.
    4. Both of these were superseded in fame and impact by Laplace's 1796 *Exposition of the System of the World*, followed by his *Celestial Mechanics*.

II. The scientific study of the "heavens" and their glory was part of the progressive naturalization by scientists of the Earth, life, mankind, and mind.

- **A.** The consensus scientific view of the Universe was that it was spatially infinite but contained only one galaxy, the Milky Way.

1. The scale of the Solar System was well known in the 18th century, but the actual distance to the stars was first measured in 1838.
2. From its parallactic displacement at opposite sides of the Earth's orbit, Friedrich Bessel determined the distance to the star Cygnus 61 to be about 10 light years from Earth.
3. This led to crude guesses at the size of the Milky Way, then considered to *be* the Universe, but in 1912, Henrietta Swan Leavitt invented a cosmic "ruler" based on variable stars.
4. Harlow Shapley used Leavitt's ruler to determine that the Magellanic Clouds were some 400,000 light years away from Earth and that our Sun was 50,000 light years from the center of the Milky Way, which was, thus, more than 100,000 light years across.

B. In 1920, Harlow Shapley and Heber Curtis debated the question of whether the Milky Way was the Universe.

1. Shapley argued that it was and thought he had won the debate, but even if he did, he was wrong about the Universe!
2. Shapley left Mt. Wilson Observatory for the directorship of the Harvard Observatory just as a new 100-inch telescope was becoming operational at Mt. Wilson.
3. The new Mt. Wilson director, Edwin Hubble, announced in 1923 that Andromeda was a galaxy, not a glowing cloud of gas within the Milky Way, as Shapley thought.
4. Hubble estimated its distance at a million light years and soon announced that there were thousands of galaxies, extending as far as the telescope "eye" could see.

C. All by itself, this transformed the vastness and complexity of the Universe, but it was just the beginning.

1. In 1929, Hubble announced that the Universe was not static—it was expanding.
2. Hubble based this claim on his analysis of stellar and galactic *red shifts*, which implied that effectively all stars and galaxies were racing away from the Earth.
3. The red shift is an optical version of the Doppler effect, more familiar in its acoustic form as the effect of motion on the perceived frequency of a sound.
4. This shift had been observed for a dozen or so stars around 1912 by Wiley Slipher, who published this observation, but it was ignored.
5. Hubble made thousands of such measurements and incorporated them into an interpretation of the Universe as expanding.

D. Of course, viewing the expansion of the Universe in reverse has a conceptually dramatic consequence.

1. An expanding Universe suggestively started from an initial first moment.
2. For some astronomers, this initial moment was the "birth" of the Universe: In other words, the Universe had a beginning in time.

III. The expansion of the Universe needed explaining, but the newly vast Universe also raised the question of what was out there.

A. The Universe was, it turned out, not just the things we could see: It was filled with things we could detect but not see.

1. In the mid-1930s, radio engineer Karl Jansky accidentally discovered that there were electromagnetic sources in the sky, giving rise to the new discipline of radiotelescopy.
2. Radiotelescopy revealed that "empty" space was not empty, that molecules and clouds of molecules, some complex, were everywhere.
3. Concurrently, cosmic rays were recognized as subatomic particles "raining" on the Earth from outer space.
4. Over the next decades, X-ray, gamma-ray, neutrino, and gravity-wave telescopes were built.

B. In 1980, astronomers—trying to answer a longstanding question concerning why galaxies are so stable—proposed that galaxies were surrounded by a "halo" of a new form of matter they called *dark matter*, which made up the bulk of the matter in the Universe.

C. In 1998, observations suggested that the expansion of the Universe was accelerating, not slowing down, as expected. The cause was *dark energy*, which made up the bulk of the matter-energy of the Universe, with dark matter in second place and "our" kind of matter just about 4 percent of the whole.

D. Furthermore, back in 1980, physicist Alan Guth had proposed an *inflationary theory* of the birth of the Universe that meant the Universe was unimaginably vaster than what we could detect.

IV. The problem of the expansion of the Universe raised the question: Did the expansion imply a beginning, or has the Universe been expanding forever?

A. Shortly after World War II, George Gamow and Fred Hoyle, with collaborators, proposed rival responses to this question.

1. Gamow proposed what Hoyle mockingly dubbed the *Big Bang theory* of the Universe.

2. Hoyle proposed a *Steady-State theory* of an eternally expanding Universe.

3. The Big Bang theory predicted a universal, uniform microwave background radiation, but it could not explain how elements heavier than lithium could be built by stars out of hydrogen.

4. Hoyle, too, needed such a nucleosynthesis theory, and he got one out of William Fowler and Margaret and Geoffrey Burbidge.

5. The discovery in 1963 of the microwave background radiation that Gamow had predicted shifted opinion to the Big Bang theory, now incorporating the Hoyle-inspired solution to the nucleosynthesis problem!

B. Quantum theory was needed to solve both the nucleosynthesis problem and the problem of the origin of the Universe.

1. Explaining our Universe using quantum theory in the 1970s solved some problems but created others, including the failure to observe magnetic monopoles.

2. In 1980, Alan Guth proposed that the Universe began with an instantaneous "inflation" of a primordial dot of negative quantum energy.

3. This inflation was by a factor of 2^{100}, and detailed observations of the microwave background radiation support its reality.

4. A corollary of this inflation is that everything we previously meant by *Universe* is only a minute patch on a vastly greater "true" Universe that is forever beyond interaction with us.

Essential Reading:

Dennis Overbye, *Lonely Hearts of the Cosmos*.

Brian Greene, *The Fabric of the Cosmos*.

Questions to Consider:

1. How do we know that the only cause of the red shift is motion?

2. Why is modern cosmology less shocking to people than Copernicus's theory was?

Lecture Thirty-One
Reconceiving the Universe, Again

In 1543, Copernicus opened a door onto a new conception of the universe. I've used that expression, "opening a door," quite a lot with respect to technological innovations; applying the medieval historian Lynn White's notion that new technology only opens a door, it doesn't force anyone to cross the threshold. But it applies to new ideas as well. New ideas open doors, so to speak, metaphorically, and the response of scientists and society to new ideas, new scientific ideas, is a very interesting index to values and attitudes that the scientific and general communities have with respect to the implications of those ideas.

In the case of Copernicus, Copernicus opened the door to a new conception of the universe in which the earth's role in the universe, the earth's place in the universe and its role in what was previously considered to be the great drama that justified the universe's existence—namely, the drama of human salvation or damnation—loses its significance. It took over a hundred years between 1543 and 1687 (using 1687, Newton's *Principia*, as the date at which the overwhelming majority of astronomers and scientists accepted the Copernican hypothesis), it took over 140 years for European culture (European intellectual culture, at any rate) to walk through that door, to move through the door that Copernicus opened to a decisive new conception of the universe. It was no longer a universe that would have been recognized by Copernicus, because Copernicus's universe was finite, and it was actually quite a pretty universe in which all of the fixed stars were in sort of a shell which he thought was only a couple of miles thick. They were very far away from the solar system, but they were in a spherical shell, and so the universe had a very nice finite spherical shape to it (we know how beautiful the sphere is from a mathematical perspective, especially for Pythagoreans). And then at the very center of this universe is the solar system, and the center of the earth's orbit is the center of Copernicus's universe. The earth is not at the center of the universe, but the universe has a well-defined shape in this Copernican model. But very quickly the door that Copernicus opened up led to a truly transformed landscape for the universe. If you can remember, hold on to that term "landscape," because at the end of this lecture it's going to come up again with a dramatically different meaning.

The new landscape on the other side of the door that Copernicus opened was one in which the universe became infinite in space, at least infinite in space, and according to a growing number of thinkers there were an endless number of stars distributed not in a nice little spherical shell centered on the solar system but, so to speak, distributed throughout space. This reflected a secularization and a naturalization of what we meant by the universe, that the universe decisively lost its character as justified by the drama of human salvation as a hope, and human damnation as a fear. It was as if the earth and human life on it was totally irrelevant in the greater scheme of things; or at least it had that appearance.

The universe did not need for its explanation any reference to human life. It could be explained, strictly speaking, on naturalistic and secular grounds. We see this already in the early 17^{th} century—well, by the end of the first third of the 17^{th} century—in Descartes's theory of the universe and how the universe mechanically, after the initial act of creation, the universe evolved naturalistically. But cosmological theory, theories of the universe really began to have a scientific character in the middle of the 18^{th} century.

Between Copernicus and Newton there were conceptually dramatic changes to our conception of the universe. For example, the work of Thomas Digges and the Italian philosopher-mystic Giordano Bruno, who argued that the universe was positively infinite. In the case of Bruno, that there were an infinite number of stars, and that there were planets around these stars, and life forms on these planets. Some of the life forms were inferior to us and some of them were superior to us. Nevertheless, one can call all of this, including Descartes's cosmology, wildly speculative.

But in the middle of the 18th century there were a number of developments that revealed this notion that the universe now needed an explanation that was strictly secular, naturalistic, scientific, and I want to read the title (it's a very long title—editors would not allow it today) of Thomas Wright, an English natural philosopher, in 1750 published a book called *An Original Theory or New Hypothesis of the Universe Founded upon the Laws of Nature and Solving by Mathematical Principles the General Phenomena of the Visible Creation*. So, okay, the universe was created by God; now we no longer need to refer to God—put God up on the shelf, so to speak—and we will now explain the universe on mathematical principles using laws of nature. And Wright tries to give an account of the Milky Way that's based as far as he can do so on principles of Newtonian physics and especially Newton's law of gravity.

Inspired by Thomas Wright's essay, the philosopher Immanuel Kant—who was not yet the philosopher Immanuel Kant; he was the aspiring physicist Immanuel Kant—published a monograph with a much shorter title, which was called *Universal Natural History and Theory of the Heavens*, which he wrote in 1755. But because of financial problems with his publisher, it didn't actually get published until 1762, and it was then pretty much ignored until the early 19th century. In that essay Kant offers an explicitly Newtonian account of the universe as an infinite, eternally expanding structure in which stars are born, explode, die, re-form, and planetary systems, solar systems, galaxies are continually forming and re-forming in a continually expanding universe. Highly speculative, but he actually uses Newtonian physics as far as possible to make mathematical sense of this, and even makes predictions about the solar system that can be, as he noted, experimentally confirmed. If they are confirmed, he thinks, then that shows that his whole theory is correct. He made a particular prediction about the rotation period of the planet Saturn, for example, which turned out not to be correct.

But sort of the most scientific expression of this new secularized conception of the universe was Laplace in his *Celestial Mechanics* at the turn of the 19th century, preceded slightly by a subset called *Exposition of the System of the World*, which he published in 1796. It was in response to his *Celestial Mechanics*, which is a Newtonian mechanics of how the solar system forms, and how the planets are in stable orbits—that they will never spiral into the sun, that the solar system has a kind of eternal character—that he is reputed to have said to Napoleon that he had no need for the hypothesis of God in order to explain the solar system, and let it go at that.

By the time we get into the 19th century, the universe is a completely secularized and naturalized structure. We have some vague scientific idea of how the solar system and the planets, the sun and the planets, could have formed into a single integrated physical system obeying laws of conservation of angular momentum, for example, and the period and the distance laws of each planet from the sun—the orbital period and the distance from the sun—but what we don't have is any sense of how big the universe is. We have some idea, there is a prevailing idea, that what we mean by the universe is the Milky Way, that the Milky Way is the universe, but we have no idea how big the Milky Way is. Given the telescopes of the time, what we would consider galaxies were to them sort of fuzzy clouds of light in the sky, which were assumed to be gaseous, that nebulae were clouds of gas in the distant sky, and they were not other galaxies. There was only the Milky Way.

Kant explicitly argued that there were many other galaxies, but he had no observational evidence for it. That's why I say it was speculative. The question is, how big is the Milky Way? How far away are these stars? The first measurement of the distance to a star was accomplished by Friedrich Bessel, a German mathematician and astronomer, who measured the distance to a star in the constellation Cygnus—the star is called Cygnus 61—as approximately 10 light years away from the earth. The mileage would be 10 times the amount that light, traveling at 186,000 miles a second would cover in a year. So 10 times that number of miles (or kilometers), and that was 10 light years. That's quite large, but not a scary number.

Based on that number, people started guessing at "How big is the Milky Way?" But these guesses had no firm basis in observational evidence, because we lacked a cosmological ruler. We lacked a measuring rod that would allow us to say how far it is from the earth to any given star. The reason why Bessel was able to calculate the distance to Cygnus is because he took advantage of the phenomenon called parallactic displacement; that is, if you measure the same object from two different locations then the object seems to have changed its position. For example, if you look at two stars that are lined up in June when the earth is at one point in its orbit, which is approximately 92 million miles from the sun, and then you look at those two stars again in December when the earth is on the other side of the sun, and it's therefore 184 million miles away from where it had been in June, then those two stars won't be lined up any more, if that should be the case.

Now, most stars don't show any evidence of this parallactic displacement because they're so far away that 184 million miles is a joke. However, the stars that are closest to us do reveal a parallactic displacement, and if you measure enough stars…. Bessel was a star cataloguer and he catalogued the positions of 50,000 stars. He came upon stars that did have a parallactic displacement, starting with Cygnus 61 (not the closest star to us; the closest star is only approximately four light years away, but there's no way of knowing by looking at a star whether it's close to us or not), so Cygnus 61 revealed a parallactic displacement. Any other star closer or within maybe another 10 or so light years might also have revealed it to him, but of those 50,000 you've got to examine all of them in order to see which ones are going to reveal a parallactic displacement. So we're stuck with 10 light years away to what at the time was considered to be the nearest star, and everything else is much more distant because it doesn't reveal any parallactic displacement so far.

In the early 20th century a woman named Henrietta Swan-Leavitt, who was a "computer" at the Harvard Astronomical Observatory. A computer meant at the time a human being whose job it was to compute, to make calculations; astronomers need lots of calculations. Henrietta Swan-Leavitt was one of many women who were tragically under-employed because of the prejudices against women in science, not to mention professionally in society as well. Henrietta Swan-Leavitt in 1912 published, through the director of the observatory, who actually published the note in her name in an astronomy journal (Edward Pickering was the director of the observatory at the time), in which she said that she had come upon a phenomenon that could be such a cosmological ruler, and it had to do with variable stars.

There are stars that vary in their brightness with a regular period, and she said that the apparent brightness of these stars, depending on their period, could be used as a ruler. What you need to do is to measure the absolute brightness (luminosity, it's called) of one of these stars, and then whenever you see a star with the same period, you can calculate its distance from you based on its apparent luminosity, because we know the rate at which light dims as a light moves away from us based on the distance.

So we know that if a 50-watt light bulb has a certain luminosity when it's 100 feet away from us, and then you move it 1,000 feet away from us, we know the formula that describes how much dimmer it's going to look when it's 1,000 feet away from us (that's it's apparent luminosity) than when it's 50 feet away from us; and we know exactly its distance and we call that its absolute luminosity, roughly speaking. In fact, very quickly a Scandinavian astronomer made such a calculation; so that here we have in the middle of the 1910s the first cosmological ruler.

Harlow Shapley was an important American astronomer of the time working in California at one of the observatories that preceded the construction of the 100 inch telescope in Mount Wilson in Southern California. Harlow Shapley estimated that the size of the Milky Way was 300,000 light years, and that the earth was about halfway out on one side of the Milky Way, about 50,000 light years away from the center of the Milky Way.

Shapley argued aggressively that the Milky Way was the universe, and in 1920 had a public debate with an astronomer named Heber Curtis in Washington that was, so to speak, on this very subject, to convince the scientific community. Are there more galaxies than the Milky Way, or is the Milky Way what we mean when we talk about the universe? Shapley believed at any rate that he won that debate, but within three years Edwin Hubble became the director of the Mount Wilson Observatory and became the master of the 100 inch telescope. Shapley was offered that job but decided to accept an offer to become the head of the Harvard Astronomical Observatory, which at the time had a much greater reputation; but it didn't own the most powerful telescope in the world, which the 100 inch became when its construction was completed in 1919. Hubble used the 100 inch telescope to show that the Andromeda Nebula was a galaxy, that it was made up of stars. It wasn't a cloud of glowing gas in the sky. It was, in fact, a galaxy. And within the next few years showed that there were dozens, hundreds, thousands of galaxies out there. As far as the telescope eye could see, the universe was strewn with galaxies. Now this is all by itself a dramatic reconceptualization of the universe, but nothing compared to 1929, when Hubble announced that his observations of the light coming from distant stars and galaxies showed that the universe was expanding.

This reflected a phenomenon called the redshift of light, which is very familiar to us really as a Doppler effect with regard to sound. You all know that when something emitting a sound wave moves away from us, the sound wave is sort of dragged out, and the sound sounds deeper than if the thing were stationary with respect to us. If it's coming toward us, the sound of a horn of a locomotive whistle, for example, is higher pitched coming towards us; it is lower pitched going away. There is a shift to the lower frequencies. The same thing happens with light. Light is in some sense a wave, although of course we now know that it's pretty complicated—it's both a wave and a particle—that the wave-like character of light obeys this Doppler shift too.

An object, let's say a star, that's moving away from us, the light will be shifted towards the lower end of the spectrum (red is the lowest end of the visible spectrum; violet is the highest end of the visible spectrum, and the colors are arranged in between the two). So when we talk about the redshift of stars, we mean that a star that's moving away from us has its characteristic light print frequencies of all the elements in that star that are glowing and emitting electromagnetic energy as light is moving away, those frequencies are shifted below what they would be measured to be in the laboratory. Of course, there could be some other, totally different explanation for this, and then all of this would be messed up. But that's what the redshift of light represents.

An astronomer named Wiley Slipher had noticed this sometime in the 1910s and had published a number of observations about this, but somehow it didn't really catch on; although I mentioned in the last lecture that the Dutch physicist Willem de Sitter knew about these redshift measurements and tried to incorporate them in his own version of Einstein's general theory of relativity. What Hubble did was to do hundreds and then thousands of these redshift measurements, and came up with: everything is moving away from us, which means that the universe is expanding.

Now we have a totally different kind of a universe. A universe which is not just vastly larger than we had thought, because it's got thousands and thousands, and we now say billions, of galaxies, each of which is made up on average of approximately a hundred billion stars. Not just vast in that sense, but it's expanding, and apparently endlessly. But worse than that, if it's expanding, then that suggests that at one point it was not. It was a point. There was an origin—a beginning in time to the universe.

If everything is expanding away from us in a spherically symmetrical way, which is what it looks like from the earth, then there must have been a time when the universe was at an atomic point, a material point—not a geometric point—but all the matter in the universe was together in one place. And so it is a kind of a natural step to suspect that there was a Big Bang. It was also a natural step for many more theologically inclined physicists to think in terms of an act of Creation. This vindicates the act of Creation.

So now we have two lines that we need to follow here. First of all, the new universe continued to be redefined throughout the 20th century at one level; namely, what's in the universe? We had simply tacitly assumed that the universe was the stuff that we could see, let's call it stars and galaxies and nebulae, and we're redefining it in terms of how many and so on. But in the 1930s we began to take seriously that there were invisible things in the universe that we had not paid attention to.

In the mid-1930s radio astronomy was founded accidentally by a couple of electrical engineers, Karl Jansky and a collaborator of his, who were working for the telephone company, and who accidentally discovered electromagnetic radiation coming first from the sun and then from other parts of the sky, and that launched radio telescopy. There is a lot of invisible stuff out there that is revealed to us only through radio telescopes that the eye can't see, including clouds of molecules that absorb photons and then radiate them at frequencies that we don't respond to visually. But now we discovered that space is loaded with molecules, including the ingredients of quite complex organic molecules. OH- is a water that's missing one hydrogen. There are clouds of this stuff distributed throughout space. Cosmic rays were discovered and were understood to be another invisible aspect of the universe. And X-rays, and gamma rays, and neutrinos, which came out of 1930s nuclear physics, were discovered to be flooding the earth, and we now have neutrino telescopes. We also have a gravity wave telescope.

In 1980 came questions having to do with the stability of galaxies. We now had sufficient information to recognize that galaxies, especially spiral galaxies, should not be as stable as they clearly are, and that led to postulating the existence of something called dark matter, which made up the bulk of the matter in the universe. It's matter that doesn't interact with ordinary matter except gravitationally, but it makes up most of the stuff that's out there.

Then in 1998 it was necessary to postulate the existence of dark energy, as it's called, and which has again been experimentally supported multiple times by further observations in order to explain certain kinds of supernovas. It turns out that Einstein's original formulation of gravitational field equations were correct, and the universe is dynamic and expanding. And it's not only expanding, but the rate of expansion is increasing. The expansion is accelerating.

We thought that the universe was going to start contracting at some point, or at least reach some stable point and not do anything, but it turns out that the expansion is accelerating. Dark energy and dark matter together now constitute about 96–97 percent of the universe, which means that the whole thing that we used to call the universe, even in its incredibly expanded form with billions of galaxies and trillions of stars, is only a minute portion of what the universe really is. And that's not all, because in the same year that dark matter was postulated in order to explain the stability of spiral galaxies, a physicist named Alan Guth postulated the inflationary theory of the universe, which is today as close as you can come to a standard view of the universe among physicists who deal in astrophysics and cosmology.

But in order to appreciate the inflationary theory I want to step back a bit and go back to what I said was one aspect of the universe that we need to consider, it is this question of, did it have a beginning in time? Which religious physicists and theologians jumped on in the 1930s as evidence that they were right, that the Bible was right, that in the beginning God created the heavens and the earth.

In the late 1940s—the idea had been floated earlier—but in the late 1940s George Gamow and a number of collaborators published a series of papers arguing that in fact this was the case. That all the matter in the universe had once been contracted into a single gigantic atom which was unstable and exploded, and led to the expanding universe, and the formulation of all of the stars and galaxies and planets and all of the elements, etc.

In these papers, Gamow and his colleagues predicted that there should be a remnant of this explosion in the form of background radiation that uniformly fills the universe, and that this radiation would now, because it's been cooling for so many years (the figure we accept today is 13.7 billion years—in those days it was somewhere between 10 and 20 billion), the frequency of this radiation is now in the microwave range. So they predicted what is called the microwave background radiation, but in fact not a lot of people took this very seriously, in part because there was a rival theory that said there is no such thing as a beginning. You start talking about a beginning, and you're going to get into religion. The universe is eternal. It's expanding; it's been expanding eternally.

If it's expanding eternally, how come the universe hasn't thinned out? Well, there is something called a creation field. Atoms of hydrogen pop out of the vacuum, consistent with quantum theory, just at the rate necessary to keep the density of the universe on a large scale constant. It's continually expanding and it looks pretty much the same way. This is called the steady state theory of the universe, and the lead figure in this was a British astronomer and physicist named Fred Hoyle, whose collaborators were Hermann Bondi and Thomas Gold. They made fun of Gamow's theory, and they gave it the name Big Bang as if to make fun of it, but that's the name that stuck.

The problem that both theories had was that nobody could understand how you could build up the elements from hydrogen. You can go from hydrogen to helium in the sun—we understood that, hydrogen and helium. How do you get past lithium, and build up the heavier elements? What process would explain that? It's called the nucleosynthesis problem. Both theories suffer from this problem.

In the 1950s and '60s, up till about 1963, the steady state theory had the lead among physicists and astronomers, I think because nobody wanted to deal with the problem of an absolute beginning to the universe. Hoyle came to Caltech and made friends with some young physicists, William Fowler and Margaret and Geoffrey Burbidge, and put them onto this nucleosynthesis problem. They solved that problem. By the early 1960s, that problem was solved, and they got the Nobel Prize for it. For various reasons Hoyle was not included.

In the early 1960s the nucleosynthesis problem was solved and it looked as though that would support the steady state theory of the universe, in spite of this bizarre creation field, because after all physicists were used to bizarre things at that time. But then all of a sudden the microwave background radiation was discovered, again by Bell Lab engineers, who were doing experiments in order to prepare for the first communications satellites and discovered this background hiss which turned out to have pretty close to the frequency that had been predicted by Gamow and his partners. Now all of a sudden the Big Bang theory was in, and has been in ever since.

By 1980, quantum theory, having been applied to solve the nucleosynthesis problem, was firmly part of cosmology. One of the problems that the Big Bang theory together with quantum theory should have resolved was the existence of something called magnetic monopoles—like the magnetic analogue of a positive charge. All of our magnets have two poles, north and south, and you can't cut it in half and get the northern half here and the southern half here. Every magnet has a north–south pole, but a magnetic monopole would be just one of those, and in principle, they should exist.

This young physicist, Alan Guth, was wrestling with this problem, and in 1980 proposed an incredible solution, not just to the magnetic monopole problem, but reformulated the whole Big Bang: which is that the universe popped out of the quantum vacuum, which was unstable in a particular way that quantum theory allows (he didn't invent that idea; that was invented by physicists before him. But at a certain point, 10^{-35} seconds after the universe popped into existence, when it was about large enough to hold in your hand or maybe put in your pocket, it went through what's called an inflation. It increased in size by 2^{100} effectively instantaneously.

Now, this inflation is reflected in the distribution of the microwave background radiation and the distribution of galaxies. It turns out that it does actually work for those purposes, broadly speaking; but what it implies is that the entire thing that we call the universe, with the dark matter, with the dark energy—everything—is a minute fraction of the total entity that inflated. The real universe is vastly, vastly larger than we can imagine, and it is out of communication with us. We cannot interact with it. Everything that we call the universe, even in the most expanded sense of 20th century physics, is a tiny patch on the real universe. In a certain sense, more than that. The attempt to unify gravity with quantum theory has led to what's called string theory, and we'll be talking about that in the final lecture. But one aspect of string theory is that our universe is one valley in a landscape of at least 10^{500} possible contemporary parallel universes. So we're really nothing, nowhere.

Lecture Thirty-Two
The Idea Behind the Computer

Scope:

J. David Bolter introduced the idea of a "defining technology" of an era or a society: for example, the mechanical clock, the steam engine, electricity, and the automobile. The computer is a defining technology today, yet in spite of computers being ubiquitous, the idea underlying the computer and giving it its power is not widely appreciated. The modern electronic digital computer has roots in the pursuit of increasingly powerful automatic arithmetic calculators and algebraic problem-solvers and in the design of automated information tabulation. But the modern computer is not a calculator or a tabulator. The idea underlying the computer derives from the solution by Alan Turing of a highly abstract problem in the foundations of mathematics. Turing imagined a machine that could solve any problem whose solution could be specified by a finite decision procedure, or algorithm. Turing and, independently, John von Neumann recognized that emerging new calculators could be reconceived as generalized problem-solving machines, even artificially intelligent machines.

Outline

I. The computer is the "defining technology" of our era, though *semiconductor-based microelectronics technologies* would be a more accurate term.

- **A.** The computer is ubiquitous today, but just what is a computer and what is the idea of the computer?
  - **1.** Through World War II, *computer* was a job description for someone hired to compute, to make calculations.
  - **2.** Scientists, mathematicians, and users of mathematics in commerce, industry, and the military require the results of vast numbers of tedious, repetitive calculations.
  - **3.** The expense, time, and error-rich character of producing these results provoked Charles Babbage to invent his Difference Engine in 1822 to produce them automatically.
  - **4.** While attempting to build a prototype Difference Engine, Babbage designed his Analytical Engine, a programmable, stored-memory calculator that could solve a much wider range of mathematical problems.
  - **5.** Neither engine was built, but the latter is often called the forerunner of what we mean by *computer*.
- **B.** The increasing size and complexity of 19th-century businesses also increased the volume of "number crunching" routinely required to manage businesses effectively.
  - **1.** Mechanical calculators became widespread in the course of the century, beginning with the Arithmometer, based on Leibniz's design and, from 1887, keyboard entry machines such as those offered by Burroughs.
  - **2.** Adding machines became ubiquitous, but the demand for more numbers fed on itself.
  - **3.** In the 1930s, *super-calculators* appeared as military, industrial, commercial, and research needs outran the effectiveness of both human computers and arithmetic calculators.
  - **4.** In 1936, Konrad Zuse applied for a patent on a programmable, stored-memory, stored-program, binary-base and floating-point arithmetic automatic calculator using mechanical relays and built a series of functional machines: the Z1, Z3, and Z4.
  - **5.** Concurrently and independently, George Stibitz at Bell Labs and Howard Aiken at Harvard (with major funding from IBM) designed and built electromechanical, relay-based, programmable super-calculators.

II. The demand for calculation drove the mechanization of arithmetic operations, but calculators are *not* defining-technology computers.

- **A.** Calculator technology surely would have followed a path of development analogous to that followed by the "true" computer.
  - **1.** Electromechanical machines, however massive, are slow and limited, and the switch to electronic technology had already begun before World War II.
  - **2.** With the invention of the transistor in 1947, totally independently of calculators and computers, calculators migrated to semiconductor technology.
  - **3.** This put them on the path to become ever smaller, more powerful, and cheaper devices.
- **B.** Through the convergence of quite independent lines of development, the "true" computer emerged.
  - **1.** Between 1927 and 1942, Vannevar Bush was involved in the design and construction of a series of "analog computers" for solving engineering problems posed by the electrical power system.
  - **2.** His 1931 Differential Analyzer was especially successful and influential, both in the United States and England.
  - **3.** John Atanasoff and Clifford Berry, impressed by Bush's machine, built a digital, *electronic* computer to solve large numbers of simultaneous linear algebraic equations, a very important problem-solving capability for science and engineering.
  - **4.** This machine used 300 vacuum tubes, was programmable, had storage capability (using condensers), used binary and floating-point arithmetic, and had an automatic printer.
  - **5.** In 1943, John Mauchly and John Eckert, familiar with the Atanasoff and Berry computer, received funding to build ENIAC, initially to produce ballistics tables for the military, but soon perceived to be a general-purpose mathematical problem-solver.
  - **6.** ENIAC was a colossus, 100 feet long with 18,000 vacuum tubes and drawing 100 kilowatts of electrical power, and it was successful, though only operational after the war was over.

III. ENIAC was a watershed machine, dividing calculating from information processing.

- **A.** The crucial piece in the story of the true computer begins with an esoteric piece of abstract mathematics.
  - **1.** In the mid-1930s, Alan Turing solved an important problem in the foundations of mathematics that had been set by David Hilbert in 1900.
  - **2.** Turing proved that the problem could not be solved, that there could be no finite, "mechanical" decision process that would guarantee the correct solution of all mathematical problems.
  - **3.** A byproduct of this proof was a machine Turing imagined that *could*, in a finite number of steps, solve any problem for which such a decision process, an *algorithm* as it came to be called, *could* be specified.
  - **4.** Turing spent a year at Princeton, where he met John von Neumann, head of the new Institute for Advanced Studies.
  - **5.** As a wartime consultant to the U.S. government, von Neumann coincidentally learned of the ENIAC project and recognized the potential for an electronic digital computer to be such a Turing machine.
  - **6.** He began the design of EDVAC, an enhanced ENIAC, in 1943 and built it at Princeton in 1948.
  - **7.** This was a realization of Turing's imagined machine in electronic form, and von Neumann laid down the basic rules for designing and programming general-purpose problem-solving computers that remain dominant.
- **B.** The evolution of the computer has been enabled by the coordinate evolution of microelectronics

technologies, especially silicon semiconductor technologies.

1. The integrated circuit was developed independently in 1958 by Jack Kilby and by Robert Noyce, and the silicon chip evolved out of that initially crude device.
2. In 1965, Gordon Moore observed that the number of transistors on a single silicon chip seemed to be doubling every year, implying that by 1975, this number would reach 64,000, which he thought likely.
3. Today, there are about a billion transistors on a single chip, just about keeping up with Moore's "law" (which is not a law of nature at all, of course), but in the near future, current technology will be undermined by quantum effects as chip features approach atomic dimensions.
4. The importance of this continual increase in the number of transistors on a chip lies in the increasing speed with which that chip can execute the instructions it is given.

C. Here, finally, is the essence of the computer as the defining technology of our age.

1. The computer is not a calculator but a universal *simulator*.
2. Nothing that goes on inside the logic or memory circuits of computer chips corresponds to anything whatsoever of interest to us, not even arithmetic calculations.
3. When a computer actually is used to make calculations, that, too, is a simulation.
4. What goes on inside computer chips is as follows: Some combination of high- or low-voltage electrical signals on the input pins of the chip package are transformed into a different combination of high- or low-voltage signals on the output pins of the package in accordance with a set of transformation rules that are wired into that chip.

D. Everything useful a computer does—calculation, word processing, running video games, *everything*—is a simulation based on software.

1. A computer program is a systematic correlation of the electrical signal transformation rules wired into a chip with something meaningful to us: music, video, letters on a screen, and so on.
2. Every program is an algorithm, a set of instructions that completely specifies a finite set of electrical signal transformations that have a symbolic interpretation given by the program.
3. The power of the computer lies in its ability, foreseen by Turing, to generate what its user can interpret as a solution to any problem for which the user can provide such an algorithm.
4. Behind the power of the idea of universal simulation lies another powerful scientific idea: information.

Essential Reading:

Andrew Hodges, *Alan Turing: The Enigma*.

Paul Ceruzzi, *A History of Modern Computing*.

Questions to Consider:

1. Is the substitution of simulation for reality a threat to our humanity?
2. What are the implications of the total artificiality of computer *science*?

Lecture Thirty-Two
The Idea Behind the Computer

Jay David Bolter wrote a very nice book quite a while ago when computers were still novel in which he referred to the computer as the defining technology of our age; presciently, since this was written in the late 1970s. And it is, although perhaps it would be more accurate to say that the defining technology of our age is semiconductor-based microelectronics technologies. That is a mouthful and very antiseptic sounding.

It is more dramatic and not incorrect to say it's the computer, because the computer is the most potent and dramatic manifestation of semiconductor-based microelectronics technologies insofar as we're talking about a technology that has really changed the world. There is a relationship here, I think, between an earlier lecture in which I talked about the industrial revolution of the 12th century, which was based on gear train technologies—harnessing wind and water power through gear trains that allowed that power to be applied to machinery of all kinds and industrial processes of all kinds. Nevertheless, historians treat the clock, which is only one instance of gear train technology, as the defining technology of the late Middle Ages and the Renaissance and early modern period. So, analogously, I think we can say that the computer is the defining technology of our age, understanding that power of the computer comes from the extraordinary continuing increase in the power of semiconductor-based microelectronics technologies.

But what is the computer? What is the computer, and especially from our purposes in this lecture, what is the idea underlying the machine that gives the machine its power to be such a force in reshaping life? I would say through World War II the term "computer" was a job description term. I mentioned in the last lecture that Henrietta Swan-Leavitt was a computer. She was one of a number of computers, all of them women I believe, who worked at Harvard Astronomical Observatory, and at astronomical observatories around the country, which were well enough supported to afford computers. That's who did the computing.

But throughout society there were people who made their living doing calculations because, especially in the 19th and early 20th centuries, the needs of scientists, mathematicians, the military, and increasingly in the 19th century, industry for the results of huge numbers of calculations continued to grow. And so one use of the term computer, which we no longer use, and we've lost track of the fact that there was once a subculture within society of people who made their living making calculations, the computer is a job description. But having said what I just said, it is more accurate to now focus on a phenomenon that emerged in the 19th century, pulled by the demand for calculations that I just referred to, and that is mechanical or automated calculation.

It was in the 19th century that we start seeing an industry, a very successful industry, that disseminated mechanical calculators into society with a point to routinizing and, of course, saving money over human computers, and increasing the efficiency of making all of the kinds of calculations that businesses, the new business models, the tremendous increase in the scale of business, the new sophistication of engineering which requires huge numbers of calculations, and I mentioned scientific researchers and the military, which needs tremendous numbers of calculations for things like calculating the trajectory of canon shells and naval guns, etc. So mechanical calculators became an industry.

The first generation of these mechanical calculators, in the early 1800s, actually picked up on the design of Leibniz for a four-function calculator. The four functions are the arithmetic functions of addition, subtraction, multiplication, and division. This, sort of, is the basic mechanical calculator, sometimes called an adding machine, of the 19th and early 20th centuries, and in the course of the century Leibniz's design was commercialized in a number of different forms. Leibniz's design was based on entering numbers by rotating gear combinations, toothed gears that were designed and interconnected in various ways to represent entering numbers, and then when you rotated the dials you got the result of the addition or the multiplication.

There were other designs that were implemented commercially for patent reasons, for example, and because people thought they were better. By the end of the 19th century, after the typewriter was invented, adding machines had keyboards (initially they didn't have keyboards; you had to actually physically manipulate the gears, or pins in pin-driven calculators), but by the end of the 19th century you had electrically operated mechanical calculators with keyboard entry. This was very helpful, but it was still limited to arithmetic calculation.

Earlier in the 19th century Charles Babbage, a British polymath, but a mathematician, I guess, primarily, although a very important figure in British science in the middle of the 19th century, Babbage had this grand vision for an automated calculating machine that would reduce, in fact he thought it would eliminate, the very large number of errors that crept into the calculations done by human beings and the printed versions of those calculations.

Now this is something that the average citizen who is not an engineer or a scientist does not often get to see, but there are, especially in the 19th century, there continued to be, as there had been for a hundred or so years before that, gigantic volumes which were nothing more than hundreds and hundreds of pages of logarithms, values of logarithms. Logarithms, which were invented in the 17th century, become a crucial way of speeding up mathematical calculations by reducing multiplication to addition, and division to subtraction. In order to use logarithms you have to know what the value of the logarithm is to multiple decimal places for every particular value of the numbers that you're using in your own calculations.

We don't need to get any further into it than that. Sufficient to say that if you were a scientist, an engineer, or in the military, you needed access to these tables of logarithms, and there were a tremendous number of errors. There were errors in the human side. There were also errors in the printing, entering those values into the printing presses, so that these were published, together with volumes that corrected the values that had been published either in the current version or in earlier versions. So Babbage said, "This is ridiculous," and everybody agreed it was ridiculous. What are you going to do about it?

Babbage envisioned an engine, which he called a difference engine, that would be able to make complicated arithmetic or simple algebraic calculations repetitively, automatically, with a printer attached to it so that it would be printed out automatically, and there would be no more errors. The calculations would be much quicker and they would be error-free. He designed this machine in meticulous detail, convinced the British government to fund its construction, but it turned out this was in fact something that is called by almost all historians of computers the first computer—at least in principle; because it turned out that the building of it, since it was mechanical and based on gear trains, it could not be made using the machining technology of the 19th century, and the materials necessary in order to have the gears that had very peculiar curves to them in order to make the calculations that he promised to make. So after spending probably the equivalent of millions of dollars today, the British government lost patience—this machine was never going to get built—and cancelled the contract, and what we have left are the drawings.

By that time Babbage had lost interest in that machine anyway, because he had come up with a vision of an even more powerful automatic calculating machine, which he called the analytical engine, meaning the algebraic engine. Forget just arithmetic problems, this could solve a certain class of algebraic equations, and this was a machine that had a memory, that was programmable and that had a printer attached to it. You would plug in the calculations, the equations that you wanted and the values for the variables, and then it would print out the solutions to those equations.

Again, this machine was never built. However, the meticulous drawings, which are in themselves beautiful, do exist, and over the last 20 or 30 years various groups of enthusiasts have built parts of the machine to see if they would work, and they do. They are quite lovely examples of 19th century technology, which in fact could only be made using late 20th century technology, but they look awesome and you realize that this machine would have worked if in fact it had been constructed. This is always called the beginning of computing; but I don't agree.

I think what we see here is another step in calculators. This is an automatic calculator. It computes in the sense that that's what calculation was called then. That's why human calculators were called computers. So this is a computer in the sense of being a calculator, but computers as the defining technology of late 20^{th} century, early 21^{st} century life are not calculators. They are much more than calculators.

The history of increasingly sophisticated calculators really picks up in the 1920s and '30s, in particular in the 1930s when, without any specific reference to Babbage's machine, in Germany and the United States very sophisticated calculators were designed. In 1936 a young German engineer named Konrad Zuse applied for a patent for an electromechanical computer that was essentially a very sophisticated calculator that used binary arithmetic. It used what's called floating point arithmetic in order to deal with very large numbers in a compact way. And it had the capacity for a stored program, in the patent application.

In fact the machines that he built didn't have all of these features, especially not the stored memory part, but they were programmable. They did use binary bits, and they did have floating point arithmetic. He went to work for the Henschel plane manufacturing company in Germany during World War II, and his initial version, which he built in his parents' home—the Z1—he scaled up to something called the Z3 machine, which he used during the war to speed up the calculations. He was working as an aeronautical engineer.

Then during the war he designed and built a Z4 machine, which was actually much more sophisticated, but still electromechanical. That machine was completed, snuck out of Germany, and wound up in Switzerland, and until about 1960 worked in a Swiss bank doing routine calculations in the bank. So Zuse has a firm place in the history of computers at the level of calculation.

Concurrently, and quite independently in the United States, Howard Aiken in Harvard University, supported very substantially by IBM in the 1930s, built the first of a series of giant electromechanical calculators. George Stibitz, who was an engineer at Bell Labs, also built a very sophisticated calculator based on telephone switching equipment that was also electromechanical.

Electromechanical calculators are not going anywhere. They're much too slow and they are enormous. These machines weighed many tons and occupied a tremendous amount of floor space. They were in a certain sense much too hopelessly complicated to use intensively on a routine basis, but they worked.

Much more interesting, from the point of view of the history of the computer as a defining technology, are the following events. In the second half of the 1930s two physicists at Iowa State University, John Atanasoff and Clifford Berry, collaborated on building a vacuum tube, a 300 vacuum tube computer, an electronic calculator that solved a certain class of algebraic equations, and that had a memory (using condensers). It had an automatic printer attached to it and it was programmable. So here we have all of the features of a computer, but it is in fact a calculator. They built this machine in the late 1930s. They used it a bit at the University of Iowa in their laboratory to solve these equations. It could solve a series of what's called linear algebraic equations. So if you have up to 10 equations with 10 variables, and they are so-called linear equations—relatively simple but very important for engineering calculations and many scientific calculations—this machine could actually solve them. And it worked.

They were inspired to build this machine by an analog computer that Vannevar Bush had built at MIT and which John Atanasoff was familiar with, which solved a very sophisticated problem in electrical engineering having to do with electrical circuit networks, complex electrical circuits, especially linking multiple utilities together so that electricity could flow from one utility to another. It's called an interconnect. Inspired by that analog computer—which had no vacuum tubes—Atanasoff and Berry built their vacuum tube computer, which was studied by John Mauchly and John Eckert in the early 1940s when they got a contract to build for the U.S. Army the machine that we came to know and love as ENIAC, which was an electronic calculator of a formidable sort; this time with something on the order of 18,000 vacuum tubes. Imagine the electrical power that it used and the heat that it generated, not to mention the failure rate of the tubes.

At least one of them (I believe it was Mauchly) went to Berry's laboratory and saw the ABC—the Atanasoff-Berry Computer—and then came back to the University of Pennsylvania where they had this contract to build ENIAC for the Army, and designed and built ENIAC. Atanasoff did not patent his computer—in fact, when the war started and he was redirected onto wartime-related research, he seems to have lost interest in it. Subsequently, Mauchly and Eckert founded a computer company after World War II and wanted to patent the computer. After a bitter and protracted lawsuit—which was fought out by the Sperry Corporation, which had sort of gobbled up various companies that Mauchly and Eckert had founded, a very bitter lawsuit—they were denied a patent on the ground that the computer technology that was in ENIAC and its successors was already in the public domain because Atanasoff and Berry had shared their knowledge with Mauchly and Eckert, and they had not patented it.

It is not clear how much Mauchly and Eckert learned from Atanasoff and Berry. But they certainly learned something, especially the idea that you could actually use an electronic computer with memory, that was programmable, that was binary, that used floating point arithmetic, to solve algebraic equations. ENIAC was a colossal calculator. ENIAC was a physically gigantic calculator, but while it was much faster than an electromechanical relay operated computer calculator, it was still used as a calculator.

What is interesting about ENIAC as a watershed machine in the history of what I believe we really mean by the computer is, again, sort of an instance of circumstance. Here we begin to get at the idea of the computer. Completely independently of all of this stuff about calculators, of the building of more and more sophisticated calculators, which are often called computers because calculating is called computing—but it's not what we mean by the term computer—in the mid-1930s a British mathematician named Alan Turing addressed a deep foundational problem in mathematics that had been posed at the turn of the century by one of the greatest mathematicians of the 20th century.

Hilbert, at a conference of mathematicians in Paris in 1900, had posed a set of problems which became sort of the gold prize of mathematics to solve these problems of Hilbert's. One of them had to do with showing that there was a decision procedure that would guarantee the solution of any mathematical problem. That from a logical point of view, you might not know the solution but you could guarantee that every mathematical problem, because it was really a problem in logic (which was Hilbert's view of mathematics), that mathematics could be formalized in a logical way (he was not exactly a logicist; he was a formalist).

He believed that mathematical reasoning, that same sort of deductive mathematical reasoning whose influence we've been tracking since ancient Greece, was an example of formal reasoning from various kinds of principles. Given the principles that we use in arithmetic and geometry, that all problems in arithmetic, for starters, have a decision procedure. Well, what Turing proved was that this was not the case. That there was no such decision procedure, and he proved that it was not possible to have a decision procedure that if you stepped through that procedure would guarantee the solution of any problem in arithmetic. In the course of generating that proof, Turing imagined a very simple machine that would embody such a decision procedure, and he showed that, in the case of arithmetic, the machine would have to be infinite in order to work.

A byproduct of his solution, a secondary consequence, was that he said, well, but of course any problem for which you *can* specify a decision procedure—if you have a problem and you know that the problem has a decision procedure that if you step through all of these steps, the problem would be solved, could be solved by this idealized machine—which is extremely simple in Turing's formulation of it, and of course would take forever to do it. It would take so long to do it that it would be ridiculous—but the idea is that it's possible to design a machine that would sequentially step through a series of instructions and would solve any problem that you could provide this decision procedure for. We now call that an algorithm—a set of instructions that if you follow the instructions will guarantee that the problem will be solved. It's sort of like instructions for buying something from IKEA, and then if you follow these instructions it will stay together when you erect it. The algorithm is a very important concept here.

Now, Turing went to the United States and spent some time studying at Princeton University. There he met, and interacted with, and shared ideas with a number of leading American logicians, but in particular the director of the newly created Institute for Advanced Study at Princeton, John von Neumann, a brilliant Hungarian mathematician, mathematical physicist, mathematical logician. Von Neumann was brilliant at just about everything that he touched, and von Neumann became a very important advisor to the U.S. government on virtually every problem involving science during World War II, including the atomic bomb project, of course. On one of his trips to Washington he met Mauchly, who was going back to Pennsylvania from Washington, and Mauchly told him about the ENIAC project.

Von Neumann recognized that while these people were building ENIAC, which was functioning as a gigantic calculator, such an electronic machine could be an incarnation of Turing's idea for a machine that would solve any problem for which a decision procedure could be specified. This was in 1943. In 1943, while ENIAC was under construction—eventually it was built and it worked, but by the time that it was operational the war was over and so it did not actually provide the calculations that the military was looking for during the war—he designed a machine that was called EDVAC that would be an incarnation of Turing's idea for a universal problem-solving machine as long as the problem has an algorithm for its solution.

In 1948 at Princeton, von Neumann's design for EDVAC was realized, and EDVAC was built and became the prototype of the next 40-some-odd years of computers. Except for those machines that are based on what is called a neural network principle, computers have what is called von Neumann architecture. They follow the rules that von Neumann laid down for sequential processing. Because electronics allows much more rapid calculations, because the individual steps that the machine has to step through in order to run through the algorithm, the instructions that it's given, that's what made the EDVAC style machine capable of solving the problems that Alan Turing had sketched out. Because Turing's machine in its conceptual form was hopelessly slow; it would have taken forever to make a simple calculation. Whereas, if it was an electronics technology, it becomes speedy enough that you can actually use the machine.

Now what happens with the development of microelectronics technologies since 1948 was, first of all, the invention of the transistor, quite independently of the computer—it had nothing whatsoever to do with the computer; it was invented in the course of exploring, at Bell Labs, certain consequences of quantum mechanics having to do with the behavior of electrons in these weird substances called semiconductors—the invention of the transistor at Bell Labs in the late 1940s, the decision of Bell Labs not to restrict the dissemination of transistor technology to the public by patenting it and demanding royalties, sort of allowing it out in the public domain. Although the people who invented it subsequently got the Nobel Prize for it, and at least one of them founded a company to manufacture transistors commercially, the transistor technology was given, essentially, to the public. The development of transistor technology from the early 1950s, especially when there was a switch to silicon as the basis for the transistors, that is what generated, so to speak, that provided the material engine for the increasing speed with which the algorithms, the instruction set that computers are given, can be stepped through. The complexity of the machine was increased with the shrinking of the size of transistors, and their integration into logic circuits, that allowed the machine to emulate what we would call the basic rules of logical human reasoning electrically.

So the first integrated circuit was invented more or less independently in 1958, and by 1965 the number of transistors in a single integrated circuit was increasing at such a rapid rate that an engineer named Gordon Moore predicted that it looks to him as though the number of transistors on a single integrated circuit is doubling every year, which means that by the mid-1970s there would be about 64,000 transistors on a single integrated circuit (what we now call a silicon chip). That turned out to be correct. Now, in fact, today we're up to about a billion transistors on a single chip, and that's pretty much still in keeping with Moore's law, as it's called. It's not a law of course; it's just an empirical observation. But we're running into atomic dimensions that make it look as though that rate of increase cannot continue for very much longer—maybe another 10 years or so.

So what is wonderful about the technology is that it speeds up the process of following the instruction set that is fed into the computer. It was this conceptualization of the computer that is what gives the computer its power, but let me point out what is this conceptualization. I think the power of the computer lies in that it is a universal simulator. It’s not a calculator. There is nothing that goes on in the computer that corresponds to anything that we’re interested in.

What goes on in the computer is that the processing chip of the computer is matching high and low voltage inputs—high input, low input—and combining them in various ways as the output of the chip. And then transmitting, shipping the result of manipulating a high input and a low input in various ways that have been built into the hardware, to equipment that then does something with that. Now what it does with it depends on the instructions that you give the computer. It could be a word processor. It could be a spreadsheet device. It could be a video game.

As long as you have an algorithm then the computer will do anything; but everything the computer does is to simulate the solution to your problem. You have to convert your problem into a form that the computer chip can process, and then it gives you back the output in the form that you’ve instructed it to simulate. So it is powerful because it is a simulating machine, and it is universal because it can solve any problem that you can give an algorithm (a rule) for solving. That can be telling it to design animations for a movie, or asking it to calculate numbers. But that is just using the computer as a calculator.

Now, the circuitry of the computer, the logic circuits in the computer are incarnations of another powerful idea, a powerful idea that also appeared in 1948; and that is the idea of information, and we will be addressing that idea in the next lecture.

Lecture Thirty-Three
Three Faces of Information

Scope:

The 19th-century attribution of physical reality to patterns and relationships challenged the dominant view that the real was substantial. The idea that information structures, too, are physically real extends this challenge. Computers and the Internet have initiated a continuing explosion in content available "online"; this content explosion is real and affects communication, as well as the conduct of scientific research, commerce, and politics worldwide. But content is not the most fundamental sense in which we live in an information age. Claude Shannon's post–World War II, content-independent mathematical theory of information made information a feature of physical reality. This apparently abstract theory has become the foundation of powerful information technologies that continue to change the world. Concurrently, the idea that DNA encodes the "secret" of life in a base-sequence information structure and the idea that black holes and even the Universe itself may be information structures have reinforced the physical reality of information.

Outline

I. We may well live in an information age, but few people realize how many different meanings *information* has.

- **A.** The most familiar meaning of *information* is related to content.
  - **1.** It is useful to distinguish information from data, on the one hand, and from knowledge, on the other.
  - **2.** Although they are reciprocally correlated, information can be understood as organized data, while knowledge is interpreted information.
  - **3.** This is not a hierarchical relation, because it is typically the case that data and their organization are informed by ideas, for example, ideas of what kinds of data and what forms of organization are likely to prove valuable.
- **B.** More information is available to more people than ever before, but this is not attributable only to the computer.
  - **1.** The dissemination of more books to more people as the literacy rate increased was already a fact of 19th-century life.
  - **2.** At the same time, mass-circulation newspapers and, by the end of the century, magazines created an information problem.
  - **3.** By the late 20th century—with the telephone, radio, and television in addition to books, newspapers, and magazines—not even scholars could keep up with their disciplines.
- **C.** The Internet exacerbated an existing problem; it didn't create the problem.
  - **1.** The idea that motivated the creation of the Internet was to give computer users direct, real-time access to files stored on other computers.
  - **2.** The search engine Mosaic and the World Wide Web unintentionally accelerated the process of consumerizing and commercializing what had been a network oriented toward the computer community.
  - **3.** This was reinforced by the creation of Netscape, Yahoo, AOL, and Google and the evolution of global interactive video games and virtual communities.

II. At the opposite pole from this everyday, familiar notion of information is a counterintuitive, mathematical conception of information that is the cornerstone of both computer and communication technologies.

A. In 1948, Claude Shannon published an epochal paper, "The Mathematical Theory of Communication."

1. Shannon was a mathematician at Bell Labs who had received degrees in electrical engineering and mathematics from MIT.
2. As a graduate student, he had worked on, and been impressed by, Vannevar Bush's Differential Analyzer.
3. His master degree thesis, "A Symbolic Analysis of Relay and Switching Circuits," explored the relationship between Boole's algebra of reasoning and digital telephone switching circuits.
4. Aware of Shannon's evolving ideas about information, Bush urged him to apply them to Mendelian genetics, leading to his doctoral dissertation, "An Algebra for Theoretical Genetics."
5. At Bell Labs during World War II, Shannon developed probability-theory–based tools for predictive antiaircraft fire control systems, modeling intelligence as signal processing.
6. Shannon's Ph.D. thesis brought him to the attention of Warren Weaver, with whom he co-authored *The Mathematical Theory of Communication* in 1948.

B. Shannon's theory strips information of meaning and connects it to thermodynamics.

1. *Information* is defined in terms of uncertainty, such that the greater the uncertainty, the greater the measure of information; information is treated as a statistical difference between what is known and what is unknown.
2. This implies that knowing the content of a message means the message is totally uninformative!
3. Shannon's problem was how an automated receiver could distinguish an incoming signal from random noise.
4. The content of the signal was irrelevant: All that mattered was recognizing the presence of a signal being transmitted and accurately reproducing it.
5. Communication becomes a stochastic process and semantics is dismissed as irrelevant.

C. Shannon showed that his problem divided into three quasi-independent problems.

1. The source problem was defined by the nature of the signal being transmitted.
2. The channel problem was defined in terms of how the signal was encoded at one end and decoded at the other.
3. The receiver problem reduced to the accuracy with which the decoded signal could be reproduced.
4. The information content of a message reduced to the number of bits required to transmit it accurately, regardless of what it was about.
5. To model this process, Shannon adapted mathematical techniques developed by MIT professor Norbert Wiener, founder of cybernetics.
6. Surprisingly, the equation correlating information and uncertainty is identical in form to the equation relating entropy to temperature in thermodynamics.
7. This finding suggested that mathematically, information and entropy are related.

D. This highly technical, semantics-free interpretation of information has been astonishingly fertile in practical applications.

1. Shannon's theory underlies all fiber optic technologies. Cell phone electronics and software are also based on Shannon's theory, as are recording and reproduction technologies for music CDs and video DVDs.
2. Shannon argued that a digital/binary *bit* stream optimized encoding, decoding, and error detection and correction processes.
3. Shannon noted early on that information storage is really a form of delayed communication; thus, his theory underlies generations of evolving information-storage technologies.

4. Shannon's early work relating George Boole's laws of thought to telephone switching circuits led to designs for the logic circuits of digital computers that are built into the overwhelming majority of today's computer chips.
5. In the 1950s and 1960s, at least, Shannon and a Bell Labs colleague were said to have applied his mathematical models to gambling and the stock market with considerable success.

III. The commonsense understanding of our age as an information age and a Shannon-based understanding of information overlap inside technologies that surround us, and they intersect a third sense of *information* that is different from both.

A. Information—like fields, structure, and relationships—has been elevated to the status of an elementary feature of reality.

1. Consider, for example, the discovery of the genetic code.
2. In the 1930s, DNA was explicitly dismissed as the key to genetics, in spite of its universality, precisely because it was chemically the same in all life forms, always containing the same four bases in the same proportions.
3. In the wake of the Watson-Crick discovery of the molecular structure of DNA, George Gamow suggested that the key to the functionality of DNA lay in a code: the precise sequence of the four bases that bind the strands of the double helix.
4. It is not the bases that differentiate one life form from another but their sequence, which is, of course, an abstraction.
5. The sequence is physically real without being material in the most fundamental sense of scientific reality: causal efficacy.
6. The sequence defines the work that the DNA does in each cell of an organism, directing the production of proteins via RNA molecules, whose work is also defined by the parallel sequence of bases.
7. Furthermore, the information structures that define each life form work through the formal structures of the proteins for which the sequence codes.

B. Information structures appear as elementary realties in astrophysics and cosmology, not just molecular biology.

1. The theory of black holes uses information theory mathematics, which itself draws on the same mathematical rules that define entropy and thermodynamics.
2. Moreover, black holes can be understood as structures that *preserve* information—a conception of black holes that Stephen Hawking, after decades of dismissing it, now accepts.
3. This recognition has reinforced the *holographic principle*, which suggests that not only black holes but the entire Universe is an information structure.
4. As extended and developed by Russian mathematician Andrey Kolmogorov as well as Americans including Gregory Chaitin and Ray Solomonoff, Shannon's information theory has evolved into *algorithmic information theory*, in which physical objects are "reduced" to information representations.

Essential Reading:

Hans Christian von Baeyer, *Information: The New Language of Science*.

Charles Seife, *Decoding the Universe*.

Questions to Consider:

1. Is information really just another name for knowledge? If so and if information is physically real, is

knowledge also physically real?

2. In that case, what happens to the subjectivity-objectivity/mind-world distinctions?

Lecture Thirty-Three
Three Faces of Information

Thanks in large part to the computer, we live in an information age. The term *information* is somewhat like the term *time* as we discussed it with respect to Augustine. Augustine, you remember, said about time that if no one asks him what it is, of course he knows what it is. Everybody knows what time is. But as soon as someone asks him to be specific and tell me what is time, then it turns out that what he thought he knew is extraordinarily puzzling, and isn't what time is after all.

It's analogous with information. Everybody knows what information is, but if you try to be specific about it, and say, "Well, what do you mean by information?" then it turns out that the sense in which we live in an information age is not at all obvious. Let's begin by sort of bounding the term information and by distinguishing it from data on the one side and knowledge on the other side without getting into complicated definitions of data and knowledge.

Information seems to me to be usefully understood as organized data. So when data are organized, then the data become information. Knowledge is interpreted information. We interpret information in ways that we call knowledge. What's interesting for the moment is to note that the terms "organize" and "interpret"—information is organized data; knowledge is interpreted information—that the terms "organization" and "interpretation" are loaded terms. They are value-laden terms.

There are all kinds of assumptions that underlie any attempt to organize, any attempt to interpret. For example, it brings the taxonomy problem to bear. Is there a natural way of organizing data, or can data be organized in multiple different ways, all of which are valid depending on what your intentions are with respect to that data? Which organization is going to be useful, for example? If you have just unorganized lists of telephone numbers, names, and addresses, that's much less valuable than organizing that data alphabetically. So you have a telephone book, which is organized by persons' last names. But there are many more valuable ways of organizing the data in a telephone book, and thanks to the computer we've been able to explore many of those, for better and for worse.

So the terms "organize" and "interpret" remind us of a problem that we encountered very early in this course—the problem of how you're supposed to define terms. There is no natural definition, I said at that time, of terms like knowledge, truth, and reality, and there is no natural definition of information. The term is defined in various ways depending on what uses we want to make of that term, and the most common use that we make of it is tied to content.

We certainly think that we live in an information age because more information, in the sense of content, is available to more people than ever before, in spite of the fact that we continually think that while we're drowning in information, we are not being given the information that we really would want in order to make intelligent decisions politically, socially, and as consumers. We are overwhelmed by information, and in that sense we live in an information age—information as content—but this sense of information is not really the fault of the computer.

The dissemination of books, in the 19th century especially, mass circulation newspapers and magazines, the near-universal literacy, so that there's a huge market for newspapers, magazines, and then the telegraph and the telephone, and radio and television, all flooded us with information. To the point that even scholars who spend their lives in increasingly narrow fields of specialization find it literally impossible to keep up with all the publications in their field, let alone in all of the fields that they would like to be able to read in, or reading generally. It's effectively impossible, for example, for anyone to read all of the books in the philosophy of science, all of the articles published in the relevant journals in the philosophy of science, in the course of any given year. You have to exercise some discrimination in terms of what you're going to read.

Now the computer intensified this. The computer intensified what was already a centuries long process of what you might call a floodtide of information. It brought it to the level of maybe dysfunctionality in which we feel that there's no possibility of even attempting to experience all the different kinds of information that are available, especially through the Internet.

So the introduction of the Internet, right from the File Transfer Protocol, which is an early phase of the Internet before it had that name, allowed you to search the hard drives of other computers that you had access to so you could all of a sudden discover lots of information that was relevant to something that you were studying that had not yet reached print, or maybe would never reach print. The introduction of the great search engines from initially Mosaic and all the way down through Netscape to Yahoo and Google; and the creation of the World Wide Web by Tim Berners-Lee, altogether have made staggering quantities of textual, visual, and auditory information available to us. We are drowning in that.

But that's one sense in which we live in an information age. But if that were the only sense, it would be relatively trivial, and the computer would be an accessory after the fact. It would not be the real cause. It is in a much deeper sense of the term information, that people I think may find initially quite counterintuitive: We live in an information age in the sense that we live in an age in which information theory plays an increasingly powerful, prominent role in technological applications, and also intellectually, in science.

Information theory can be attributed to Claude Shannon, a man who was working at the time for Bell Labs. In 1948 he published an essay called "The Mathematical Theory of Communication," which later that year appeared as a book co-authored with Warren Weaver, who had been a very important director of the Natural Science Division of the Rockefeller Foundation in the 1930s. This is in some sense the founding document of information theory as it became a prominent factor in technology and science since 1948.

Shannon didn't invent this out of whole cloth. There were people who had been exploring a mathematical theory of communication, and information is the content of communication channels, after all. So a mathematical theory of communication existed before Shannon, but Shannon's work turned out to be epical.

He had been a student at MIT and he got his initial degree in electrical engineering. He did his masters degree on a symbolic analysis of relay and switching circuits, which was relevant to the work of AT&T, of course, using relays and switching circuits in order to direct telephone calls as people dialed them, which is what people did in the days when you had to dial a telephone number. As the dial rotated, it selectively closed various electrical circuits that activated relays that eventually settled on one particular circuit that was the number that you had dialed.

What Shannon showed was that using a mathematical model he developed, he could dramatically increase the efficiency of the use of relays by the telephone company. But part of his model was based on a familiarity he had with George Boole's *Laws of Thought.* I mentioned in the lecture on attributing reality to relationships the importance of symbolic logic—the rise of symbolic logic in the 19th century—and one of the figures I mentioned was the Englishman, George Boole, who formulated a logical version of *The Laws of Thought*. And even then, Charles Sanders Peirce—the American philosopher, scientist, and logician—noted that these laws of thought, these laws of human reasoning, the ways we use the logical connectives that were built into early symbolic logic, could be implemented in electrical circuits. So you could have electrical circuits that reasoned; that you could enter in the appropriate signals on the input side and what would come out would be the solution to problems of logical inference.

Without being influenced by Peirce, whose work I mentioned before was barely published in his own lifetime, Shannon went back to Boole's *Laws of Thought* and showed that you could use relays (telephone switches) to build circuits that simulated the laws of thought. You would set the input signals on the relays and out would come inferences based on "and," "or," "not," and "if then" logical relationships. So you could plug in a series of logical premises and out would come the calculation, the logical inference to be drawn from those premises. Of course, without the content; it's totally irrelevant, because as I've mentioned many times, the validity of a deductive argument is a function of its form, not of its content. If a deductive argument is valid, it's because of the relationship among the premises and between the premises and the conclusion, not because of what the argument happens to be about. That was something that Aristotle had already realized and became increasingly important when a symbolic notation for logic was invented in the 19th century.

Shannon, when he was at MIT, worked on Vannevar Bush's differential analyzer, and he was influenced by Bush, who knew that Shannon was interested in a mathematical theory of communication and information, and Bush suggested to him that he apply these ideas to the emerging field of population genetics, which sounds odd, but that's what Bush had in mind. Shannon responded to that, and his doctoral dissertation had the title *An Algebra for Theoretical Genetics*, applying these ideas to the field of population genetics which was looking at the rates at which genes flowed through populations over time. So there is a kind of analogy, you can see, to circuit design.

It was through that work in population genetics that Shannon initially contacted Warren Weaver who, as I said, in the 1930s was an extremely prominent figure in American science, himself a mathematician who worked as the Director the Natural Science Division of the Rockefeller Foundation. He was very instrumental in funding leading edge science and making expensive instruments available to American researchers so that they could catch up to the level of European science at the time.

In 1948 Shannon published his "Mathematical Theory of Communication," which has the startling characteristic that he strips away the content. Information theory has nothing to do with information content, which should strike you as bizarre. That whole first opening part of this lecture in which we talk about being awash in content has nothing whatsoever to do with the mathematical theory of communication that Shannon formulated. In his own words in that paper of 1948, what he wrote was:

> The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have meaning; that is, they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem.

Wow! That's dismissing the meaning of what we say over the telephone and the meaning of what we write in our books and magazine articles. That's irrelevant to the engineering problem. What is the engineering problem? The significant aspect of the engineering problem is that the actual message is one selected from a set of possible messages. The system must be designed to operate for each possible selection, not just the one that will actually be chosen, since this is unknown at the time of the design of the system.

If you are designing a communication system, you have to design it in such a way that it is capable of carrying any one of a large number of possible messages. It has to be designed in such a way that it could transmit any one of those messages, whether it's a cry for help or a poem. If the number of messages in the set is finite, then this number can be regarded as a message of the information produced when one message is chosen from the set, all choices being equally likely. It doesn't matter what the message is about. We can attach a number to a communication channel that reflects the total set of possible messages that can be sent through that channel.

What Shannon did was he developed a mathematical theory for the design of communication channels that separated the problem into a source problem, a channel problem, and a receiver problem, and then showed that you could formulate mathematically what is the optimal means of accurately recognizing and reproducing a signal given any communication channel. We're not interested in the physical character of the channel. There is a mathematical model of an information channel which treats information as essentially a stochastic phenomenon.

Shannon applies statistics, the specific form of which he actually adapted from the work of Norbert Wiener, an MIT professor who was the founder of the science called cybernetics, which intensively used the idea of positive feedback loops, which have occurred in a number of lectures. What Shannon did was to analyze mathematically what it would take for an automated receiver to recognize that an input was a signal, a meaningful signal rather than random noise, and then to accurately reproduce that signal either for transmission or for storage, regardless of what it was about. We don't care what it's about. And in fact the statistics have to do with uncertainty.

So from his point of view, information is designed in such a way that the more uncertain the content of the message is, the more information it carries. If you received a message that you already knew, the information content is zero in his mathematical model. The uncertainty, getting a signal whose form is uncertain to you, is highly informative, but you have to be able to distinguish between an input that is a meaningful signal as opposed to random background noise. How can you do that given any particular information channel?

From our point of view, the idea that you can have a mathematical theory of information in which content and meaning are stripped away is startling. The idea of treating information as a stochastic process, treating the communication channel and the information that flows through that channel using statistics, is a strong reinforcement of the whole intellectual phenomenon that we've seen over the last 150 or so years, in which we have applied statistics' stochastic character to fundamental natural processes.

We saw this in the 19th century with regard to the kinetic theory of gas, and we saw it with regard to the concept of statistical laws, and the role of chance in random mutations in the evolutionary theory, and in radioactivity. We saw it deeply embedded in quantum theory. Here we have the same stochastic mathematical modeling applied to information, which might seem odd, because how can that be applied to meaning? But take the meaning out, and now we're treating information as a signal that has a certain form, and we don't care what the form stands for—what meaning a person puts on that form.

Now this has to sound hopelessly abstract to you. It seems to me that it has to be the case that there is no way that this can have any practical applications. But it turns out that that's quite wrong. On the contrary, the techno-sciences built on Shannon's mathematical theory of information are blockbusters. For example, in no particular order, the fiber-optic networks that are now being installed all over the world are based on Shannon's mathematical model of information and the communication channel that messages are distributed from.

It was Shannon who showed that the closest you can come to the most efficient means of transferring information accurately with error correction incorporated is bits—a binary bit stream. So the Internet is based on Shannon's mathematical model of information. All your cell phones are based on Shannon's mathematical model of information. The so-called CDMA (Code Delay [sic Division] Multiple Access), TDMA (Time Delay [sic Division] Multiple Access), technologies which underlie the overwhelming majority, if not all, of the cell phones in the world in some form or other, all rely on algorithms that are founded ultimately in Shannon's information theory. Music CDs and DVDs reflect Shannon's information theory. The theory of deconstructing the message and storing it as a series of pits to be read by a laser on a music CD or on a DVD is based on Shannon's algorithms. Cryptography—the whole idea of encoding and decoding messages nowadays—utilizes Shannon's algorithms for the efficiency with which messages can be coded and decoded. And this doesn't exhaust the applications.

For example, hard disk storage drives also use Shannon's information theory, again because from his point of view, detecting a signal accurately and then reproducing it accurately can either be for purposes of transmissions to another channel, or for the purposes of storage, which is transmission with a time delay, or for the purposes of reproduction, let's say through a speaker. So it doesn't matter whether we're talking about music CDs, video, DVDs; whether we're talking about cell phones; whether we're talking about hard disks for computers; whether we're talking about fiber-optic systems; all of these utilize Shannon's information theory.

Furthermore, as if this weren't enough, remember what I said about Shannon back when he was a young man and did his masters thesis on the switching network of the telephone company. Shannon showed that you could use electrical switches in order to incarnate, so to speak, you could make models of human reasoning, logical reasoning, using these electrical switches. Shannon, in the late 1940s, laid down the fundamental electrical circuits that became the logic circuits of computer chips. All of the computer chips in the von Neumann architecture family of computers—which is the overwhelming majority of computers in the world—are still using logic chips, which at their core always incorporate Shannon's logic circuits, which are sort of electrical implementations of George Boole's laws of thought. That's why Boolean algebra is frequently taught to people who study computer science—and variations and extensions of those, so that his work is embedded in the logic chips of the processing units of every single computer chip following the von Neumann architecture. I excluded the so-called neural network chips that have a different logic.

Now I don't know if it's cute or not, but it's interesting that Shannon, together with a colleague at Bell Labs, and a friend at MIT who may or may not have participated in the adventure, but certainly was intellectually responsible, decided to adapt his use of probabilities, statistics, mathematical model from information to gambling. And in the 1950s and '60s, certainly in the 1950s, Shannon and his Bell Labs colleague went to Las Vegas, where supposedly they made a very great deal of money. But nothing compared to how much money they are reputed to have made when they applied this model to Wall Street, and benefited from being able to identify statistical patterns that paid off handsomely for them. At least, that's the story.

Shannon was canny enough not to make an issue out of this, and so he and his colleague were never banned from the gambling casinos the way card counters were subsequently. And it is the case today that the overwhelming majority of trades going on in the stock markets—on Wall Street, or the New York Stock Exchange, for example, the London Stock Exchange—are computer trades that are based not on the content of the stocks being traded, the nature of the company, but on statistical patterns that complex algorithms are looking for in stock trading data; noticing for example (I'm just making this up) that whenever IBM stock moves up in a certain way, Texas Instruments stocks move down in a certain way, and then using that information to selectively buy and sell IBM and Texas Instruments stock.

To a very considerable extent, actually it seems to be the overwhelming majority of stock trades today, really have nothing to do with the character of the company's stock being traded like, well, they just invented something, or they haven't invented anything in a year. This is analogous to Shannon stripping away the content from information and treating information as a statistical pattern.

Now we have two senses of the term information, and I want to add a third. The first, of course, we live in an information age because we're awash in content. The second, and I think much more profoundly, we live in an age in which information theory is the underpinning of many of the technologies that have shaped and are shaping our daily lives in a wide spectrum of ways. The third sense in which we live in an information age sounds like it's right out of science fiction, and that is the sense in which information is attributed physical reality, that information structures have physical reality, that information structures *are* physical reality. That would be the most extreme claim.

Now there's one sense in which information structures began to be understood as real, and that's in the decoding of DNA. We will be talking more about that in the lecture on molecular biology, but we all know about the DNA code. The power of DNA to regulate cell metabolism is contained in the sequence of the bases that make up the DNA molecule. Everybody's, every organism's DNA has the same bases. It's the sequence that makes the difference, and sequence is a pattern; it's a relationship. It's not the base whose properties give the instruction to the cell to manufacture some protein at a particular time or to stop manufacturing at another time. It's the particular sequence of these same bases.

It was recognized in the 1930s that everybody's DNA, whether you were a plant or a fly or a human being, has the same bases; that many people think that this must be an unimportant molecule, because, how could it be? It doesn't make a difference whether you are a fly, a plant, or a human being. But it turned out that it's the sequence. So that is a sense in which information by itself—information is a particular kind of relationship—that's the way Shannon treated it. It's a statistical pattern. The information is a relationship that has physical reality.

This notion is extended much more dramatically in physics. For example, the physics of black holes uses information theory mathematics, which itself draws on the same mathematical rules that define entropy and thermodynamics, to analyze black holes. In fact, now the most current thinking in the early 21st century—which Stephen Hawking recently accepted, although he had been opposed to it for years, and made a bet that it was wrong, but he now paid off on the bet because he had to acknowledge that it was right—is that all of the information content associated with black holes sucking in energy and matter is contained in the black hole, and is contained on the surface of the black hole. Nothing is lost inside the black hole. A complete description of what got sucked into the black hole is part of the structure of the black hole. We don't know how to read that, but it's part of the structure of the black hole, and, curiously, is a function only of the surface area of the hole, not of the volume, and that seems to be a real puzzle.

That has led to what's called the holographic principle, which is that in some sense the universe is an information structure. You know the difference between a hologram and a photograph is that the photograph is strictly two-dimensional. You can't look behind the photograph to see what the objects in the photograph look like from behind. But in a hologram, which is also two-dimensional, all of the three-dimensional information is contained, so that appropriately stimulated, you can walk around a hologram and see the three dimensional character of the objects that superficially look like they're only two-dimensional in the hologram; that three-dimensional objects are in fact information structures in some physically real sense.

This idea, of pursuing information structures as physically real entities, and that material entities are (and certainly energy structures are) informational structures ultimately, is explored in a subset of physics called algorithmic information theory, which is indebted to Andrey Kolmogorov, the Russian mathematician, who did a lot of the deep mathematical thinking, as well as deep American thinkers such as Gregory Chaitin and Ray Solomonoff. Algorithmic information theory is used as a means of defining three-dimensional objects as information structures, which certainly seems dramatic and maybe even revolutionary, but it turns out to have explanatory power and in some cases to also translate into techno-science applications.

Lecture Thirty-Four
Systems, Chaos, and Self-Organization

Scope:

Atomistic thinking presumes that we discover the truth about reality by decomposing physical, chemical, biological, and social phenomena into elementary building blocks from whose properties we can synthesize the world. Three closely related 20th-century ideas challenge the adequacy and the correctness of this presumption: the ideas that phenomena are produced by systems, that apparently chaotic "real-world" systems are orderly, and that natural and social phenomena are produced by self-organizing systems. The distinctive features of these ideas are that systems display properties that are not displayed in, or derivable from, the individual properties of their constituents. In other words, that wholes are causally more than the sum of their parts; that the concept of lawfulness, already stretched by having to accommodate statistical "laws" and randomness, must include orderliness of a precise mathematical sort but without predictability; and that natural and social phenomena maintain themselves in stable, long-lived, non-equilibrium states via energy inputs.

Outline

I. In the two previous lectures, "computer" and "information" were single names, but each referred to three very different ideas; in this lecture, *systems*, *chaos*, and *self-organization* are three different names for a single complex idea.

- **A.** Systems theory, chaos (or complexity) theory, and self-organization theory are three facets of one idea.
  - **1.** Both chaos theory and self-organization are characteristics of systems and, thus, presuppose the existence of a system.
  - **2.** Only some systems are chaotic or self-organizing, but there is an intimate connection between chaos and self-organization and, of course, between both and the dynamics that distinguish systems from non-systems.
- **B.** Systems thinking contrasts sharply with atomistic, "bottom up" thinking.
  - **1.** Atomistic thinking assumes that entities with fixed, inherent properties are the elementary explanatory or compositional units of reality.
  - **2.** All experiential phenomena are the results of typically complex interactions among these entities.
- **C.** Systems thinking is "top-down" thinking.
  - **1.** The systems approach is process-based rather than atomistic, and it emphasizes structure/form and relationships.
  - **2.** A system is a distinctive organization of mutually adapted parts, the nature of the adaptation being such as to enable the functionality of that specific system.
  - **3.** In a system, the parts cannot be analyzed independently of their position and function in the whole.
  - **4.** Systems have a holistic character: A system functions only as a dynamic whole of parts working together.
  - **5.** As a whole, a system displays *emergent* properties that its individual parts do not have: Typically, this is what is meant by "The whole is greater than the sum of its parts."
- **D.** These emergent system-level properties are as real and as causal as the properties attributed to "atoms" in the atomistic approach to nature.

1. Molecules are, in this sense, mini-systems: Even a simple molecule, such as sodium chloride, has properties that neither of its atoms separately possesses while lacking properties that these atoms possess on their own.
2. The functioning of a complex molecular-system, such as DNA, powerfully illustrates the causal efficacy of emergent properties.
3. The same is true of a large-scale biological system, such as an ant colony, which also displays self-organization and reorganization, if disrupted, without a central controlling authority.

E. Nature is pervasively systemic.

1. Moreover, natural phenomena typically display a hierarchical system architecture based on coordinated modular subsystems.
2. Herbert Simon has argued that such a module-based hierarchical structure has strong evolutionary advantages.
3. The cell, for example, is a system with modular subsystems of its own, but the cell as a whole is also a modular subsystem within a grand hierarchy of tissue systems, organized into organ systems, organized into organisms. In turn, these organisms are "modules" within ecological systems that are themselves elements within a total environmental system that is the Earth.
4. Indeed, plate tectonic theory strongly reinforced the growing recognition, in the 1960s, that the Earth was a system, whose largest interacting units were the atmosphere, the oceans, the land, and the dynamic internal structure of core, mantle, and crust.

F. The properties of a system are determined by the form of its organization.

1. The relationships among parts and their mutual adaptation to one another and to the functionality of the whole are the determinative features of a system.
2. George Cuvier used this principle to reassemble the skeletons of fossil animals from their jumbled bones.
3. In artificial systems, these relationships and this adaptation are obviously the result of deliberate design decisions.
4. Because such adaptation is pervasive in nature, some people find the idea of intelligent design attractive, but the Darwin-Wallace theory of evolution proposes a process that generates apparent design spontaneously.

II. In 1963, one Earth subsystem, the atmosphere, gave rise to *chaos theory*.

A. Accurate weather prediction requires modeling the atmosphere as a system.

1. In 1963, meteorological physicist Edward Lorenz noticed the exquisite sensitivity of his then state-of-the-art atmospheric model to minute variations in initial conditions.
2. Following up on this observation led Lorenz to recognize that the atmosphere is a complex system that is composed of associated (weather) subsystems and is non-linear and "chaotic" in its behavior.
3. That is, weather systems interacting within the total atmospheric system are exquisitely sensitive to even small variations in the parameters that determine them, such that small changes in these parameters at one place can lead to different weather conditions thousands of miles away.
4. Jokingly, this was called the *butterfly effect*, and it explains why long-term weather forecasting is so difficult.

B. The behavior of such non-linear systems is not predictable using the tools and assumptions of traditional Newtonian deductive-deterministic physics, nor is it periodic or equilibrium-seeking.

1. Lorenz and a growing community of mathematicians and scientists across disciplines began to study chaotic systems.

2. What emerged was a recognition that these systems were not chaotic at all, in the sense of hopelessly disordered and anarchic, which led to changing the name *chaos theory* to *complexity theory*.
3. Complex systems, characterized by an exquisite sensitivity to small variations in critical parameters, display a new kind of order, one that is well described by a family of mathematical equations.
4. Just as scientists in the 19th century had to redefine the lawfulness of nature to accommodate statistical laws, now they had to redefine order to accommodate system structures that were non-linear, non-periodic, and non-predictable in detail yet were stable, maintaining a distinctive structure over time far from equilibrium.
5. A hurricane is a dramatic example of such a structure, emerging out of atmospheric and oceanic interactions, growing and maintaining itself over weeks, and modifying its structure as it interacts with other systems.

C. The motivation for this redefinition was the wide range of applications of these equations to natural and social phenomena.

1. The study of the mathematical equations that described “chaotic” behavior turned out to be applicable to a much wider range of phenomena than weather systems.
2. Nature is pervaded by non-linear systems, but before the 20th century, modern science simplified these to linear systems because that’s what the available mathematics could describe.
3. Social phenomena, for example, the fluctuations of the stock market, also lend themselves to analysis by these equations.
4. But weather systems also display another underappreciated behavior: They are self-organizing, as in the cited case of the hurricane.

III. Self-organization theory is a subset of general systems theory and closely connected to chaos/complexity theory.

A. In the 1970s and 1980s, chemist Ilya Prigogine emerged as the champion of self-organization theory.

1. Initially, Prigogine called attention to and studied fairly simple chemical systems that self-organized into fairly complex structures that were stable over time.
2. In effect, all you need to do is combine the right ingredients, “mix,” and stand back: Structures emerge by themselves.
3. Prigogine’s research expanded to include recognition of self-organization as a general feature in nature and especially of chaotic/complex systems.
4. What they all have in common is that the structures that emerge are non-linear, stable far from equilibrium, and adaptive: Within limits, they can evolve in response to environmental change.
5. An extraordinary example of self-organization is the development of the human embryo.

B. The spontaneous emergence of order in nature challenges the idea of entropy in thermodynamics.

1. The second law of thermodynamics implies that entropy in a closed system must increase over time and orderliness must decrease.
2. But with an available source of energy, systems can self-organize out of available, unordered ingredients and spontaneously generate stable structures that can themselves evolve over time into more complex structures.
3. In fact, just this property is central to emerging nanotechnologies and is already being exploited commercially.
4. John Holland and Arthur Samuel, around 1950, began to explore the spontaneous emergence of order in the context of computer programs that could learn from their own experience.

5. Samuel created a program that became the world checkers-playing champion, and Holland created a family of programs called *genetic algorithms*.

IV. All this is a profoundly new mindset for scientists, one that has become interwoven with theories of science as well as with our expectations about how we use technology.

- **A.** We are much more sensitive today to the complexity of the Earth as an environmental system.
- **B.** The most marvelous expression of self-organization is the formation of the human embryo, which spontaneously emerges out of non-linear interactions.
- **C.** Hierarchical systems structures are characteristic of almost all natural phenomena and also of technological systems fundamental to how we live our lives—such as the telephone system, the electrical grid network, and the Internet.

Essential Reading

John H. Holland, *Hidden Order: How Adaptation Builds Complexity*.

Ilya Prigogine, *Order Out of Chaos*.

Questions to Consider:

1. If systems themselves emerge out of self-organizing preexisting elements, then isn't atomistic substance metaphysics right after all?
2. Does the centuries-long prejudice favoring equilibrium as the norm suggest that our thinking is always shaped by analogous prejudices?

Lecture Thirty-Four
Systems, Chaos, and Self-Organization

In the previous two lectures we saw how a single term could refer to three very different ideas. In Lecture Thirty-Two, for example, we saw how the term *computer* can refer either to a human being whose job it is to make mathematical calculations, or to a machine that was designed in order to make automatic mathematical calculations, or to what we really mean by the term computer; that is to say, a universal simulation machine, as I tried to describe that.

In Lecture Thirty-Three we saw how the term *information* is used routinely to refer to content as, for example, the content in a book, the information that you get from a book or a telephone message. It also refers to Claude Shannon's "The Mathematical Theory of Information," which has no reference to content whatsoever, which is content neutral, content independent, and yet has become the basis for a suite of powerful technologies that surround us and that we use every day. Finally, the term *information* has become, in physics over the last quarter century, increasingly promoted as a feature of reality, that in fact in the extreme that the universe is an information structure.

In this lecture I want to talk about one multifaceted complex idea that is referred to by three different names. So we have just sort of the inverse of the phenomenon that we saw in the previous two lectures. The three different names are systems theory, chaos theory (which many of its students now prefer to call complexity theory), and the theory of self-organizing systems. These are really three facets of a single complex idea. They are interrelated ideas so that they really correspond to one family or cluster of ideas, but there is no single name that refers to them. I'm going to refer to them very broadly as systems, because system is the overarching idea.

Chaos theory requires that what is behaving chaotically be a system, and self-organizing systems are obviously systems. Not all systems are chaotic, not all systems are self-organizing, but self-organization, chaos or complexity, and the systems idea are all intimately interconnected. They have, over the past 20 or 30 years, become so fundamentally embedded in all of our scientific and technological thinking, they are so much integrated into our scientific theory construction, and into the way we implement technologies, that it's hard to imagine today how it can have been an innovation to have been thinking in terms of systems. But we will appreciate that when we recognize the contrast between systems thinking and the atomistic style of thinking that we have seen grew to be so powerful a foundation of scientific theories across disciplines in the 19th and early 20th centuries.

Systems thinking is almost the mirror image of atomistic thinking. Systems thinking is sort of the convergence of process style thinking, of structure, the idea of structure that we discussed that emerged in 19th century chemistry initially, and the idea of relationships being physically real entities that have causal consequences. The systems idea is an expression of process thinking, and it is another illustration of recognizing the power of structure or form and relationships.

When we think of a system we are thinking of a group of parts that are mutually adapted to one another in relation to the functioning of that whole assembly of parts. There is a top-down character to a system that is not present in atomistic style thinking, which is bottom-up thinking about nature. We've seen this so many times now. The atomistic style of thinking is essentially a Lego style of thinking, that you build up reality out of fundamental units that have fixed properties. When you put them together you can see how the properties of different pieces fit together in order to generate the world as we understand it. Each part can be studied in isolation from its relationships to any other part because relationships, as we saw in an earlier lecture, were conceived to be in a sense accidental. They were secondary phenomena. The important thing is to identify, to make an inventory of all of the fundamental bits in nature and their properties, and then we will be able to synthesize nature out of those bits.

Systems thinking says, oh no, you can't do that, because even though it looks like the parts in this system are the same as the parts in that system, parts in a system must be analyzed only in relation to the way they fit into the whole. To understand a system you have to understand the functioning of the whole. You can't start from the bottom and build your way up. You have to know from the beginning what the function of this system is, how it operates, how it's supposed to operate in order to understand whether the individual parts are properly designed, properly functioning, and have the proper relationship to one another.

This conception of system is really a very different way of thinking about nature and, it turns out, a very different way of thinking about technology than the atomistic style of thinking. It is a kind of maturation of the process style of thinking that we saw began to emerge in the 19th century with the ideas that we discussed, for example, of energy, of the field, of evolution as a process. Here we have, especially after World War II, this growing recognition that we really need to start recognizing that nature is composed of systems, and not composed of fundamental units that have been put together in any old way.

Systems are characterized when we have the sort of folk saying that "the whole is greater than the sum of its parts." That is the central characteristic of a system. The system has characteristics, the system has properties that are not possessed by its parts. The parts have properties, and those parts interact with the other parts, but they do not have the properties that the system possesses. This is, for example, present even in a simple molecule. A simple molecule like sodium chloride has properties that neither sodium possesses nor chlorine possesses. That's pretty obvious, since chlorine is a toxic gas, sodium is a metal that reacts explosively with water, and yet when you put sodium chloride into your blood, which is mostly water, then it doesn't explode, and the gas that is chlorine does not bubble through your body and harm you. So sodium chloride has properties that are not present and could not be predicted from sodium by itself or chlorine by itself.

But if we jump to the other extreme and think of a molecule like DNA: DNA has properties that the individual sub-molecules that make up DNA—the sugars and the phosphates and the four bases that carry the genetic code, as we say—they do not have properties that the entire DNA molecule has. That is quite interesting because it turns out, and this is very typical for a system, the formal structure of the system is very important to the properties that the system displays.

For example, it is the sequence of the bases within the DNA molecule that determines whether the organism is going to be an ant or a sheep or a human being. The bases are the same in the ant, the sheep, and the human being, but the sequence, the relationships among the bases, give the DNA molecule in an ant, in a sheep, in a human being, different properties than they would otherwise have. So that's a beautiful illustration of how structure, form, relationships are embedded in this idea of systems, which have distinctive properties not possessed by the individual elements.

Since I mentioned ants, think of an ant colony: an extraordinarily complex system in that, in a simple case, the ant colony is made up of worker ants that live out their lives inside the nest, forager ants that roam around bringing food back to the nest, and warrior ants that protect the nest and protect the foraging ants. Every species of ant has a distinctive ratio among the warrior ants, the foraging ants, and the worker ants.

This is a function of the individual species, and so whatever proportion it is, if you go into an ant colony and you scoop out a bunch of ants (very disruptive and probably a politically incorrect thing to do), if you do that, within hours the ants start to reconfigure themselves to restore the appropriate proportions among worker ants, foraging ants, and warrior ants characteristic of that species. Very, very interesting phenomenon, since there is no central authority that is determining that. Somehow the relationships among those ants are such that those relationships cause changes in the embryological development and the physiological development of the ants, because the warrior ants are much bigger than the foraging ants, which are bigger than the worker ants that stay behind in the nest.

So here we have an ant colony—bees are another example of that, of course—any social creature, like termites and of course like human beings, is going to display systemic properties that are not possessed by the individuals. Those systemic properties, those so-called emergent properties you see, the system has a holistic character. The system is not simply a collection of parts, it has a character of its own (that's what holism refers to) that displays properties that are distinctive only when the system is functioning properly. Those are called emergent properties. They only emerge at the level of the system.

Notice that nature is pervasively systemic, that all around us, now that we've become alert to this idea, we recognize that nature is pervasively systemic; that, for example, a cell is a collection of subsystems. There are within the cell, just very briefly, you've got the nucleus as a subsystem, you've got the extranuclear bodies like mitochondria, the Krebs cycle that generates ATP that provides the energy for all cellular metabolic processes—the Krebs cycle is a kind of a system within a subsystem within the cell.

So the cell is a collection of subsystems. This is sometimes referred to as the concept of modularity. There are modular sub-subsystems that make up systems within nature, and Herbert Simon has given a very powerful argument of why from an evolutionary basis this makes a great deal of sense. Evolution can explain why in fact nature has a hierarchical systemic character, that it is made up of a hierarchy of systems, subsystems, sub-subsystems, and the basic units, so to speak, are modules, and sometimes modules within modules. The cell itself is clearly a collection of these modules—the DNA in the nucleus; the RNA; the ribosomes; I mentioned the mitochondria; the Krebs cycle, which is a relational structure rather than a single physical body, a very complex series of reactions that has to take place where the atoms are interacting in mutually adapted ways in order to wind up generating the ATP molecule. The ATP molecule by itself can be considered a sub-module. You can get dizzy from this.

But the cell itself is a module within the tissue. The tissue is a module within the organ. The organ is a modulus system within the total organism. The organism—us, for example—we are modules within our community. The community of human beings is a module within the total environmental system that makes up the planet. The planet itself, we have begun to understand, is a collection of interconnected systems. Collection maybe is the wrong word; it's not sufficiently dynamic.

The planet itself is a system. For example, plate tectonics theory has shown us, again only since the 1960s, that the crust of the earth, the mantle underlying the crust, the liquid core surrounding the solid core, that all of those elements—the solid core, the liquid core surrounding it, the mantle extending for thousands of miles up to just below the surface of the earth, and the crust that makes up the continent and the ocean beds—are all interconnected in dynamic ways.

The welling up of mantle material pushes the ocean floor apart. When the ocean floor hits the continents it goes down back into the mantle, melts, sinks down to the point where the mantle interacts with the liquid core, and then shoots back up and eventually forms new ocean floor. It is a cycle that takes about a hundred million years before any piece of ocean floor comes back to the ocean floor again.

The oceans, the atmosphere, and this plate tectonic theory of the earth from the surface down to the core constitute a system, so that a phenomenon like global warming can only be understood in the context of this total system. Of course, one can recognize that the planet itself is a subsystem within the solar system, which is itself within—you get the idea—the Milky Way, and you eventually build up to the entire universe.

So this system idea: nature really is pervasively systemic. At every level we see that to really understand any feature of nature we need to think of it in terms of its systemic character. What relationships there are among the parts that we identify, how those parts themselves constitute systems, and how those parts are mutually adapted to one another so that when you tinker with one part you are not merely improving that part, you are changing, perhaps, the way it functions within the total system.

Now here is an interesting feature about systems that we're going to be pursuing in a moment, and that is artificial systems. For example, an automobile is a system of mutually adapted parts. The engine is one modular subsystem, and within the engine one can think of the pistons and the cylinders and the valves, etc. In artificial systems, the mutual adaptation of the parts is a reflection of deliberate design decisions. A designer who understood that the purpose of this car is to be a racing car has deliberately designed the parts of the engine system, for example, so that they can function in the ways that a racing car engine needs to function, as opposed to the way that the parts of a family sedan have its engine function.

So, for example, tinkering with the valves of a family sedan engine by simply replacing them with valves from a racing car is not going to improve the performance of the family sedan engine. Those valves are not properly adapted to, for example, the valve gear and to the pistons and to the shape of the combustion chamber, etc.

In nature, this mutual adaptation of parts is not deliberate as far as we can tell. In fact, it is the appearance of deliberate design decisions in nature that has led people to believe in intelligent design.

In the 19th century, Georges Cuvier, at the very beginning of the 19th century, faced with the challenge of putting together fossil bones that had been dug up, and which he was presented as a national professor of zoology, Cuvier developed this idea that the parts of an animal, the bones of an animal, are mutually adapted to one another and to the function of the animal as a whole. So, for example, if the animal is a predator animal, then it's going to have certain kinds of skeletal structure in order to be able to succeed in hunting and killing its prey. If it's a prey animal, there will be a different kind of relational structure among the bones. Using this principle (which he developed, of course, in more detail) he was able to start putting these bones together—because they didn't come nicely packaged, when you dug them up they were just a mishmash of bones, and how do you know which one belongs to the victim and which one belongs to the predator?

The Darwin–Wallace theory of evolution has as perhaps its most distinctive character an explanation of how you can have the appearance of design without a designer. We talked about that when we talked about the theory of evolution, and that is what makes the theory of evolution objectionable to some who don't want to give up the idea that there is a designer. But that is a powerful aspect of the theory of evolution, that scientifically speaking it explains the emergence of what looks like deliberate design decisions let's call it randomly (or I prefer spontaneously, and we'll talk about that when we get to self-organizing systems in a couple of minutes).

Now one of the kinds of systems in nature (let's call it a natural phenomenon) that displays this kind of systemic character is weather. We talk about weather systems, but often don't think of what the term system means in the context of talking about weather systems. A hurricane is a weather system, for example, and it clearly has a structure. It is stable over some period of time, at least days and sometimes a week or two, and the hurricane maintains itself as a distinctive kind of weather system over long distances and fairly substantial periods of time.

It was in the analysis of weather that the second idea that I mentioned—the idea of chaos—emerged in 1963, when a meteorologist named Edward Lorenz was running what was then considered super-duper state-of-the-art computer models of the atmosphere, which is extremely difficult to model because of the complex interactions—very characteristic of a system if you approach it as a system—of the factors that determine the weather. He modeled humidity and atmospheric pressure and winds and surface temperatures over the ocean, over the land, the sunlight, cloud cover, etc.

What Lorenz noticed was something that startled him, and startled everyone else too, which was that his models, these computer models of the atmosphere, were exquisitely sensitive to the initial conditions that you put into the equations for the model. If he varied the initial conditions by as little as 1/1000—if he changed something from one mile an hour to one mile and one-thousandth of a mile an hour, if he changed the wind velocity—then he could get a totally different weather pattern three days later than if he had not modified it by 1/1000.

This was astonishing because classically, just as there is this kind of predilection in modern science for the atomistic style of thinking, there has been, ever since the 17th century, a predilection for linear modeling in science. That is to say, a linear assumption is that a small change in the input leads to a small change in the output. A big change in the input leads to a big change in the output. The equations that scientists use have this—or they strive to have this—linear character, because linear equations are much easier to solve than non-linear equations. Linear behavior is much easier to model than non-linear behavior. And within a broad range, those models work.

Another predilection that we have seen again and again is the assumption that natural phenomena are always striving to get to equilibrium. They want to settle down once and for all. The combination of linearity and equilibrium is very distinctively characteristic of modern science from the 17th century into the 20th century.

But what Lorenz was saying was that there is a high degree of non-linearity, of dynamism in atmospheric systems; that here is a system in which the output can change dramatically if there is a tiny change in the input. You may have heard of what is called the butterfly effect, which he wrote about as a kind of a joke. A butterfly flaps its wings in Brazil and it rains in New York, because even that tiny little change in air pressure caused by the fluttering of the butterfly's wings (this is not meant literally) can ramify and lead to a dramatically different weather pattern several days later and thousands of miles away.

Now, Lorenz's insight was picked up over the next 20 years approximately, but especially during the late 1960s and throughout the 1970s, by a range of scientists, mathematicians, biologists, economists, and physicists. What they discovered was they could find mathematical equations describing systems of this sort. What emerged was while the behavior in these systems is not linear, it is not periodic, it does not follow a simple repeating pattern, it is not predictable in the traditional sense (you cannot predict where any given molecule of oxygen in the atmosphere is going to be three days later), nevertheless, there is a kind of order that emerges. It's a new kind of order that emerges in these chaotic systems.

Now they are not truly chaotic because they do have a mathematical structure, a mathematical form, and they have a kind of order that is not traditional, but it does have an orderliness to it that is very marked. So, for example, you can use these equations to show how the branching of the lungs develops in the human body; you know, lungs look sort of like an upside down tree stripped of its leaves. How the neurons develop in the brain, spreading out within the embryo, how the huge number of neurons in the brain spreads out in a pattern. It's been applied to economic theory, to modeling stock market fluctuations.

It turns out that nature is rich with non-linear systems, chaotic systems whose behavior has an order distinctive from the traditional deterministic order that was characteristic of 17th, 18th, 19th century science. Remember how we talked about statistical laws as what seemed like an oxymoron initially, but in fact we came to understand that statistical patterns could have a lawful character even though they were not deterministic in the traditional sense.

In chaos theory, which as I said its proponents often prefer to call complexity theory, you can have systems where the relationships are such that they are exquisitely sensitive to tiny variations in the values of the elements of that system. As a result, the large-scale behavior of the system can be very different than you had anticipated because you were either unaware, or you had not thought, that such a small change could ramify and have such a big change. Not unlike, to be a little facetious, when Congress writes up a bill with the best of intentions and then three years later it turns out that there are totally unexpected consequences because that small change in the wording of one law then was seen to have tremendous social and political and economic consequences down the line.

Now, the one feature of the weather system that brings chaos theory into the domain of self-organization is that natural systems all self-organize—there is no one else to organize them. For example, a hurricane emerges spontaneously. Nobody said, now it's time for a hurricane; let's do this and this and this in order to make the conditions for a hurricane right. A hurricane is a structure; it's an orderly structure. Within the framework of chaos theory it has the kind of order that the equations of chaos theory describe. A hurricane is an orderly structure that emerges spontaneously.

In the 1960s and ’70s the chemist Ilya Prigogine had become a major champion of this idea of self-organization as a fundamental feature of natural phenomena. He showed that there are chemical systems in which basically all you have to do is mix the ingredients, stir them, and peculiar stable structures will form all by themselves, some of them moderately complex for a simple chemical system. But then there are more complex chemical systems, and then there are physical systems and biological systems, and I mentioned the atmosphere, where the structures are really complex and are stable over long periods of time, and they emerge spontaneously.

This is a really dramatic new focus in science, because of course in the 19^{th} century with the rise of thermodynamics, as we discussed in that lecture, the concept of entropy was that orderliness runs down over time. The expectation was that physical systems run down over time. The idea that order can emerge spontaneously in nature requires a reconception of what we mean by entropy, and Prigogine was very central to that.

The reason why I call it a new focus in physics and not say a new invention is because Prigogine did not invent this idea. He became the champion of it, and he developed it scientifically in a way that led to his being awarded the Nobel Prize. But in fact back in the early 1950s John Holland and Arthur Samuel, who at that time were working for IBM, began first to develop the idea of spontaneously emerging order within computer models that they were developing, which came to be called genetic algorithms in the form in which John Holland was interested in them. He then became a major figure within the complexity theory/self-organization theory school. There is an institute in Santa Fe, New Mexico, called the Santa Fe Institute which is devoted to these kinds of studies, and he is a principal figure there, has been a principal figure there from the time it was started.

Arthur Samuel was interested in writing a computer program that could learn, and he did, and he wrote a computer program that in the 1950s became the world checkers champion. John Holland wrote computer programs that could display spontaneous learning. So this idea that order can emerge spontaneously out of the interactions of relatively simple elements that observe simple rules of interaction, that you can be surprised to discover the kinds of order that emerge and how stable these orderly structures can sometimes be, was a very powerful insight. It really came to fruition in the 1970s and after, when there was this convergence of systems thinking, of chaos theory, and of self-organization.

Now this is a profoundly new mindset for scientists, which has become so interwoven with our theories today, so interwoven with our expectation from the way we use technology that while it is invisible to us, it is in fact actively affecting such things as the Internet, for example.

It is certainly central to dealing with an issue like global warming. We are much more sensitive today to the complexity of the environment as a system. The whole notion that the earth is a system at the level of the environment, and that global warming is a feature of the way we have changed elements of the earth’s environmental system without thinking of the consequences on the functioning of the whole. All of these are illustrations of systems thinking, together with the recognition that self-organization is a fundamental feature of nature.

In fact the most marvelous expression of self-organization is the formation of the human embryo, which again spontaneously emerges out of the kinds of interactions, non-linear interactions, that are characteristic of the fertilized egg and its subsequent development.

How do we deal with this recognition? Well, that’s what science today increasingly is attempting to model: systems and systems behavior. Understanding the logic of hierarchical systems structures, which are characteristic of nature, of almost all natural phenomena, and also of technological systems. That technological systems, the telephone system, the electrical grid network in the United States, the Internet that I mentioned—these are complex systems, and now we’re trying to understand them at the level of systems.

Because the functionality of these systems is so fundamental to the way we live our lives, I suggest that this complex, multifaceted idea of systems theory, complexity/chaos theory, and self-organization theory is one of the greatest scientific ideas of all time, and it is an idea that is revolutionizing what we mean by scientific knowledge.

Lecture Thirty-Five
Life as Molecules in Action

Scope:

The explanation of all life phenomena (except for the human mind) in terms of the deterministic motions of lifeless matter was central to Descartes' mechanical philosophy of nature. The rival, vitalist, view that life was not reducible to lifeless matter came under increasing pressure in the 19^{th} century, especially from biophysics- and biochemistry-based research programs. From a focus on the organism and its behaviors, biology shifted to a focus on the cell and its molecular processes, finding expression in the enzyme/protein theory of life, reinforced by the discovery that proteins were configurations of amino acids. Sealing this shift was the further discovery that DNA molecules—and within each of them, a distinctive sequence selected from the same four bases—defined every life form on Earth. By the 1980s, the molecular theory of life was transforming medicine by way of a flourishing biotechnology industry based on its research findings and transforming the meaning of life, as well.

Outline

I. The claim that life is a matter of specific molecular processes, and no more than that, is both old and new.

- **A.** A radically materialistic interpretation of life goes back to Greek antiquity and was built into modern science.
  - **1.** Epicurus's atomic theory of matter, based on the earlier ideas of Democritus and Leucippus, was itself the basis of a rigorously materialistic theory of life, mind, and soul.
  - **2.** Epicurus's ideas were disseminated in the Roman world by Lucretius and, through him, to the Renaissance.
  - **3.** Descartes' mechanical philosophy of nature claimed that all natural phenomena, including all life phenomena, were the result of matter in motion.
  - **4.** For Descartes, animals were machines (*bêtes machines*), which justified vivisection to study these complex devices.
  - **5.** Humans were machines, too, in their bodily subsystems, but not the mind, which Descartes excepted as an immaterial entity.
  - **6.** Eighteenth-century Cartesians defended an exhaustive materialism that included the mind, stimulating the first attempts at reducing mind to brain.
- **B.** In the 19^{th} century, the idea that life and mind were strictly physico-chemical phenomena rapidly grew to dominance.
  - **1.** With respect to the mind, advances in neurophysiology; the beginnings of experimental psychology; and the work of Pavlov, John Watson, and even Freud brought this topic within the domain of mechanistic science.
  - **2.** With respect to the body, the cell theory of life was developed largely by chemists and biologists committed to a mechanical interpretation of life.
  - **3.** Indeed, by the late 19^{th} century, basic research in biology was increasingly a matter of biochemistry, i.e., of understanding life phenomena by studying cell structures and reactions in the cell.
  - **4.** Emil Fischer's discovery that proteins are built up out of amino acids and can be synthesized in the laboratory strongly reinforced the mechanistic view.

II. At the same time, molecular biology is a new idea.

- **A.** The term seems to have been used first in 1938 by Warren Weaver of the Rockefeller Foundation, responsible for research grants in the biological sciences.

1. Weaver was committed to strengthening physics and chemistry as the basis of truly scientific biological research: To understand biological phenomena meant "reducing" them to chemical and physical phenomena.
2. This mindset in biology became pervasive, however, only in the wake of Watson and Crick's discovery of the molecular structure of DNA in 1953.
3. Initially at least, DNA was considered to contain all by itself the secret of life and to function as an absolute monarch dictating all life processes.

B. But the wholesale embrace, after 1953, of molecular biology as the foundation of all biological research clearly built on other shifts within science that began in the late 19th century.

1. The rise of quantum theory, in principle, reduced chemistry to physics.
   a. Chemical reactions were believed to be based on exchanges of orbital electrons.
   b. Into the mid-1930s, with the rise of nuclear physics, quantum mechanics was a theory of orbital electrons.
   c. Although the quantum mechanical equations for real chemical reactions were too difficult to solve, in principle, chemistry was physics and biochemistry was biophysics.
2. The Cartesian claim that even life was just matter in motion received a much more sophisticated formulation.

C. One expression of the impact of quantum physics on chemistry and biology was the spread of new physics and physical chemistry instruments and, later, of physicists themselves into the biology laboratory.

1. X-ray crystallography is a preeminent example: it was based on 20th-century physics and initially developed to test physics theories.
2. X-ray crystallography is immediately applicable to determining the structure of any molecule that can be crystallized without disrupting the arrangement of its atoms.
3. Obviously, this applied just as well to the structure of molecules of interest to biologists.
4. Concurrently, Swedish physicist Theo Svedberg developed the ultracentrifuge to settle an important issue in chemistry: whether very large molecules were robust or loose conglomerations of much smaller molecules.
5. Svedberg's machine quickly showed that Hermann Staudinger's defense of macromolecules was correct, though Hermann Mark showed that these molecules were flexible, not rigid.

D. Mark used these new instruments intensively in his research and became an influential founder of polymer chemistry.

1. Linus Pauling, one of the earliest chemists to apply quantum mechanics to the analysis of chemical bonds, visited Mark's lab in 1930.
2. Pauling was impressed with Mark's experimental methodology and, on his return to the United States, aggressively pursued funding to buy new instruments for his lab.
3. He succeeded eventually in receiving sustained Rockefeller Foundation funding through Warren Weaver, beginning around 1937.
4. By that time, the electron microscope had been invented and was being produced commercially.
5. Weaver was already committed to the ultracentrifuge, supporting Svedberg's research in Sweden in exchange for providing the machine and ongoing updates to the Princeton University biology department.

E. In the 1930s and 1940s, Rockefeller Foundation money "pushed" the latest physics-based instruments keyed to biochemical research into many U.S. biology labs.

1. The results were impressive, including Dorothy Crowfoot Hodgkin's discovery of the molecular structure of penicillin and vitamin B12.

2. Around 1940, Linus Pauling demonstrated that the antigen-antibody reaction was a matter of molecular structural properties and, later, that sickle cell anemia was a structural flaw in blood cells caused by a misplaced amino acid in one protein.
3. In 1951, Pauling showed that RNA had an alpha-helical structure, but he lost the "race" to discover the structure of DNA to Watson and Crick, who used the X-ray crystallographic data collected by Rosalind Franklin and her collaborators.

III. The excitement surrounding the discovery of the structure of DNA made molecular biology the hallmark of state-of-the-art biological research.

A. By 1957, with Matthew Meselson and Franklin Stahl's demonstration that DNA replicates by "unzipping" and forming new complementary helices, DNA was hailed as the key to understanding life.

1. Understand how DNA determines the chemical reactions that make up all cellular processes and you understand life.
2. In 1912, Jacques Loeb had written an influential book titled *The Mechanistic Conception of Life*, but when Paul Berg and his collaborators announced the success of their recombinant-DNA experiments in 1972, molecular biology became practically the only game in town.

B. In the course of the next two decades, molecular biology of DNA became the cornerstone of the commercial biotechnology industry.

1. Biotechnology based on DNA manipulation has already had a profound influence on clinical medicine and promises vastly greater influence in the 21^{st} century.
2. By 1982, the FDA had approved the sale for humans of insulin "manufactured" by genetically modified bacteria, and the list of similar substances continues to expand.
3. In 1980, the first transgenic plants and animals were created, and the former especially has led to the steadily growing genetically modified food and agricultural industry.
4. Transgenic animals are having a major impact on research into human illnesses and the effectiveness of new drugs.
5. Stem-cell research promises extraordinary new possibilities, but whether these will be fulfilled is a 21^{st}-century story.

Essential Reading

Michel Morange, *A History of Molecular Biology*; *The Misunderstood Gene*.

James B. Watson, *The Double Helix*.

Questions to Consider:

1. What are the implications for our belief that life is special in the growing power of molecular biology?
2. If genes act only in conjunction with factors internal and external to the organism, how could a human clone be more than superficially similar to a donor?

Lecture Thirty-Five
Life as Molecules in Action

The idea that we're going to be exploring in this lecture is molecular biology, a seemingly innocuous technical name that you might just blow off, but in fact what it stands for is the idea that life is molecular processes, and that's all that it is. The idea of molecular biology is that in explaining the molecular processes in living things we will have explained life itself, and as that explanation matures we will be able to synthesize life out of the ingredients that go into those molecular processes.

When we look at it that way, then the idea of molecular biology is an extraordinarily profound idea. Therefore it's one that we really need to explore, see how it emerged, and appreciate the extent to which it is changing the world in which we live. And we really know this, as we'll see in a moment, that we experience those changes.

On the one hand, the idea of molecular biology, or the idea that life is reducible to the interactions of bits of matter, is a very old idea. It goes back, as we have seen in earlier lectures, to Epicurus and Lucretius in antiquity. The Greek atomistic philosopher Epicurus explicitly argued that all living things are just combinations of atoms, and that when the atoms reconfigure themselves they form either other living things or dead things, but that there is nothing more to life than a peculiar configuration of lifeless atoms. Of course, Epicurus himself was indebted to the earlier Greek atomists, Democritus and Leucippus, and his follower Lucretius in the Roman period made this idea famous in the Roman world through his epic poem, *On the Nature of Things*, in which he incorporated this atomistic theory of Epicurus's.

More recently, the idea that life is a matter of matter in motion and no more than that, that there is nothing special about life that requires some special kinds of laws that are not present in physics, or as we might say, in physics and chemistry, goes back to Descartes. Descartes's mechanical philosophy of nature, as we saw, is totally committed to the idea that everything in nature is an expression of matter in motion. He left out, as only one exception, the human mind/soul as something immaterial, an immaterial reality and therefore not subject to the laws of nature, not reducible to matter in motion.

But living things, he thought, all animals were, as far as he was concerned—the expression he used was *bête machine*—they were beast machines, and therefore they were only machines. He saw no moral or ethical problems involved in, for example, vivisecting animals in order to understand them, because their screams and cries were really just the kind of thing you would get from a machine that was poorly lubricated or that you were taking apart. As you tried to wrench a stuck nut then it made a squealing noise—the same thing.

Human beings were machines also. All aspects of the human body, of the processes within us—respiration, digestion, reproduction—also were ultimately to be explained as matter in motion. Only the mind, Descartes thought, or he said—maybe he said it to avoid being condemned as a heretic—but he left room for the mind/soul to exist independently of this reduction of all of life to matter in motion.

Eighteenth century Cartesians were quite often much more rigorous than Descartes, and they began the speculation that the mind, too, is a product of the peculiar configuration of matter that makes up the human brain and the nervous system, and that the mind, too, is within the framework of a mechanical philosophy of nature. We see the first theories attempting to correlate the structure of the brain with the mind in the late 18th and early 19th centuries.

In the 19th century this particular theme, the reduction of mind to brain and thus to matter in motion, so that even the mind comes within the purview of this, what we now call the molecular biological theory of life, expressed itself as neurophysiological studies where we began to study the nervous system in detail and how it reduces the phenomena that go on in the brain. The creation of the science of experimental psychology, the emergence in the early 20th century of such schools of psychology as Pavlov's theory of reflex action, and John Watson's invention of behavioral psychology, which in its strict sense reduces the mind so that it is within the framework of a mechanistic theory of nature. Even Sigmund Freud, who believed that, ultimately, we would have a scientific theory of psychology which meant that it would be rigorously materialistic and deterministic. But in the absence of such a theory, then he developed his famous techniques in psychoanalysis.

This idea even included the mind by the late 19th and early 20th century. Meanwhile, of course, as we saw in the lecture on the cell theory of life, the introduction of the concept of the cell in the 1830s, and the acceptance that the cell was the fundamental unit of life, led to the kind of cellular researches that we talked about, which were dominated by biologists who had a mechanistic interpretation of the cell.

The rival vitalistic view, that there was something special about life that was not reducible to physics and chemistry, by the end of the 19th century was overwhelmed by the studies of people we referred to—Justus Liebig and Hermann Helmholtz and others—who saw in the operation of the cell chemical processes unfolding, and they analyzed these processes in terms of chemicals. By the end of the 19th century, biology had become pervasively biochemistry; that to do research into life at the most fundamental level was to be doing biochemistry, or really to be doing the chemistry of living things. But those chemical reactions were not themselves alive. (This is a very good illustration, by the way, of systems thinking.)

Life is not to be found in the individual molecules that make up the chemical reactions associated with life. Life is a property of the system when you put those molecules together in an appropriate mutually adapted way. So that if we understood the structure of the cells, and we understood the relationships, then we would be able to recognize how we could put things together in order to make life emerge as a system property—at the level of the cell, at the level of the organism.

This finds particularly powerful expression and reinforcement in Emil Fischer's recognition early in the 20th century, in the very beginning of the 20th century, that proteins and enzymes (enzymes are a special class of proteins) are merely combinations of amino acids, and that amino acids can be synthesized by any decent chemist in the laboratory. If you string amino acids together, then you get proteins, and proteins at the time were believed to be the fundamental basis of life.

The idea that life is reducible to physics and chemistry is an old idea in a certain level. On the other hand, molecular biology is a relatively new idea. That is to say, the term itself was only coined in the late 1930s, apparently first used by Warren Weaver, who we saw in the lecture on information theory played a significant role in the development of biological science and also information theory, oddly enough, in the United States. But as an executive of the Rockefeller Foundation responsible for giving out grants in biological sciences in the 1930s, Weaver was a very, very powerful influence in bringing physics and chemistry into biological research, in reinforcing physics and chemistry as the foundations of biological research. He coined the term molecular biology to refer to the emergence within biological research of what he saw as the most fundamental and most important feature of biological research: namely, to understand the most fundamental biological processes using the concepts and the tools of physics and chemistry.

But really, molecular biology caught on in a big way only after the DNA period starting in 1953. Beginning in 1953 with the discovery of the structure of DNA by Watson and Crick, one can see that there was a tremendous increase in the attention that was given to molecular biology. This was in the period in which DNA was initially conceived to be, so to speak, the king within the life sphere. If we could only understand DNA, we would understand all of life, that the DNA molecule was like the ultimate royal authority dispensing all of the information necessary for an organism to be created out of a fertilized egg, and for all cellular processes to operate. Hopefully they operate correctly, in which case the organism is healthy.

The focus on DNA after 1953 reinforced a development that had been going on literally for centuries since Descartes, especially since the cell theory of life, and in particular in the 1920s and 1930s when we see physics and chemistry moving into biology in a big way. This movement is a very important one to understand. First of all, I mentioned earlier that biology had become invaded and occupied, or, if you don't like that language, a major focus of biological research by the end of the 19th century, was biochemistry.

But what happened in the early 20th century was that as quantum theory developed between especially 1912, 1913, when Niels Bohr postulated the quantum theory of the atom, through the first phase of quantum theory, namely the formulation of quantum mechanics in 1925, even in that 13-year period we see a recognition that, in principle, chemistry has been reduced to physics. Because, what is it that chemists study? They study the interaction of atoms through their orbital electrons, through sharing orbital electrons. That is what is responsible for chemical reactions. The behavior, the exchange of electrons between two atoms is what forms a molecule.

Since quantum theory is about the behavior of orbital electrons, in principle—only in principle at that time in the 1920s and '30s—we can say that chemistry exists because quantum theory is not sophisticated enough, and we can't solve the extremely complex equations that quantum theory would use to describe the actual behavior of multiple atoms interacting under the conditions in which chemical molecules form. But in principle, chemistry is reduced to physics.

So if biology has been at a certain level, namely at its most fundamental level, reduced to chemistry, then it has really been reduced to physics. Then the Cartesian notion that life is a form of matter in motion, extremely complex motion, is resurrected in a much more sophisticated form within this framework of the intersection of biology, physics, and chemistry, which was increasingly recognized as such in the 1920s and '30s.

What happened in the 1930s was that physics instruments began to be used by chemists working in biological research so that ideas of physics—especially, for example, ideas borrowed from quantum physics and thermodynamics—became increasingly used by chemists as they studied biological processes at the molecular level. This is another illustration, as we saw in an earlier lecture, of how instruments matter and how instruments interact with theory.

The X-ray crystallograph, a machine that was invented by physicists in order to use X-rays to explore certain concepts in quantum physics, and especially was recognized as being capable of revealing the structure of molecules, the relationship of atoms within molecules; in the mid-1920s physicists used the X-ray crystallographic techniques that were developed, the machines, the hardware that was developed, in order to study certain ideas in quantum theory. But the fact that X-ray crystallography could reveal structure, which we now appreciate emerged out of the 19th century as the key to understanding complex chemical reactions, made chemists want to apply X-ray crystallography within the study of molecular biological processes, to understand the molecules by understanding their structure using X-ray crystallography.

At the same time a physicist in Sweden named Theo Svedberg invented a machine called the ultracentrifuge, which spins very, very rapidly: 100,000 rpm, 200,000 rpm, and 300,000 rpm. Svedberg invented this machine in 1924. By 1926 he was using it to generate data, and using it in order to study the question of whether there were such things as very long molecules, or whether all molecules, even the ones that seemed very long, were really patched together out of little units, smaller molecules that were linked together with weak bonds, which is what most chemists had thought at the time.

A chemist named Staudinger had argued that there were such things as macromolecules, very large molecules containing thousands and tens of thousands and even hundreds of thousands of atoms, and that they were rigid, that they had an integrity. The macromolecule was in fact a unit. It wasn't just built up out of lots of pieces like beads strung on a string where each bead was a relatively small molecule, maybe of a couple of hundred atoms at the most. That was the prevailing view.

Svedberg's machine was able to show very quickly that in fact macromolecules were real, that there were such entities as macromolecules. However, it turns out, through the work of a German chemist named Herman Mark, who extended Staudinger's ideas and showed that in fact the macromolecules are flexible, they're not rigid the way that Staudinger thought they were. Staudinger maybe overemphasized the rigidity in order to emphasize the integrity of the macromolecule, that it had an integrity of its own independent of the units out of which it was built up.

Mark became one of the pioneers of polymer chemistry, extremely famous as a polymer chemist using the techniques of X-ray crystallography and the ultracentrifuge, etc., and for founding the discipline called polymer chemistry out of which almost every plastic that we use emerges. So an extremely important theory.

In 1930 a young Linus Pauling visited Herman Mark's laboratory. Pauling was one of the first to recognize, and to emphasize, the centrality of quantum theory to chemistry. In 1940 his textbook on the nature of the chemical bond essentially established the rules for using quantum theory in order to understand chemical bonding. So in 1930 Pauling visited Mark's laboratory, not long before Mark had to flee Nazi Germany and came and resettled here in the United States. Pauling was deeply impressed by the way Mark's laboratory used these instruments from physics—X-ray crystallography, for example, and the ultracentrifuge. When he came back to the United States, Pauling became a kind of a machine for generating grants to the Rockefeller Foundation to buy these kinds of instruments in order to do biological research through chemistry, using these instruments from physics and, of course, guided by his understanding of quantum theory.

The man he had to get the money from was Warren Weaver. Weaver was deeply committed to getting physics into biological research. He funded lots of laboratories around the United States to acquire these instruments, plus the newly invented—after Pauling visited Mark, in 1931, the electron microscope was first introduced—getting electron microscopes into the hands of American biological researchers, to getting X-ray crystallography machines, getting ultracentrifuges, as well as other techniques, such as electrophoresis and chromatography, which I'm not going to discuss. These are the core techniques that were used in order to study the molecules and the molecular processes that are fundamental to life phenomena. And Pauling succeeded.

Well, Weaver himself had a deep commitment to the ultracentrifuge, having given Theo Svedberg a quarter of a million dollars to create an ultracentrifuge institute at his university in Sweden. The return to America for that quarter of a million dollars was that Svedberg not only gave to the Princeton biology department the latest model ultracentrifuge, but he kept them up to date as the machine kept being improved, in order for Princeton to be able to have a department that was at the cutting edge of biological research as Weaver conceived what that research ought to be like.

Now, an illustration of how chemists using these techniques from physics, instruments from physics, moved into biology in important ways is reflected in, for example, the work of a very excellent woman biologist, Dorothy Crowfoot Hodgkin (not associated with Hodgkin's disease), who used X-ray crystallographic technique in the early 1940s to discover the structure of penicillin. She worked out the complete molecular structure of the penicillin molecule, then she worked out the complete molecular structure of vitamin B12, which is what she wound up getting a Nobel Prize in physiology of medicine for.

Meanwhile Linus Pauling, who was supported by grants from 1937 to 1951 in this area, and focused his research on using these physics instruments and concepts in his biochemical research, made fundamental contributions to what Weaver had called molecular biology. In the early 1940s Pauling showed that the relationship between antigens and antibodies, between the antibodies created by our immune system and the antigens that enter into the bloodstream from outside the body, that this is a structural process. The relationship between antigen and antibody is a structural one. The molecules lock onto one another.

There is an issue here of molecular recognition. How is it that an antibody recognizes an antigen that it is capable of destroying? How does that happen? Well, Pauling showed that this was a structural feature. Emil Fischer, I had said in an earlier lecture, had developed this idea of lock and key relationships between molecules, that the antigen molecule, the antibody molecule, are like a lock and a key. The ones that fit together are the ones that act on one another. Antibodies can destroy those antigens that they can lock onto.

Here we see a structural feature that is fundamental to a fundamental life process. This is a clear example of molecular analysis (in this case molecular structure), that a biological problem reduces to a molecular biological problem, which reduces to a problem in chemical structure. And of course it was possible to analyze this through the use of the X-ray crystallograph and other techniques which chemists developed, in many cases borrowing ideas and concepts and instruments from the physics community.

In the late 1940s Pauling showed that sickle cell anemia is the result of a structural deformation of red blood cells in which the electric charge is not uniformly distributed around the red blood cell. Instead of being disk shaped it's puckered or elongated, and this causes problems in the circulatory system because sometimes these cells cannot fit through the capillaries, and so the tissues in the body are not sufficiently oxygenated. They're not getting enough oxygen.

Pauling showed that this sickle cell anemia, a very important and debilitating illness, is caused by a change in one amino acid in one particular protein, which we would say is produced by a particular gene. So the gene misreads, the gene causes one particular amino acid in a long chain for the protein that is responsible for the shape of the red blood cell to be out of order, and as a result we see that the red blood cell is misshapen, and that's what causes the disease. Nowadays we think that this is only partially true, but that was another powerful illustration of how physics and chemistry are the linchpins of biological research.

Then, of course, Pauling at the beginning of the 1950s, in 1951, went on to discover the single-stranded alpha helix structure of RNA molecules, looking for the nucleic acid that ever since Friedrich Miescher, back in somewhere around the 1870s, had suggested that there was a nucleic acid, there was an acid in the nucleus that was important for cell division and reproduction. Pauling first picked on RNA, and used X-ray crystallography to find the structure of RNA as the alpha helix, and was now studying DNA when he was scooped by Watson and Crick in 1953. They discovered, using the X-ray crystallographic data of Rosalind Franklin and her collaborators, they were able to interpret that data and understand that the data were telling us that the DNA molecule had a double helical structure.

In 1957 the last doubters as to whether DNA was really what we mean by gene, or that what we mean by the genes are somehow in or on the DNA molecule, were more or less convinced by a beautiful experiment by two biologists named Meselson and Stahl, who were able to show how the DNA molecule replicates, which was as speculated by Watson and Crick in 1953. The two strands separate from one another; they sort of unzip in a systematic way. They unzip, and as they do so each strand forms a complementary strand, and then you now have two DNA molecules, two double helixes. This process of course goes on at every stage at which the DNA molecule reproduces.

The Meselson–Stahl experiment in 1957 really, I think, locked up the idea that DNA is the molecule to understand, and if you could understand that molecule you will understand life. I think that the dominance of molecular biology since the 1960s in biological research must be understood in relationship to this reaction to the discovery of the structure of DNA. We see that there's a long history leading up to this. It wasn't that all of a sudden in the 1950s and '60s people were saying that, you know what, life is just a matter of matter in motion, or that life can be explained at the level of physics and chemistry. There is a long history here, which I've attempted to give a little bit of a clue to.

In 1912 Jacques Loeb had written a book called *The Mechanical Conception of Life* that had a very strong influence on many biological and psychological researchers. Loeb was a strict reductionist, reducing life to physics and chemistry, and that idea continued to be influential long before the 1950s. But what happened, and especially since 1972 when Paul Berg and his collaborators introduced the first successful recombinant DNA techniques in which they took genes from a virus and a bacterium and coupled them in a functional way, that that really unleashed the biotechnology industry, which over the last few decades has fundamentally changed medicine, and therefore is fundamentally affecting us. It will be even more fundamentally affecting us, barring some calamitous implosion of Western civilization, over the coming decades because of the continually growing understanding of the way that molecules function, the way that processes in the cell, and in organs, and in organisms interact in ways that can be understood once we get down to the molecular level.

Of course, nowadays molecular biology is such a buzzword that if your research is not in molecular biology then that's bad. Lots of research that is not in biology, that is not really within the framework of molecular biology as strictly understood, is called that anyway. A number of biology departments at universities and colleges across the country have renamed themselves to be the department of molecular biology, or at a minimum one of the curricula that you can follow within the biological science department would be a program, a track in molecular biology. That's practically a *sine qua non* nowadays to be recognized as having a modern biology department.

The impact of molecular biology on us is much deeper than I think most of us realize when you start putting together all of the different ways in which it has influenced the practice of medicine. Molecular medicine is the norm. We have an increasing number of medications that are derived from the techniques of manipulating molecules at the level of the cell or lower, or manipulating DNA. For example, using bacteria that have been genetically altered to produce insulin: the Food and Drug Administration approved the commercial production of insulin using genetically altered bacteria in 1982. We have now a wide range of human hormones that are produced by bacteria.

In 1980 the first transgenic plants and animals were created, in which plants and animals were genetically modified by putting plants from one species together with another in order to produce specific effects. Or to introduce viruses or bacterial genes of a particular sort into plants and animals in order to improve the properties of the plant as a whole—so, the whole genetically modified food industry.

In the case of transgenic animals, using animals to explore diseases, especially human diseases, much more accurately, by using animals to carry the disease or by using animals to produce substances that human beings need and that previously had been synthesized in more expensive or complicated ways, or could not be successfully synthesized, but now are produced by these animals, because genes have been inserted in them to allow them to do that.

So there are just so many ways, besides the promise of genetic engineering and stem cell research, which are largely unfilled yet—almost totally unfilled yet. We have not been able, in a systematic way, to genetically engineer our bodies so that they function better, but we are clearly on track to do that. The same thing is true with the potential impact of stem cell research, if we can use these techniques in order to produce tissues and organs in order to replace ones that have failed or that are in the process of failing.

Molecular biology is an idea that gestated from antiquity through the 17th century and has become a major transformational idea in the late 20th and now early 21st century.

Lecture Thirty-Six
Great Ideas, Past and Future

Scope:

Scientific ideas, built on the ideas of science and techno-science, have changed the world and, for the foreseeable future at least, will continue to do so. At the “highest,” most abstract level, the historic dominance of Parmenidean substance metaphysics has given way to a progressively greater role for Heraclitean process metaphysics. The idea that all natural phenomena were produced by chemical “elements” made up of truly elementary particles has been qualified by the idea that also elementary are hierarchically ordered systems manifesting relational and information structures and self-organization to sustain lawful but unpredictable, far-from-equilibrium states. Self-organization is fundamental to the emerging nanotechnology industry, which promises to become the defining technology of the early 21st century, while a synthesis of Parmenidean and Heraclitean metaphysics is fundamental to string theory and its highly controversial attempt to unify the forces of nature into a comprehensive theory of everything.

Outline

I. The mosaic “big picture” that emerges from the individual lectures in this course is that science, allied to technological innovation, became the dominant driver of social change because society empowered it to play that role.

- **A.** The biggest single piece of that mosaic picture was the emergence in ancient Greece of the idea of science itself.
  1. That ancient idea of science erupted in the 17th century as modern science.
  2. It is an expression of particular definitions of *knowledge*, *reason*, *truth*, and *reality* and the relations among them.
  3. The invention of mathematics as a body of knowledge matching these definitions and the connection of mathematics to knowledge of nature were fundamental to the idea of science.
- **B.** One lesson to be learned from this Greek invention of the idea of science is the centrality of definition to science.
  1. Scientific reasoning inevitably begins with definitions of terms and concepts, but these definitions are contingent.
  2. Scientific definitions are not “natural”; they must be proposed, and they change over time, as scientists’ explanatory objectives change.
- **C.** The idea of techno-science also emerged in antiquity, in the Graeco-Roman period.
  1. Although the idea of techno-science may seem an obvious extension of the pursuit of knowledge of nature, it is not.
  2. Plato and Aristotle explicitly excluded know-how from knowledge and explicitly separated understanding from action.
  3. This elitist view of theory-based science as different from, and superior to, practice-based technology was prominent in the 19th century and continues today.
  4. Secondly, Graeco-Roman science was so modest that the idea that science could be the basis of powerful new technologies was truly visionary.

II. The second largest piece of the mosaic was the emergence of modern science in the 17th century.

- **A.** The second cluster of lectures aimed at showing that the rise of modern science was an evolutionary development, not revolutionary.

1. One of the roots of modern science is the rebirth of cultural dynamism in western and central Europe in the period 1100–1350.
2. The invention of the university recovered and disseminated to tens of thousands of students the Greek ideas of knowledge, logic, mathematics, and knowledge of nature.
3. The university also disseminated the secular and naturalistic values that are implicit in pursuing knowledge for its own sake.
4. These values were reinforced by the concurrent industrial revolution, which recovered and innovated upon Graeco-Roman know-how in agriculture and industry in conjunction with expanded commerce.
5. This created a broad and deep body of mechanical know-how in Western society.

B. A lesson about the science-society relationship from this cluster of lectures is the dependence of the social impact of science and technology on society.

1. Technological innovations, as Lynn White said, merely open doors.
2. The same innovations have had very different impacts on different societies.
3. In each case, the way innovations are implemented in a society reflects values and institutions characteristic of that society, not of the technology.
4. But this is just as true of scientific knowledge as of technological know-how: Ideas are analogues of innovations.

C. A second root of modern science is the culture of the Renaissance (1350–1600).

1. In the 15th and 16th centuries, the idea of progress was explicitly identified with growth of knowledge and knowledge-based know-how, techno-science.
2. The Humanists made important Greek mathematical and scientific texts available to the Latin-speaking West, and they developed critical methodologies for recovering corrupted texts that influenced the scientific method.
3. Mathematics became the basis for a wide range of new technologies, reinforcing the view that mathematics was the key to knowledge of nature.
4. The response of Western societies to Gutenberg's new print technology illustrates how technologies merely open doors and created the medium modern science would adopt.

D. The emergence of modern science reflects its indebtedness to antiquity, the late Middle Ages, and the Renaissance.

1. The ideas of knowledge, deductive reasoning, mathematical physics, and progress were all part of the intellectual environment, as was the university as an institution that taught these ideas at an advanced level.
2. The accomplishments of the founders of modern science in the 17th century are built on these ideas, including the idea that knowledge of nature will give power over nature and that this is the key to progress.

III. Modern science matured in the 19th century, and its theories and ideas became fertile from the perspectives of understanding nature and acting on nature.

A. These theories reflect two distinct approaches to the study of nature: the substance or atomistic approach and the process approach.

1. The atomic theory of matter, the cell theory of life, the germ theory of disease, and the gene theory of inheritance, in their initial formulations, all reflect the atomistic approach.
2. Theories in physics and chemistry based on new ideas of energy, fields, and structure reflect the process approach.
3. The Darwin-Wallace theory of evolution explains the range of living things as the changing outcome over time of an ongoing process.
4. Concurrently, the idea of statistical laws underlying natural and social phenomena challenged the determinism implicit in the idea of knowledge as scientists had assimilated it.

5. **5.** Quantum mechanics is our deepest theory of matter and energy, and it is a probabilistic theory.

B. Twentieth-century theories reveal a continuing challenge to elementary substance approaches to nature.

1. **1.** The context of 20th-century scientific theories reveals the influence of new institutions created specifically to promote science-based technological innovation.
2. **2.** This reinforces the extension of Lynn White's dictum about the relationship of technology to science: The science-society connection is dynamic and reciprocal, such that neither is independent of the other.
3. **3.** Twentieth-century science and technology reflect the increasingly cross-disciplinary character of scientific research and its applications, which couples society back to science through the response of society to technological innovations.

IV. We can, cautiously, anticipate scientific ideas and technological innovations that will transform 21st-century life.

A. The social impact of technological innovations is unpredictable, but at least two families of innovations can be predicted with confidence to open many new doors in the coming decades.

1. **1.** We are just beginning to develop commercial applications of nanotechnologies, but these will almost certainly define a new stage of techno-science.
2. **2.** It is already clear that self-organization is the key to the successful mass production of nanotechnological devices, and this is another illustration of how an abstract idea or theory can have important practical applications.
3. **3.** The second family of innovations is the continuing development of biotechnologies, which are inherently self-organizing.

B. There are two areas of science that can also confidently be predicted to have major social impacts in the next half-century.

1. **1.** One of these areas is the continuing naturalization of consciousness via molecular and computational neuroscience, with profound consequences for what it means to be human.
2. **2.** It is likely that new technologies for controlling moods, behavior, memory, and learning will be developed, posing deep ethical and moral challenges.
3. **3.** The other area is the pursuit by physicists of a theory of everything, a theory that unites the four fundamental forces of nature into a single, comprehensive, universal theory of matter and energy, indeed, of the Universe.
4. **4.** Quantum theory seems to be the best foundation for such a theory, given that the standard model already unites three of the four forces. String theory has the greatest visibility as the approach to full unification, but it has serious problems.

C. The pursuit of unification is interesting in and of itself.

1. **1.** The quest for unification seems perennial in Western culture.
2. **2.** Monotheism is the product of one unification, and Greek materialistic monism, another.
3. **3.** It is also interesting that so many modern scientific ideas echo ideas articulated by Greek philosophers more than 2000 years ago.
4. **4.** With some scientists claiming that we are now, *really*, on the threshold of unification, it is important to recall that we have been there before!

Essential Reading

Mark Ratner and Daniel Ratner, *Nanotechnology: A Gentle Introduction to the Next Big Idea*.

Leonard Susskind, *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design*.

Questions to Consider:

1. Are we today better equipped to manage the social impact of emerging nano-, bio-, and mind-technologies than we were when managing the last generation of innovations?
2. If we are approaching the end of creative scientific theorizing, what are the cultural implications of such a development?

Lecture Thirty-Six
Great Ideas, Past and Future

In the very first lecture of this course I said that by the end of the lectures the individual explorations of ideas would fit together to form a coherent picture, as a picture that emerges out of a mosaic. You've got all these individual little tiles, or pieces of a jigsaw puzzle, and from the individual pieces you don't see the overall picture, but when you put all the pieces together correctly, then a picture emerges. I said in the first lecture that that would be the case with this course, and so we have a right to ask now, in this closing lecture, what is the image that has emerged? If we put together all of the pieces that we have sketched out (mixing metaphors), then what is the picture that we see?

I think that the picture is that science is as much a social as an intellectual phenomenon. That's the picture. The picture reveals that science is a driver of social change—which was the motivation for the whole course, to try to understand how scientific ideas have changed the world, how they continue to change the world. That science is a driver of social change because society has empowered science to be a driver of social change. That, I think, is the conceptual picture. That is the image of science that emerges from putting together all of the ideas that we have been exploring.

Let me suggest how that happens. The biggest piece in the mosaic was the discussion in the first six lectures of how the idea of science emerges out of very deliberate, highly controversial at the time, definitions of knowledge, reason, truth, and reality among the ancient Greek philosophers. That in the context of these very specific definitions the idea of knowledge of nature, and in particular of mathematics as the underlying order of nature, linked to experiment and observation, but that mathematics as an underlying order emerges as part of an idea of knowledge of nature. So the idea of science in its first articulation is keyed to these deliberate definitions.

A generic lesson that we learn from this is that definition plays a fundamental role in the practice of science; and continues to do so, of course, as we saw when the atom continually is redefined as we find out more things about it, that it wasn't the solid atom that Newton and Dalton thought, and that it wasn't just the solar system model as conceived by Rutherford, etc. This is one generic lesson that emerges: that contingent definitions of scientific terms, that scientific concepts, are not natural. They are invented. They are formulated with specific objectives in mind.

The idea of science in the ancient world represented one big piece of the mosaic. And the tail-end of that piece, so to speak, a little projection from that, was the idea of techno-science; which is quite startling in antiquity for two reasons. First, because the knowledge of nature that was possessed in the Greco-Roman period was barely useful in any way. So the claim that knowledge of nature would be the source of powerful technologies is a very interesting claim. The second reason why the idea of techno-science startles us is because, as we noted, Plato and Aristotle, the Greek philosophers who defined knowledge in the way they did, explicitly excluded know-how from knowledge. They didn't want know-how to be a part of knowledge, and Plato and Aristotle would not have considered it a plus for science, for knowledge of nature, that it was being used in order to act on nature. That was, for them, a much less noble activity. That was art; that was craft; that was not true knowledge of the kind that ennobles the soul or that reflects the highest form of human being in the world.

This elitism with regard to science and scientific knowledge, that it should not be translated into technological innovation, continued right through the 19th century. Here in America there were bitter controversies over pure science versus applied science—the commercialization of science. I referred in one of the lectures to Joseph Henry, professor of physics at Princeton in the early 19th century, who invented an electric telegraph before Morse did but refused to commercialize it. He sort of just showed Morse the error of his ways in terms of physics, but did not want to be a consultant to his company or to have a share in the company by being their science advisor.

So that was one piece of the mosaic, and one of the powerful lessons that it gave us was an insight into the role that conjectural, contingent definition plays in the process called science.

The second largest piece of the mosaic was the rise of modern science in the 17th century. We needed to understand how the emergence of modern science in the 17th century was not a revolutionary development, but it was an evolutionary development out of developments in the Renaissance, in particular from the 12th century through the Renaissance, specifically highlighting the role of the idea of progress. The idea of progress came to be identified with technological innovation, and especially with the application of scientific knowledge, mathematics initially, to generate new kinds of technological capabilities—the idea of progress as a secular knowledge. We saw how the 12th century industrial revolution (as I called it), the 12th century cultural Renascence, and the university as an institution, a vehicle of that cultural Renascence, was deeply imbued with secular and naturalistic values as opposed to religious values—and was sometimes in conflict with religious values, as for example in the problem with usury and the expansion of commerce at that time—and through the Renaissance provides not just the seedbed for ideas for modern science, but a motivation for pursuing knowledge, and for linking that knowledge to technological action of the sort that causes the physical and social world to be changed.

We saw how Francis Bacon and René Descartes in the early 17th century, founders of modern science, explicitly stated the promise of true knowledge of nature would translate into power over nature. Here the lesson is, what we saw repeatedly was that technological innovations opened doors, but the way societies responded to them is a function of the society, not a function of the innovation. The same innovation, so to speak, at some technical level in China, Islam, Japan, and in Western Europe had evoked very different responses from the respective societies. We saw this in the case of printing, especially, and with reference to gunpowder and the compass as well, and the use of mathematics in order to generate new kinds of technologies that were put into action by society. Society determines whether that society will enter through the doors that are opened by technological innovations.

But then we saw that a third lesson is that scientific ideas also open doors. We saw this in the case of Copernicus's redefinition of the universe. We saw this in the case of the 17th century founding knowledge of nature on an impersonal method, removing the person from the knowledge claims, and insisting that knowledge was generated by the operation of an impersonal, an objective methodology, as we would call it today. It was keyed to mathematics as the language of nature, experiment and observation captured in universal laws with a mathematical form.

We see here how indeed the emergence of modern science, how deeply indebted it was to the idea of science as it was articulated in ancient Greece, and the motivation to science and to the translation of scientific knowledge into action on the world that is contained within the idea of progress. The idea of progress is a motivator. It's a driver. And that's why, even though we don't normally associate the work of somebody like Newton with the idea of progress, the social perception of scientific knowledge and its value is carried to a considerable extent, and in the 19th century explicitly so, by this idea that knowledge is going to give us transformative power over our experience.

We then began to accumulate individual tiles in this mosaic by looking at the ideas underlying the great theories of science, especially in the 19th and 20th centuries when those theories became fertile enough to be translated into technological action—what I called techno-science. There I divided the ideas into two clusters. I pointed out how through the 19th century there was a strong prejudice in favor of an atomistic style of thinking, and we saw this reflected in the atomic theory of matter, in the cell theory of life, in the germ theory of disease, and in the gene theory of inheritance.

Beginning in the mid-19th century, and increasingly since then, we have seen the rise of what I called a process style of thinking through the idea of energy, the idea of the field, the idea of relationships having causal efficacy. For example, the structure, as we just discussed in the preceding lecture, the structure of molecules: the same atoms arranged differently in space have different properties. Evolution as a process—what evolution explains is by way of a process rather than by things—by identifying atoms (metaphorically speaking) with fixed properties, and the rise of the notion of statistical laws, and the introduction of probability (stochastic processes) into nature at the most fundamental levels of phenomena.

In quantum theory, really our ultimate theory of matter and energy, a fundamentally stochastic dimension to quantum theory that has a probabilistic character to it. We saw that that prevented Einstein from accepting it as the ultimate theory of nature because of his insistence on a more classical deterministic notion of what it meant to explain; namely to deduce with certainty. So probability is a stopgap from that perspective, but the consensus of the physics community is that quantum theory is correct, and that its probabilistic character is a reflection of the ultimately probabilistic character of the most fundamental processes in nature.

We looked at 20th century theories that carried forward these classical ideas, the idea of science and the styles of thinking which have become intertwined by the end of the 20th century—the quantum theory, the relativity theory, the idea underlying the computer, the idea of a mathematical theory of information, the systems idea, molecular biology. These individual ideas now fit together, I think, and show that scientific ideas win acceptance and change over time in ways that reflect the role that science plays in society. That institutions needed to be created in order to make it possible for these scientific theories and the rich ideas at their cores to translate them into technological action. We saw again how society created institutions in the 19th century and the early 20th century—commercial institutions, industrial institutions, academic institutions, governmental institutions—in order to empower science to become the agent of change that it has been, primarily of course since the early 19th century.

Here we have, I think, a useful image that emerges out of these individual lectures. That while the individual pieces have an individual character of their own—we can talk about the quantum theory—but always connecting the theories to other theories that they are co-related with. We saw that, again and again, I would have to say, “Well, as we saw with the cell theory of life…” or “As we saw in the rise of probability theory…” And these ideas cross-fertilize one another in ways that are not immediately obvious, as we saw in molecular biology and the indebtedness of molecular biology to quantum theory, to chemistry generally, to physics generally. This was true in so many other areas.

This cross-fertilization is a reflection of the fact that these ideas do not exist in a vacuum. You don’t have a specific individual who is sitting and thinking deep thoughts that are completely original with them. Ideas function within a social context. They have to be transmitted. They have to be disseminated. We talked about the role of writing and the role of text in disseminating knowledge. Ideas need to find manifestation, dissemination, transmission, and they need to be taught. These are all social functions. So, again, ideas emerge as door openers, and the way that a society responds to those ideas is because society makes the decision to respond to those ideas.

Now as we come to the beginning of the 21st century it is, I think, reasonable to ask if we can identify what, over the next few decades, are likely to be ideas that are going to be perceived as changing the world, over the next few decades, in ways that are analogous to the way that science and technology have changed the world over the last 200 years.

Extrapolating from the status quo is a perilous thing to do, even when you’ve been on a four hundred year roll. But assuming that there are no catastrophic changes to Western society over the next few decades (which is something we all hope for, but there are other possibilities), assuming that current institutions, roughly speaking, sort of morph into modifications of themselves but don’t radically change, then it seems to me that we can, from the point of view of science and techno-science, we can identify three areas that are likely to be perceived by society, to be empowered by society, to generate fundamental change.

The most pragmatically rich one of these is, of course, nanotechnology, which I referred to in an earlier lecture. Nanotechnology is very likely to be the techno-science of the 21st century that semiconductor physics-based microelectronics technologies were in the last third of the 20th century. Nanotechnology will be intensively using quantum physics and quantum chemistry. When you're talking about a nanometer, a nanometer is a billionth of a meter, so now we're talking about sizes that are comparable to the size of small clusters of atoms. Once you get down to atomic, small molecule sizes, or the sizes of atoms, then the behavior of those atoms is no longer reliably captured by classical physics—physics from the 19th to the mid-20th century. You've got to use quantum physics. And so quantum physics and quantum chemistry will become important knowledge bases that will be used to create new technologies based on structures that small.

Interestingly, it is increasingly being discovered by companies that are doing research in nanotechnology that self-organization is a critical factor in fabricating nanostructures—structures on this scale of a billionth of a meter—making machines, making devices, making tubes, and making containers for atoms and molecules, making little cages. What they are discovering is that the chemicals that they mix under the appropriate combinations and circumstances of temperature and pressure, etc., self-organize, just as Prigogine described. Without this self-organization it would be tedious, in fact perhaps even impossible, to commercially manipulate one atom at a time in order to create these structures. But it turns out you don't need to do that, that the kind of self-organization associated with organic molecules in living things also takes place among inorganic substances when you manipulate them at this nano level.

There have been in the last few years, especially, a growing number of reports of how to make carbon nanotubes, for example, which ultimately perhaps will be woven into nanofibers that self-organize as tubes when you mix the ingredients in the right way. Very recently a cubic cage that forms automatically once you put down a two-dimensional structure of atoms using the same kind of technique we used to make computer chips, called photolithography; that with the right materials organized in the right way, as soon as you release the two-dimensional structure from the surface on which you laid it down, it forms all by itself into a cube with holes in the sides, and you can trap small molecules or atoms inside the cube and deliver them by moving them from one place to another inside these cages. We also have other size cages that self-form. The idea of self-organization that we discussed in the last lecture is proving to be a powerful new technological tool. So again, techno-science, science-based technology.

The second area that I think is likely to be perceived as changing our world, but perhaps not through technologies, is the continued development of neuroscience, the new kinds of imaging techniques that are allowing us to co-relate brain and mind with increasing detail. This represents really the last step in the total naturalization of humanity, and it has been announced throughout the 19th century with the scientization of psychology, but in fact it's only now that we can really begin to claim that we're beginning to understand how the mind co-relates with specific states of neurons and complexes of neurons within the brain. A lot of this work is coming out of the use of functional MRI (magnetic resonance imaging) techniques and other similar high technology instruments based on science, including quantum physics. Magnetic resonance imaging is based on quantum physics phenomena; namely, the magnetic moments of hydrogen atoms.

What we are going to encounter over the next 20 years is a serious challenge to the last area in which human beings could think that there was really something special about them. This in a sense is the undoing of that little bit of humanity that Descartes tried to buffer from mechanization back in the 17th century: the mind. He thought the mind is not material, so it is not subject to mechanism, we can have free will. Neuroscience has the potential over the next few decades of profoundly influencing our self-image. What the social consequences of that will be are obviously quite unclear, and it may not happen. But it does look as though that's the track on which cognitive neuroscience is moving.

The third area is the one that has prompted a whole mini-industry, and that is the area of what some physicists call "theory of everything." That is the unification of gravity with the standard model in quantum theory, so that we have one single theory that encompasses the four fundamental forces responsible for the behavior of all natural phenomena. If we had such a theory then, in principle at least, we would have an explanation for everything.

Quantum theory, of course, explains the behavior of matter and energy at the atomic level. Through quantum chemistry, at the molecular level, we have a growing field of molecular biology, molecular psychology—explaining the function of the nervous system and the function of the mind in terms of molecules; molecular psychiatry is a well-defined discipline with its own journals and a growing body of knowledge—and even molecular sociology, in the sense of identifying those segments of the genomes of social creatures that are responsible for social behavior. Most recently the genome of the bee, in order to see what segments of that genome are like what segments on the genes of primates, for example, in order to identify that is where sociality comes from; that social behavior, social values are ultimately keyed to molecular structures.

Since the behavior of molecules and atoms is ultimately reducible to quantum theory, a theory of everything would promise to explain everything—everything, in principle, right from matter and energy to sociology. The theory that claims to be on the threshold of doing this is string theory, and that's where the mini-industry is. The mini-industry is in books for the general public about string theory. Now, a reaction to string theory by some physicists is that it's a dead end and we have to admit that it's a dead end and look for other ways of unifying gravity with the general theory of relativity, with the standard model in quantum theory.

What is really interesting, I think, in this process is not the string theory by itself—which contrary to all of these popular books, some of them by quite competent physicists, really is not comprehensible to the general public, to people who do not have significant training in physics and mathematics. Because once you start talking about 12-dimensional space–time structures, and the complex transformations of equations that you need to take into account, people read the words, but I don't think there is a real comprehension of what it means to say that, "What we're now going to say is that ultimately matter and energy are all manifestations of vibrating strings." Yes, anybody can understand that, but now what?

What I find fascinating here is the goal of unification. Remember that the Romantic nature-philosophers of the late-18th, early-19th centuries believed in the ultimate unity of nature, the unity of life, the unity of all the forces of nature. There is a very interesting strand of thought here of desiring unification, of wanting to pull everything together into a single source. All life comes down to a single original cell. All of the universe comes down to a single original instant out of which the entire universe emerged. So unification is an interesting idea all by itself, and the longing for unification as opposed to having a palette of theories that you can dip into to paint the picture of reality that you want to paint.

It is difficult in thinking about unification not to hear echoes of monotheism, for example, the idea of condensing all the gods of pagan antiquity into one god. And also echoes on a secular level, of ancient Greek philosophy at the level of materialistic monism. In an earlier lecture I mentioned that some of the earliest Greek philosophers, like Thales, believed that there was really only one stuff out of which all of nature was composed. I mentioned that he called that stuff water, but perhaps more generically he meant fluid. So the idea that all of nature emerges out of a single stuff that is variously processed, that is condensed or rarified or combined in various ways, is already a theme in ancient Greek philosophy.

It is, I think, extremely interesting that so many ideas that have been fleshed out and incorporated into 20th and 21st century science can actually be linked to speculations in ancient Greek philosophy, like the concept of the atom, like the concept of the field in ancient Stoic physics, like this unification idea. I think the thrust to unification within physics has very interesting cultural echoes and cultural implications.

The question that we confront at the close of this course is: Are there great scientific ideas in our future, or are all the great scientific ideas in the past? If the theory of everything pans out, will it now become the case that in the future, science has pretty much done its job and techno-science will dominate? That applications of the knowledge that the theory of everything will give us will be the dominant factor changing our world, but not new scientific ideas?

This claim has been made before. The claim that science is pretty much over has been made before; explicitly at the turn of the 20th century, right around 1900, when physicists were convinced that they pretty much had nature wrapped up, except for a couple of small points. Those small points turned out to be quantum theory and relativity theory.

So it is tempting to say that the same thing is likely to happen now, and that new scientific ideas will appear in the next few decades that will fundamentally transform 21st century science the way 20th century science transformed 19th century science. On the other hand, since, as people say, “A broken clock is correct twice a day,” maybe by saying this now, saying that now science really is over, maybe it is. Only time will tell.

Timeline

9000 B.C.E. .... Domestication of grains and fruits begins

7000 B.C.E. .... First evidence of copper smelting; evidence of drilled teeth

6000 B.C.E. .... Earliest evidence of wine making; large-scale settlements in the Middle East

4500 B.C.E. .... Horizontal loom weaving

4000 B.C.E. .... Modern wooly sheep

3500 B.C.E. .... Sumerian cuneiform writing

3000 B.C.E. .... Beer brewing in Sumer; earliest gold jewelry; twill weaving using warp-weighted loom

2800 B.C.E. .... Bronze in use in Sumer; Egyptian hieroglyphic writing

2000 B.C.E. .... Spoked-wheel chariots

1800 B.C.E. .... Egyptian medical and mathematical papyri; Babylonian Code of Hammurabi; alphabetic writing in Ugarit

1500 B.C.E. .... Iron manufacturing; cast bronzes in China; vertical loom weaving

1300 B.C.E. .... Earliest Chinese inscriptions; Phoenician alphabetic writing

1250 B.C.E. .... Glass manufacture in Egypt

1000 B.C.E. .... Steel making on a limited scale

800 B.C.E. .... Hellenic Greeks adopt Phoenician alphabet

700 B.C.E. .... Homeric epics written down

500 B.C.E. .... Cast iron in use in China

5th century B.C.E. .... Thales, Pythagoras, Parmenides, Heraclitus, Anaxagoras, Empedocles

4th century B.C.E. .... Plato, Aristotle, Euclid, Epicurus

3rd century B.C.E. .... Roman conquest of Greece; Archimedes, Apollonius, Aristarchus

2nd century B.C.E. .... Antikythera machine

1st century B.C.E. .... Vitruvius; Chinese invention of paper

1st century C.E. .... Pompeii buried by Vesuvian ash; Frontinus on aqueducts of Rome

2nd century C.E. .... Hero of Alexandria's book of machines; Baths of Caracalla in Rome; watermill complex near Arles; Ptolemy and Galen

451 .... Conquest of Rome by Goths

521 .... Justinian closes Athenian philosophy schools

1086 .... Domesday Book inventory of England

1092 .... Start of the First Crusade

1170 .... Universities of Bologna and Paris founded

1268 .... First weight-driven mechanical clock

1329 .... Start of the Hundred Years' War between England and France

1347 ....First outbreak of plague in Europe

1350 ....Petrarch founds the Humanist movement/idea of progress

1415 ....Brunelleschi rediscovers perspective drawing

1425 ....Jan van Eyck introduces oil-based paints

1453 ....Gutenberg introduces printing with movable metal type

1487 ....Vasco da Gama sails around Africa to India

1492 ....Columbus's first voyage to the New World

1512 ....Michelangelo completes the Sistine Chapel ceiling painting

1515 ....Ferdinand Magellan begins first around-the-world voyage

1543 ....Copernicus's *On the Revolutions of the Heavenly Spheres*; Vesalius's *On the Structure of the Human Body*

1554 ....Gerard Mercator's mathematics-based maps of Europe

1600 ....William Gilbert's *On the Magnet*; Giordano Bruno burned at the stake in Rome

1609 ....Kepler's *New Astronomy* claims elliptical planetary orbits

1610 ....Galileo's telescope-based *Sidereal Messenger*

1618 ....Start of the Thirty Years' War

1619 ....Kepler's *Harmony of the World*

1620 ....Francis Bacon's *New Organon*

1628 ....William Harvey's *On the Motion of the Heart and Blood in Animals*

1632 ....Galileo's *Dialogue Concerning the Two Chief World Systems*

1637 ....René Descartes introduces algebraic geometry

1638 ....Galileo's *Discourses on Two New Sciences*

1648 ....Treaty of Westphalia ends the Thirty Years' War

1660 ....Royal Society of London founded

1665 ....Robert Hooke's *Micrographia*

1666 ....French Royal Academy of Science founded

1673 ....Anton Leeuwenhoek's first published microscope observations

1684 ....Leibniz's first calculus publication

1687 ....Newton's *Principia Mathematica*

1704 ....Newton's *Opticks*; Newton's first calculus publication

1709 ....Jacob Bernoulli introduces modern probability theory

1750 ....Thomas Wright's Newtonian cosmology

1758 ....John Dollond patents color-corrected microscope lens

1767 ....James Hargreaves's spinning jenny

1771 ....Richard Arkwright's water-powered spinning "frame"

1776 ..............................U.S. Declaration of Independence; Adam Smith's *The Wealth of Nations*

1776 ....Watt-Boulton steam engines commercially available

1782 ....Lavoisier discovers oxygen, initiates chemical revolution

1789 ....French Revolution

1794 ....Erasmus Darwin's poem *The Botanic Garden*

1799 ....Laplace's *Celestial Mechanics*

1800 ....Volta invents the electric battery

1807 ....John Dalton introduces modern atomic theory; 1807

1807 ....Georg Friedrich Hegel's *Phenomenology of the Spirit*

1807 ....Robert Fulton's *Clermont* steamboat

1809 ....Jean-Baptiste Lamarck's *Zoological Philosophy*

1822 ....Joseph Fourier's analytical theory of heat published

1824 ....George Boole's laws of thought; Sadi Carnot's *Reflections on the Motive Power of Heat*

1828 ....George Stephenson's *Rocket* steam locomotive

1830 ....Michael Faraday invents the dynamo

1835 ....Charles Darwin returns from his global voyage on H.M.S. *Beagle*

1835 ....Adolphe Quetelet founds social statistics

1838 ....Friedrich Bessel measures the distance to star Cygnus 61

1838/39 ....Mathias Schleiden and Theodore Schwann's cell theory of life

1844 ....Samuel F. B. Morse's pilot installation of an electric telegraph

1845 ....Faraday introduces the field concept

1847 ....Hermann Helmholtz proclaims conservation of *Kraft* (meaning "force" or "power"); the term "energy" would be introduced in 1850

1849 ....Louis Pasteur discovers two forms of tartaric acid crystals

1850 ....William Rankine coins *energy* for *Kraft*; Rudolph Clausius founds thermodynamics, coins the term *entropy*

1851 ....William Thomson proclaims the arrow of time

1856 ....William Perkin discovers the first synthetic dye

1857 ....Pasteur's essay on fermentation founds the germ theory of disease

1858 ....Alfred Russel Wallace's essay on evolution by natural selection

1859 ....Darwin's *On the Origin of Species*

1862 ....Morrill Land Grant Act triggers growth of engineering education in the U.S.

1865 ....Mendel publishes results of his researches

1865 ....Maxwell's *A Dynamical Theory of the Electromagnetic Field*

1865 ....Auguste Kekule announces the ring structure of the benzene molecule

1865 ....First effective transatlantic telegraph cable

1877 ....Robert Koch isolates the cause of anthrax

1879 ....Pasteur introduces modern vaccination

1882 ....Koch isolates tuberculosis bacterium and, a year later, cholera

1882 ....Thomas Edison inaugurates centrally generated electricity

1885 ....Pasteur shows that dead bacteria confer immunity

1895 ....Roentgen discovers X-rays

1896 ....Henri Becquerel discovers radioactivity

1898 ....Marie Curie names *radioactivity*, isolates polonium, then radium

1897 ....J. J. Thompson discovers the electron

1900 ....Hugo de Vries and others rediscover Mendel's results; Max Planck's quantum hypothesis

1903 ....De Vries's *The Mutation Theory*; William Bateson coins the term *genetics*

1903 ....Ernest Rutherford and Frederick Soddy determine lawful randomness of radioactive decay

1905 ....Einstein's "miracle year" of publication

1910 ....Thomas Hunt Morgan localizes the "gene" for fruit-fly eye color

1910 ....Ernest Rutherford's Solar System model of the atom

1912 ....Henrietta Leavitt Swann's variable-star cosmic "ruler"

1913 ....Niels Bohr's quantum theory

1914 ....World War I begins

1915 ....Einstein's general theory of relativity

1918 ....World War I ends

1923 ....Edwin Hubble announces that Andromeda is a galaxy

1925 ....Heisenberg and Schrödinger found quantum mechanics

1926 ....Heisenberg uncertainty principle; statistical interpretation of quantum mechanics

1929 ....Hubble announces the expanding Universe; Paul Dirac founds quantum electrodynamics

1931 ....Electron microscope invented

1935 ....Karl Jansky detects radio signals from the Sun

1935 ....First virus "seen" using electron microscope

1936 ....Alan Turing publishes his principle of the universal computer

1938 ....Warren Weaver coins the term *molecular biology*

1939 ....World War II begins

1945 ....First atomic bombs; World War II ends; ENIAC becomes operational

1947 ....Transistor invented at Bell Labs

1947–1949 ....George Gamow and colleagues propose the Big Bang theory

1948 ....John von Neumann constructs EDVAC; Claude Shannon founds mathematical information theory

1953 ....Watson and Crick announce the double-helix structure of DNA

1956 ....Dartmouth conference on artificial intelligence

1957 ....*Sputnik I* orbits the Earth

1958 ....Jack Kilby and Robert Noyce invent the integrated circuit

1963 ....Penzias and Wilson detect microwave background radiation; Edward Lorenz triggers chaos theory

1964 ....Murray Gell-Mann and George Zweig found quantum chromodynamics

1969 ....Neil Armstrong walks on the Moon

1971 ....First test of ARPANet, leading to the Internet in the 1990s

1971 ....Electro-weak unification wins acceptance

1972 ....Recombinant DNA research begins

1973 ....DEC introduces first “mini-computer” PDP-8

1973 ....Standard model of quantum field theory formulated

1980 ....Alan Guth’s inflationary theory of the Universe; dark matter proposed

1981 ....IBM PC introduced

1984 ....String theory becomes “respectable” in physics

1989 ....Disintegration of the Soviet Union

1990 ....Hubble Space Telescope launched into orbit

1991 ....Tim Berners-Lee introduces the World Wide Web

1995 ....Sixth quark, called *top*, discovered

1998 ....Dark energy proposed

2000 ....Human genome decoded

Glossary

aether: In 19th-century physics, a name for a universal space-filling form of matter or energy that served as the medium for immaterial fields of force.

algorithm: A series of well-defined operations that, if followed precisely, is guaranteed to solve a specified problem.

alphabetic: A name for a writing system that constructs the words of a language out of intrinsically meaningless symbols, in contrast with syllabic or ideographic writing systems.

amino acid: Typically in biology, this refers to one of 20 variants of a complex molecule—in which an NH_2 grouping of atoms shares a carbon atom with a so-called carboxyl group—out of which living cells construct proteins.

analytic geometry: Using algebraic equations to represent geometric forms and to solve problems in geometry or problems in algebra that previously had been solved using geometry, a Greek preference that was still common through the 17th century.

axiom: A statement whose truth is self-evident, hence, can be used for purposes of inference without requiring a proof that it is itself true. Sometimes used loosely for a statement that we are to take as true without further proof because true statements can be inferred from it deductively.

binary system: In arithmetic, a number system employing only two symbols, 0 and 1, to represent all possible numbers and the results of all arithmetic operations; more generally, any strictly two-place characterization of phenomena: for example, on-off or true-false.

block printing: Printing texts by carving the writing symbols into a block of wood that is then inked and pressed onto the writing surface.

cartography: Mapmaking.

central-vanishing-point perspective: A technique for creating the illusion of depth on a two-dimensional surface, for example, a wall or a canvas, such that the viewer "sees" the content of a painting as if the depth were real.

chromatic aberration: Distortion that worsens as magnification increases, caused by the fact that the focal point of a lens is a function of the frequency of the light rays striking it, while natural light contains multiple frequencies, leading to multiple foci and blurry images.

classification problem: Identifying classification categories that organize some set of objects into groups in ways that reflect features of those objects rather than values projected by the classifier.

coal tar: The residue, long considered waste, from burning coal in a closed vessel in order to generate a flammable illuminating gas that was sold for lighting (gaslight) and for cooking and heating.

coke: Burning piles of coal in a controlled way, such that only the outer layer of the pile is consumed, converts the inner material into coke, which can substitute for charcoal in iron-making, dramatically lowering costs.

concrete: A construction material composed of a binder or cement; an aggregate, typically sand and/or gravel; and water. Modern concrete, so-called Portland cement, is very similar to Roman cement, which used quicklime, pozzolana (volcanic ash soil), gravel, and water. The strength of concrete comes from the chemical combination of the water with the binder.

contingent: Dependent, for example, on context, time, or circumstances, hence, not necessary.

conventionalism: The view that classification categories—*tree*, *fish*, *planet*—have no reality apart from the individual objects being classified and reflect features of those objects that have attracted the selective attention of the classifier.

cosmos: Ancient Greek name for the Universe as an ordered whole, though not all Greek philosophers meant by *cosmos* everything that is, as we do.

cuneiform: A way of writing in which the symbols of a writing system are inscribed into a medium, for example, into clay tablets using a stylus.

deduction: A form of reasoning in which the truth of an inferred statement, the conclusion of a logical argument, is guaranteed, that is, follows necessarily, from the truth of some other statements, the premises of that argument.

demonstration: Literally, a "showing," but in reasoning, a deductive logical argument.

dialectic: In Greek logic, a form of reasoning in which the premises of an argument are not known to be true—either self-evidently or deductively—but are assumed to be true in order to explore their logical consequences.

digital: In modern technology, the representation of any phenomenon in discrete numerical terms, typically binary, in contrast with continuous analog representations. Where analog computers are customized to specific problems, digital computers have a universal character (if the numerical representation is valid!).

double-entry bookkeeping: Introduced to the West from Islam circa 1200 and popularized during the Renaissance, this method of record-keeping allowed precise tracking of debits and credits at a time when the scale and complexity of commerce were growing.

dynamo: A machine, commercialized from the 1870s, based on Michael Faraday's dynamo principle of about 1830, in which an electric current flows in a conductor as the result of the relative mechanical motion of the conductor and a magnet.

electrochemistry: Using electric currents to dissociate chemical compounds into their constituent elements, thereby identifying the constituents and permitting the study of "pure" elements.

electro-weak theory: The 1960s theory developed by Sheldon Glashow, Abdus Salam, and Steven Weinberg that unified the electromagnetic force, exerted by photons, and the so-called weak nuclear force, exerted by a family of particles called intermediate vector bosons, that is associated with radioactivity but also affects the electron family of particles, quarks, and neutrinos.

emergent property: A property of a whole that is not displayed by the individual parts of the whole *and* has causal consequences of its own.

empiricism: The view that all knowledge claims are ultimately validated by observational experience.

engineering drawing: A means of exhaustively characterizing the form of a three-dimensional object, however complex, using two-dimensional drawings. Renaissance engineers adapted perspective drawing to achieve this end and invented cutaway and exploded representations to show how machines were built; later, engineers and architects adopted orthogonal projections as a standard.

Enlightenment: A name given by 18^{th}-century intellectuals to their age as one in which reason was used to improve mankind's physical, moral, social, and political condition.

enzyme: Enzymes are proteins that function as catalysts in metabolic processes; that is, they enable reactions but are not consumed in those reactions. Like all proteins, they are composed of amino acid complexes.

epicycles: A name for hypothetical centers of uniform circular motion for the planets to account for the fact that, viewed from the Earth, the planetary motions seem to be neither uniform nor circular.

ether: See **aether**.

feedback: A term popularized by Norbert Wiener's cybernetics theory in the 1940s, feedback refers to returning a portion of the output of a system or process to its input. Positive feedback reinforces the input, leading to a continually increasing output up to the limits of a system; negative feedback reduces the input and can, thus, be used to regulate the ratio of output to input.

floating point arithmetic: A scheme for representing numbers of any size compactly for purposes of automated calculation, as in a computer.

fractal: A name coined by the mathematician Benoit Mandelbrot to describe a family of shapes that occur throughout nature and are describable by a particular family of highly abstract mathematical functions. These shapes violate the traditional conceptualization of objects as being one, two, or three dimensional.

germ plasm: In the 1880s, August Weismann argued that sexually reproducing organisms inherit their distinctive character through a line of sexual cells, the germ plasm or germinal plasm, that is wholly isolated from the life experiences of the organism—hence, no inheritance of acquired characteristics, contra Lamarck. For us, DNA is the germ plasm.

hieroglyphics: An ideographic writing system, such as the one initially used by the ancient Egyptians in the 3rd millennium B.C.E. It evolved over the next 2000 years into increasingly stylized symbols that eventually represented syllables rather than ideas.

hydrostatics: The study of floating bodies in equilibrium, whose principles were first formulated by Archimedes in the 3rd century B.C.E. He also studied hydrostatics, the behavior of fluids, for example, water, in motion and the pressures they exert, which is directly relevant to the design and construction of water clocks and water- and air-powered machinery.

ideographic: A writing system in which each symbol, typically pictorial, expresses an idea.

induction: A form of reasoning in which the truth of some statement follows only with some probability from the truth of other statements; hence, it may be false even if those other statements are true, in contrast with deductive reasoning.

innovation: Not a synonym for invention but the form in which an invention is realized in the course of a process that integrates invention, engineering, and entrepreneurship.

kinetic theory of gases: The mid-19th-century theory developed especially by Clausius, Boltzmann, and Maxwell that the observable properties of gases—pressure, temperature, and viscosity—and relations among them are the result of, and are explained by, the motions of vast numbers of unobservable atoms or molecules of which they are composed; furthermore, these motions have only a statistical description.

logic: The name given to the study of forms of reasoning and their rules, independent of what the reasoning is about.

logical proof: See **proof**.

metaphysics: The study of the ultimately real, as opposed to what only appears to be real. The term occurs first as a description of an otherwise unnamed text of Aristotle's that deals with the first principles of being.

modern science: A name for an approach to the study of natural phenomena that emerged in the 17th century, was extended to social phenomena in the 18th century, and is considered to have developed into what we mean by *science* today.

mutation: A discontinuous variation typically in some heritable attribute of a cell, organism, or today, a DNA molecule, by comparison with its "parent." Hugo de Vries made mutations the basis of his 1901 theory of inheritance and of evolution, replacing natural selection with mutations.

nanotechnology: The manipulation of matter and the creation of structures on a molecular scale, with features measured in nanometers, billionths of a meter, or about 10 angstroms on an alternative scale. A DNA molecule is about 4 nanometers wide, and the read/write head of a state-of-the-art hard drive floats about 3 nanometers above the disk.

naturalism: The view that nature is the sum total of what is real, a view espoused by Aristotle against Plato's view that the ultimately real were supra-natural forms.

nucleosynthesis: The synthesis of the rest of the elements out of the hydrogen that is assumed to have been the universal form of matter in the early Universe.

perspective drawing: See **central-vanishing-point perspective**.

plasm: See **germ plasm**.

polymer chemistry: The study and manipulation of the properties of large molecules built on long, linear chains of carbon atoms. Plastics are polymers.

population genetics: Statistical models of the distribution of genes in large populations of randomly breeding individuals. Conceptually, the development of population genetics in the 1920s echoes the ideas underlying the kinetic theory of gases, statistical mechanics, and thermodynamics and the statistical laws of radioactivity and quantum mechanics.

process metaphysics: The view that reality is ultimately characterized by, and is to be explained in terms of, rule-governed processes, as opposed to the substance metaphysics view.

proof: A proof is a logical argument in which the truth of the statement to be proven is shown to follow necessarily from statements already accepted as true, hence, a deductive logical argument.

proteins: Complex, typically very large molecules made up of combinations of the 20 amino acids living cells manufacture, each protein possessing a distinctive spatial arrangement, or folding, of its components. Proteins, which determine cell metabolism, are manufactured on molecules called *ribosomes* in response to instructions from DNA via messenger RNA.

quantum chromodynamics (QCD): The quark theory of matter that developed in the 1960s in which hadrons, protons, neutrons, and all other particles that respond to the so-called strong nuclear force—thus, not electrons and neutrinos—are built up out of some combination of six quarks held together by gluons. Quarks and the electron-neutrino family of particles, called *leptons*, are now the *really* elementary forms of matter.

quantum electrodynamics (QED): The theory that developed in the 1940s out of Paul Dirac's 1929 quantum theory of the electromagnetic field. It describes the interaction of electrons, protons, and photons and is, thus, the quantum analogue of Maxwell's electromagnetic field theory.

rationalism: The view that deductive reasoning is both the only route to truth and capable of discovering all truths.

reverse engineering: Decomposing an artifact or a process in order to identify its components and mode of operation.

rhetoric: In ancient Greece, techniques of persuasive arguing that use the power of speech to win arguments, as opposed to the use of logical reasoning to prove the point.

science: Literally, knowledge, but for mainstream Western philosophy since Plato, it means knowledge that is universal, necessary, and certain because what we know is deducible from universal problems, not from individual facts.

semiconductor: A substance that is capable of being either a conductor of electricity or an insulator, depending on certain subtle and controllable changes in its makeup. Virtually all electronics technology since the 1960s has been based on semiconductor materials, especially silicon.

skeptics: Philosophers who deny the possibility of universal, necessary, and certain truths about nature; hence, they deny the very possibility of knowledge à la Plato-Aristotle and that anyone has achieved it.

spectroscope: An optical device that separates the many individual frequencies that make up the light incident upon it. Because the atoms of each element, when excited, radiate a distinctive set of frequencies, the elements in starlight and in laboratory specimens of matter can be identified.

spinning jenny: The name given to the single-operator–multi-spindle machine invented by James Hargreaves in the 1760s that revolutionized the production of cotton thread.

spontaneous symmetry breaking: An idea adopted by physicists in the 1960s to explain how a uniform state of affairs can evolve into a non-uniform one.

standard model: The name for the quantum theory that unified the electro-weak theory and quantum chromodynamics, hence, the electromagnetic, weak, and strong forces. Since the 1970s, this theory has matured into our most powerful theory of matter and energy.

statistical mechanics: An extension of the ideas underlying the kinetic theory of gases by Boltzmann, Maxwell, and J. Willard Gibbs and developed further by others in the 20th century, including Einstein, for deriving observable properties of systems of material bodies from statistical models of the behavior of their parts.

statistical thermodynamics: The development of the kinetic theory of gases led Boltzmann and Maxwell to apply statistical models to the laws of thermodynamics and, thus, to energy flows.

stereochemistry: The study of molecular properties that derive from the spatial arrangement of the atoms in a molecule, as distinct from the properties that derive from the atomic composition of the molecule.

string theory: The name given to one approach to the final step in unifying the four fundamental forces in nature by uniting the standard model of quantum theory with the force of gravity, now described by the general theory of relativity, which is not a quantum theory. String theory proposes that all forms of matter and energy at all levels are variations on fundamental entities called *strings* that vibrate in 11-dimensional space-time.

substance metaphysics: The view, tracing back to the teachings of Parmenides, obscure even in antiquity, that the ultimate constituents of reality are timeless, changeless "things" with fixed properties, out of which all changing things are constructed and by means of which all change is to be explained.

syllabary: A writing system in which each symbol stands for a syllable in that language and the set of symbols/syllables allows the construction of all words in that language.

symbolic logic: A symbolic notation for recording and analyzing logical arguments and their properties, developed in the 19th century and leading to a revolution in logical theory and to the creation of a new discipline: mathematical logic.

symmetry: Initially descriptive of properties of mathematical forms, in the 19th and, especially, the 20th centuries, it was made into a fundamental principle of the physical world in physics, chemistry, and biology. In physics, symmetry plays a central role in so-called gauge theories, which attempt to unify the four fundamental forces in nature by supposing that they are the "debris" of symmetries that defined

uniform forces in the very early history of the Universe but fragmented as the Universe cooled. See **spontaneous symmetry breaking**.

system: An ordered whole of mutually adapted parts keyed to the functionality of the whole.

taxonomy: A taxonomy is a systematic classification scheme that may be explicitly artificial, such as the familiar public library Dewey decimal system for classifying books (*not* created by the philosopher John Dewey!), or it may be natural. See **classification problem**.

techno-science: A name for technologies whose design and effective operation are dependent on scientific knowledge. Historically, technological innovations were quite independent of scientific theories, but this situation began to change in the 19^{th} century. The commercial exploitation of these technologies led to the systematic coupling of science and engineering in industrial corporations, research labs, and academe.

temperament: See **tuning system**.

transistor: A device, invented at Bell Labs in 1948 by William Shockley, John Bardeen, and James Brattain, that exploits the properties of simple solid semiconductors to perform electronic functions then performed by much larger, less reliable, more expensive, and more power-consuming vacuum tubes.

tuning system: In music, a set of mathematical relationships among the notes of the octave that, when applied to the construction of musical instruments, maintains harmonies among the notes and minimizes dissonances. Tuning systems were inspired by Pythagoras's insight that mathematical relationships distinguish music from noise, but no one has discovered a single temperament or tuning system that is dissonance-free. Western music over the past 200 years employs equal temperament, a system in which the octave is divided into 12 equally spaced tones.

verisimilitude: Renaissance Humanist idea of the truthfulness of history writing that employs imaginative reconstructions and, by extension, the truthfulness of paintings that obviously are not what they seem to be.

water frame: A name given to the large water-powered version of Hargreaves's spinning jenny built by Richard Arkwright; together with related water-powered machinery for carding and weaving, the water frame initiated the mass-production era, setting the stage for the steam-power-based Industrial Revolution.

Biographical Notes

abu-Kamil (c. 850–930). Early Islamic algebraist, born in Egypt, and author of an influential text translated during the Renaissance containing 69 algebraic problems and their solutions.

al-Khwarizmi (c. 780–c. 850). The earliest known Islamic algebraist. His book of problems and solutions, along with that by abu-Kamil, influenced the shift of European mathematics from geometry to algebra.

Anaxagoras (c. 500–428 B.C.E.). Greek philosopher who proposed that all material objects were composed of a vast number of atoms of many different properties.

Archimedes (c. 287–212 B.C.E.). Greek mathematician and physicist whose combination of deduction and experiment influenced Galileo and Newton. He formulated a mathematics-based theory of the so-called simple machines and founded the science of hydrostatics.

Aristarchus of Samos (c. 320–c. 250 B.C.E.). Greek mathematician and astronomer who used trigonometry to estimate the distances to the Sun and Moon and proposed a Sun-centered Solar System that Copernicus read about in a text by Archimedes.

Aristotle (384–322 B.C.E.). Greek philosopher born in Macedonia, where his father was physician to the king. He studied with Plato for many years but then founded his own rival school, also in Athens. His comprehensive writings, especially on logic and nature, and his metaphysics, were extremely influential for more than 2000 years.

Avery, Oswald (1877–1945). American bacteriologist (born in Canada) who, together with Colin MacLeod and Maclyn McCarthy, argued in the early 1940s, based on their experiments with pneumonia bacteria, that DNA was responsible for inheritance.

Avicenna (980–1037). Islamic philosopher (Aristotelian) and physician, whose masterwork, *The Canon of Medicine*, became a standard text, alongside Galen's, for more than 500 years in European medical schools.

Bacon, Francis (1561–1626). English educational reformer; also reformer and "father" of the experimental method in modern science described in his book *The New Organon* (1620); and political opportunist. Became Lord High Chancellor under King James but was convicted of bribery.

Bernard of Clairvaux (1090–1153). Extremely influential 12th-century French theologian and Church leader, head of the Cistercian order of monasteries that extended over much of Europe. He opposed the rising secular intellectualism that became institutionalized in the emerging universities and especially persecuted the philosopher Peter Abelard.

Bernard, Claude (1813–1878). French biologist, founder of experimental medicine, and an extremely prolific author of research publications, many of whose results remain valid today. He was a positivist, favoring facts over concepts, and championed a homeostatic view of metabolism.

Bernoulli, Jacob (1654–1705). Swiss mathematician, member of a family of outstanding mathematicians in the 17th and 18th centuries, whose posthumously published *The Art of Conjecturing* pioneered probability theory and its application to political and commercial decision-making.

Bohr, Niels (1885–1962). Danish physicist, deeply philosophical as well, whose 1913 proposal to quantize the orbital motion of electrons became the foundation of quantum mechanics. In the late 1920s, with Werner Heisenberg, he formulated the Copenhagen Interpretation of quantum mechanics.

Boltzmann, Ludwig (1844–1906). Austrian physicist who founded statistical mechanics and statistical thermodynamics, posited the kinetic theory of gases (with James Clerk Maxwell), and insisted on the physical reality of atoms.

Boole, George (1815–1864). British mathematician who founded modern mathematical logic by introducing a symbolic notation for logical reasoning. His 1854 book, *An Investigation into the Laws of Thought*, was of immense influence in the history of information theory, computers, and artificial intelligence research, as well as in mathematical logic.

Boyle, Robert (1627–1691). Irish natural philosopher, heir to the title earl of Cork, and member of the Oxford group of natural philosophers that founded the Royal Society of London. Boyle conducted experiments with Robert Hooke, using an air pump of their design, on the physical properties of air; these were considered exemplary of the experimental method of the study of nature. He was an atomist and an early "scientific" chemist.

Brahe, Tycho (1546–1601). A Danish astronomer, the greatest observational astronomer of the pre-telescope era, who used instruments of his own design in an observatory funded by the Danish king. He rejected Copernicus's theory for his own version of an Earth-centered Universe. His data were used by Johannes Kepler to support Kepler's claim that the planets move in elliptical orbits.

Brunelleschi, Filippo (1377–1446). Italian painter, sculptor, and architect; famous for his rediscovery of perspective drawing and his innovative design and construction plans for the cathedral in Florence with its vast dome and cupola.

Bush, Vannevar (1890–1974). American engineer, science administrator, head of the World War II Office of Scientific Research and Development, author of the report that launched large-scale postwar federal support for research, and computer pioneer.

Cardano, Jerome (Girolamo) (1501–1576). Italian mathematician, physician, and founder of probability theory applied to gambling games. He promoted the study of algebra and published Tartaglia's solution to the cubic equation.

Clausius, Rudolf (1822–1888). German physicist and a founder of thermodynamics, Clausius introduced the concept of entropy, implying the irreversibility of time and the "heat death" of the Universe. With Maxwell and Boltzmann, he also created the kinetic theory of gases.

Comte, Auguste (1798–1857). French social and political philosopher and philosopher of science; founder of positivism—basing knowledge on facts, not ideas—and of sociology.

Copernicus, Nicolaus (1473–1543). Polish astronomer and physician whose theory of a moving Earth eventually redirected astronomy. Copernicus spent years studying in Italy after graduating from Jagiellonian University in Krakow and became proficient in Greek, translating into Latin the work of an ancient Greek poet recovered by the Humanists. It is interesting that Copernicus used virtually the same data that Ptolemy used yet reached dramatically different conclusions.

Crick, Francis (1916–2004). English physicist. After working on radar and magnetic mines during World War II, Crick collaborated with James Watson on the spatial arrangement of the atoms in DNA molecules; the two shared the Nobel Prize for that 1953 discovery.

Ctesibius (3rd century B.C.E.?). A Greek "mechanic," son of a barber, who invented a wide range of useful machines, including a complex water clock and a water organ, that were developed further by others over the next 300 years.

Curie, Marie (1867–1934). Born in Warsaw, Curie moved to Paris with a newly married older sister in 1891 and married Pierre Curie in 1895. They shared a Nobel Prize in physics in 1903 with Henri Becquerel for the discovery of radioactivity, named by Marie in 1898. After Pierre's death in 1906, Marie became the first woman professor at the Sorbonne, and in 1911, she was awarded the Nobel Prize in chemistry for her isolation of radium.

Dalton, John (1766–1844). Not the first atomist of modern times—Boyle and Newton were among his many predecessors—Dalton's *New System of Chemical Philosophy* (1807) became the foundation of 19th-century atomic theories of matter, first in chemistry, later in physics.

Darwin, Charles (1809–1882). Born into a wealthy English family, Darwin married a cousin, Emma Wedgwood, and devoted his life to biological science. In addition to his theory of evolution, Darwin published extensively on many subjects and would be considered a major 19th-century scientist independent of evolution.

Darwin, Erasmus (1731–1802). Charles Darwin's paternal grandfather and author of several once-popular (although later mocked) epic poems on nature that incorporated evolutionary ideas of his own.

Davy, Humphrey (1778–1829). An English physicist/chemist, Davy was extraordinarily productive in both "pure" and applied research, pioneering electrochemistry and discovering the elements sodium and potassium, as well as inventing a safety lamp for coal miners, an electric arc lamp, and a process for desalinating seawater.

Dee, John (1527–1608/09). English mathematician and mystical nature philosopher. Dee was actively involved in training ship pilots in the new mathematical techniques of navigation and in mathematical cartography, as well as promoting mathematics literacy for the public. He designed "magical" stage machinery for plays and made the first translation into English of Euclid's *Elements*.

Descartes, René (1596–1650). Descartes was a founder of modern science, modern philosophy, and modern mathematics. He promoted a deductive method for acquiring knowledge of nature and developed a rigorously mechanical philosophy of nature in which only contact forces were allowed: no action at a distance. He made epistemology (the theory of knowledge) central to philosophy, and he invented analytic geometry, making algebra central to mathematics.

De Vries, Hugo (1848–1935). Perhaps the leading figure in founding modern genetics, De Vries, a Dutch botanist, rediscovered Mendel's ignored earlier work after developing his own similar theory and gave the credit to Mendel. He developed an influential theory of mutations as the "engine" of evolution.

Dirac, Paul (1902–1984). Trained initially as an engineer at Bristol University in England, Dirac became one of the greatest theoretical physicists of the 20th century. His 1929 relativistic theory of the electron became the cornerstone of quantum electrodynamics, the most important theory in physics in the mid-20th century.

Dolland, John (1706–1761). An English weaver by training, Dolland became a self-educated scientist, developing and patenting the first compound microscope lenses corrected for chromatic aberration.

Dumas, Jean Baptiste (1800–1884). A French chemist who developed a technique for calculating relative atomic weights, Dumas also pioneered structuralism in chemistry through his theory of substitution of atoms in geometric "types" of molecules.

Einstein, Albert (1879–1955). Given all that has been written about him, perhaps the most amazing fact about Einstein is that, in 1904, no one, with the exception of his closest friend and sounding board, Marcel Grossmann, would have predicted his subsequent accomplishments. In spite of his epochal 1905 papers, his reputation flowered only from 1911. He was appointed director of the Kaiser Wilhelm Institute for Physics in 1914 and, in 1915, published the general theory of relativity. He resigned in 1933 and settled at the Institute for Advanced Studies in Princeton, which was created in part to provide a "home" for him.

Empedocles (c. 490–430 B.C.E.). An early Greek natural philosopher who formulated a four-element theory of matter—earth, air, fire, water—that, together with attractive and repulsive forces, lasted into the 18th century.

Epicurus (341–270 B.C.E.). A Greek moral philosopher primarily, who adopted Democritus's atomic theory of matter and adapted it to his moral and social views. Against Anaxagoras, he held that atoms differed only in size, shape, and weight and that all properties of material objects derived from diverse configurations of their constituent atoms.

Erasmus of Rotterdam (1466–1536). One of the great Humanist scholars and the first author, it is said, to live wholly off his fees from publishers based on the sale of his books, especially his bestselling *In Praise of Folly*.

Euclid (c. 300 B.C.E.). A Greek mathematician, whose synthesis of 200 years of Greek mathematics into an axiomatic system in his book, *The Elements*, was of incalculable influence in Western philosophy, mathematics, and science, right down to the present day. Almost nothing is known of his personal life.

Euler, Leonhard (1707–1783). One of the greatest mathematicians of all time and, perhaps, the most productive. Born in Basel, he lived most of his adult life in Germany or Russia, writing on pure and applied mathematical problems even after he became blind. He encompassed all of mathematics but contributed especially to "analysis," another name for algebra, and made important contributions to astronomy, optics, mechanics, and engineering mechanics: the rigorous solution of engineering problems.

Faraday, Michael (1791–1867). A gifted and highly prolific experimental physicist and chemist, Faraday was effectively wholly self-educated, though he was never proficient in mathematics. He became Humphrey Davy's assistant at the Royal Institution in London through an accident, and he was later Davy's successor. He discovered the dynamo principle in 1830, and invented the concepts of electric and magnetic fields and lines of force, predicting that light was an electromagnetic phenomenon. He rejected the atomic theory.

Fischer, Emil (1852–1919). A German organic chemist famous, first, for his synthesis of sugars and, later, for synthesizing amino acids, then combining them to form proteins. His lock-and-key metaphor for how enzymes act on cell molecules was and remains a powerful heuristic in molecular biology.

Fourier, Joseph (1768–1830). French mathematical physicist whose *Analytical Theory of Heat* was extremely influential, both in terms of its equations and in separating descriptive physics from metaphysics. His use of simple trigonometric functions to model any periodic behavior, however complex, remains one of the most powerful tools in science and engineering.

Francesca, Pierro della (1420–1492). One of the great Renaissance painters, he was also a mathematician and wrote perhaps the first account of perspective drawing as a mathematical technique, *De prospectiva pingendi*. This then became a staple of 15th-century artist's manuals, especially after Leone Alberti's influential *Della pittura* (1436).

Galen (c. 129–199). Greek physician and medical theorist, prolific writer and experimenter, and physician to various Roman emperors. Galen was to medieval and Renaissance medicine what Aristotle was to philosophy: the authority. His theory of health as a balance among four humors was influential into the 19th century, though his anatomy and physiology were overthrown in the 16th and 17th centuries.

Galilei, Galileo (1564–1642). Italian mathematical physicist and founding "father" of modern science, combining deductive reasoning and extensive experimentation à la Archimedes. Born in Pisa, he became a professor of mathematics first there, then in Padua, after his telescope-based observations of the Moon's irregular surface and Jupiter's moons made him famous. His condemnation for teaching Copernicus's theory as true came in 1633.

Galilei, Vincenzo (1520–1591). Galileo's father; Vincenzo was a musician and a music theorist at a time of intense controversy over tuning systems and their mathematical models. He broke with his teacher, Zarlino, who defended an expanded Pythagorean system, in favor of equal-temperament tuning. Vincenzo's books reveal clever experimentation to support his claims.

Gamow, George (1904–1968). Born in Russia, Gamow moved west after earning his Ph.D., studying the new quantum physics first in Germany, then with Bohr in Copenhagen, before settling in the United States. He predicted the quantum tunneling effect in 1929; proposed the Big Bang theory of cosmology in the late 1940s, predicting the microwave background radiation detected in 1963; and proposed that the sequence of bases in the Watson-Crick DNA model was a code for producing proteins out of amino acids.

Gutenberg, Johann (c. 1397–1468). Widely but by no means unanimously considered the inventor of movable-metal-type printing. Almost nothing about Gutenberg's life and work is free of uncertainty except that he was born in Mainz on the Rhine River, apprenticed as a goldsmith but became a printer, and printed a number of deluxe copies of the Bible using metal type in the early or mid-1450s.

Guth, Alan (1947–). American physicist who, in 1980, proposed the inflation model of the Universe, preceding Gamow's Big Bang. Subsequent refinement by others, as well as by Guth, and detailed observation of the microwave background radiation's minute non-uniformities led to a consensus in favor of the inflation model.

Hegel, G. F. W. (1770–1831). A German philosopher, Hegel was the single most influential philosopher of the 19th century, the creator of a system that integrated deduction, history, and time. He held that reality is the deterministic unfolding in time of reason, which manifests itself as nature and as the human mind.

Heisenberg, Werner (1901–1976). A German physicist, Heisenberg invented, in 1925, what was later called "quantum mechanics." Over the next five years, he formulated the famous uncertainty principle and, in collaboration with Bohr, an interpretation of quantum theory that was probabilistic and strictly empirical. Bohr broke with Heisenberg over the latter's role as head of Germany's wartime atomic bomb research effort.

Helmholtz, Hermann (1821–1894). A physicist and pioneering neuro-physiologist, Helmholtz was Germany's leading scientist in the second half of the 19th century. He formulated the scientific principle of the conservation of energy, studied the transmission of signals in nerves, and developed a theory of hearing that became the basis for designing stereo audio equipment.

Heraclitus (c. 540– c. 480 B.C.E.). Other than that he lived in the Greek city of Ephesus in what is now Turkey and probably wrote before Parmenides, not after, nothing is known about Heraclitus. That he wrote one or more works on philosophy is known, and in these, he clearly insisted on the reality of change, suggesting that the object of knowledge is the *logos*, or orderliness, of processes, not timeless objects and their properties.

Hero (or Heron) of Alexandria (flourished c. 60). A Greek "engineer" before the term existed, Heron created a school for engineering in Alexandria and left behind a number of books describing mechanical and optical machines based on physical principles, including the action of compressed air, water, and steam.

Hertz, Heinrich (1857–1894). A German physicist who, in the 1880s and independently of Oliver Lodge in England, confirmed the prediction of Maxwell's theory of electromagnetic waves traveling freely through space. This finding became the basis for the broadcast radio technology developed 10 years later by Guglielmo Marconi.

Hippocrates (c. 460–377 B.C.E.). A Greek physician, medical theorist, founder of a medical school, and teacher. His school was on the island of Kos, where he was born, and pioneered a wholly naturalistic approach to illness and treatment.

Hoffman, August (1818–1892). An eminent German organic chemist, Hoffman was called to London by Prince Albert to teach at the new Royal College of Chemistry, where his student William Perkin synthesized the first artificial dye from coal tar. Hoffman later returned to Germany, founded the German

Chemical Society, and played an active role in German chemists' dominance of the commercial dye industry and the many important industrial applications of coal-tar chemistry.

Holland, John H. (1929–). American computer scientist and creator of "genetic" algorithms: computer programs based on Darwinian evolution and genetic theory that display adaptation. Holland is a theorist of complex systems and self-organization and was actively involved with the Santa Fe Institute and World Economic Forum, in addition to teaching computer science at the University of Michigan.

Hooke, Robert (1635–1703). An English natural philosopher, Hooke collaborated with Robert Boyle on experiments to determine the properties of air, studied the properties of metallic springs, and invented a spiral spring-controlled balance wheel for a watch (replacing the pendulum). He was a pioneering microscopist, invented numerous scientific instruments, attempted a theory of gravity, and played a leading role in the rebuilding of London after the great fire of 1665.

Hoyle, Fred (1915–2001). An English physicist, Hoyle, together with Herman Bondi and Thomas Gold, proposed the Steady State theory of the Universe as a counter to Gamow's Big Bang theory, a name mockingly assigned by Hoyle. Hoyle also wrote science fiction and argued that life came to Earth from space.

Hubble, Edwin (1889–1953). Hubble was a midwestern American astronomer who became director of the Mt. Wilson observatory in 1919 and, with its 100-inch reflecting telescope, soon discovered that the sky was filled with galaxies, contrary to the consensus view that the Milky Way was the Universe. In 1929, Hubble announced the expansion of the Universe and devoted the rest of his life to observations aimed at determining its size and age.

Huygens, Christiaan (1629–1675). A Dutch mathematical physicist, mathematician, and astronomer, Huygens was a central figure in the creation of modern science, first to demonstrate that curved motion required a force and to recognize Saturn's rings as such. He developed a wave theory of light; made important contributions to algebra, probability theory, optics, and mechanics; developed accurate pendulum clocks and their theory; and independently of Hooke, invented a spring-balance wheel-driven watch.

Joule, James Prescott (1818–1889). An English physicist whose experiments on the quantitative relationship of mechanical motion and heat led, in the hands of others, to the idea of conservation of energy and the creation of thermodynamics.

Kekule, Friedrich August (1829–1886). A German organic chemist, Kekule is best known for his contributions to structural chemistry, especially the hexagonal ring structure of benzene and his prediction of the tetrahedral form of the carbon atom's valence bonds, which became the basis of polymer chemistry in the 20th century.

Kelvin, Lord/William Thomson (1824–1907). An Irish-born mathematical physicist, Thomson was knighted for designing and overseeing the laying of the first successful transatlantic telegraph cable in 1866. He played key roles in the development of thermodynamics and electromagnetic field theory but was wedded to the reality of the aether and believed that the Earth was probably only 100 million years old and, thus, too young for Darwin's theory of evolution to be correct.

Kepler, Johannes (1571–1630). A German astronomer who first formulated the modern conception of the Solar System, which is very different from that of Copernicus. The data Kepler used came from Tycho Brahe, whose assistant he became when Brahe relocated to Prague. When Brahe died, Kepler took the data and applied them, first, to a Pythagorean theory of his own that failed to match the data; he then let the data guide his theorizing, arriving at elliptical orbits, not circular ones.

Khayyam, Umar (1048–1131). Islamic mathematician, astronomer, and poet who had effectively achieved a general solution to the cubic equation centuries before Tartaglia, and whose text *Algebra* anticipates Descartes' invention of analytic geometry.

Koch, Robert (1843–1910). A German biologist who, with Louis Pasteur, founded bacteriology and formulated the germ theory of disease. His Nobel Prize was for discovering the bacterium that causes tuberculosis, then rampant, but he developed methodologies for isolating microorganisms that resulted in his discovery of anthrax and cholera bacteria, as well.

Lamarck, Jean-Baptiste (1744–1829). Lamarck was almost 50, with very modest credentials as a botanist, when in 1793 the committee running the French revolutionary government made him a national professor of invertebrate zoology. His theory of the emergence of all life forms from a common ancestor by natural forces was an important predecessor of Charles Darwin's theory, and one of which Darwin was acutely aware.

Laplace, Pierre-Simon (1749–1827). A French mathematical physicist and theoretical astronomer of great influence who managed to prosper under Louis XVI, the revolutionary government, Napoleon, and the restored Bourbon monarchy! He proved the long-term stability of the Solar System under Newtonian gravitation, developed a mathematical theory of the origin of the Solar System out of a cloud of gas, published an important essay on probabilities, and championed a rigorous materialistic determinism.

Laurent, Auguste (1807–1853). At one time a graduate student of Dumas (above) contemporary with Pasteur, Laurent seems first to have developed a theory that the spatial arrangement of atoms in a molecule determines properties of the molecule. His "nucleus" theory was subsequently overwhelmed by Dumas' extension and adaptation of it, a source of some bitterness to Laurent.

Lavoisier, Antoine de (1743–1794). Unlike Laplace, Lavoisier did not survive the French Revolution. His research led him to believe that combustion involved combination with one component of air, which he named *oxygen*. This led him to propose a "revolution" in chemistry, one that laid the foundation for the modern theory of elements. His widow married Benjamin Thompson (below).

Leavitt, Henrietta Swan (1868–1921). An American astronomer, Leavitt graduated from what became Radcliffe College and became a human "computer" at Harvard College Observatory, eventually rising to head of a department there. Her specialty was variable stars, and she identified 2400 new ones, especially the Cepheid variables that she recognized as providing a cosmic "ruler" for measuring absolute cosmic distances.

Leibniz, Gottfried (1646–1716). A German philosopher, mathematician, and physicist, Leibniz, like Descartes, was influential in all three of those areas. He formulated a rationalist, deterministic but anti-materialistic philosophy; invented the calculus independently of Newton (publishing first), using a notation that has become universal; anticipated late-19th-century topology and symbolic logic; and first called attention to the quantity in mechanics that we call kinetic energy.

Liebig, Justus von (1803–1873). A German chemist of enormous influence, partly through his own mechanistic theories of chemical reactions, but largely through the many subsequently prominent students trained in his laboratory. Liebig studied the chemistry of fermentation long before Pasteur and never accepted that the cause was a living organism (yeast). He also dismissed the significance of atomic structure within molecules and the early germ theory of disease.

Linnaeus, Carl (1707–1778). Swedish botanist whose binomial system for classifying plants based on their sexual organs became universally adopted. An aggressive proponent of his system as a natural one, he was forced to acknowledge late in life that it seemed to be conventional, which implied that species and genera were conventional, not immutable features of reality.

Lucretius (c. 99/94–c. 55/49 B.C.E.). Roman poet and natural philosopher whose epic poem in hexameters, *On the Nature of Things*, disseminated Epicurus's atomic theory of matter and morality, somewhat modified by Lucretius.

Mach, Ernst (1838–1916). An Austrian experimental physicist of note but remembered mostly for his theory of scientific knowledge as based on perceptual experience and incapable of penetrating to a reality behind experience, which is why he opposed the reality of atoms.

Maxwell, James Clerk (1831–1879). One of the greatest of all mathematical physicists, Maxwell was born in Edinburgh. He became, in 1871, the first professor of experimental physics at Cambridge University and established the Cavendish Laboratory there. Under the leadership of Lord Rayleigh, J. J. Thomson, and Ernest Rutherford, the laboratory became a leading center for important new developments in physics into the 1950s.

Mendel, Gregor Johann (1822–1884). An Austrian monk and botanist, Mendel lived in the Augustinian monastery in Brünn (Brno) effectively for the last 40 years of his life, becoming abbot in 1868, which ended his experimental work on plants. Mendel twice failed to pass the exams for an advanced teaching license. In between failures, he spent three years at the University of Vienna studying science and mathematics and, on returning to the monastery in 1854, began the years-long breeding experiments that resulted in his posthumous fame.

Mercator, Gerard (1512–1594). Mercator was born in Flanders and, after a religious crisis that led to his becoming a Protestant, studied mathematics in order to apply it to geography and cartography. He migrated to the Lutheran town of Duisberg in Germany in 1552, living there for the rest of his life and producing the first modern maps of Europe over the next 10–15 years. In 1569, he produced a map of the Earth based on his projection of its surface onto the inner surface of a cylinder. He coined the term *atlas* for a collection of maps.

Morgan, Thomas Hunt (1866–1945). An American geneticist, Morgan began his career as an embryologist, studying fertilization at the cell level. In 1907, after becoming a professor at Columbia University, he shifted his research to the mechanism of heredity. Initially critical of the gene concept, he became a major proponent of it after 1910 and trained a number of influential students, among them, Hermann Muller (below).

Morse, Samuel F. B. (1791–1872). Morse was a financially unsuccessful American artist who, returning from Europe in 1832 after a three-year stay, learned about electromagnetism from a fellow passenger. Morse became obsessed with the idea of an electric telegraph and, eventually, with advice from the physicist Joseph Henry, among others, succeeded in getting Congress to fund a pilot line from Baltimore to Washington in 1843. This inaugurated the commercialization of the telegraph using Morse's code.

Muller, Hermann Joseph (1890–1967). Born in New York City, Muller attended Columbia University and received his Ph.D. under Thomas Hunt Morgan's direction in 1916, by which time he was Morgan's active collaborator in research and publication. His Nobel Prize–winning discovery of genetic mutations induced by X-rays was made while he was at the University of Texas, but he spent the mid-1930s at the Institute of Genetics in the Soviet Union, leaving because of his opposition to Lysenko's anti-Mendelian theories, which were approved by Stalin. He returned to the United States in 1940.

Müller, Johannes (1801–1858). Müller was a German physiologist who was committed to the vitalist view of life and to Romantic nature philosophy, yet his research laboratory, first at the University in Bonn, then in Berlin, was the training ground for an extraordinary group of influential life scientists, virtually all of whom were mechanists!

Newton, Isaac (1642–1727). Great both as an experimental and as a theoretical physicist, Newton's "miraculous year" was 1665, when an outbreak of plague caused Cambridge University to close and he went home. In notebooks he kept then, there are the clear antecedents of most of his great ideas in

mechanics, optics, mathematics, and astronomy. Newton devoted much of his time (and the bulk of his surviving writing) to biblical chronology and interpretation and alchemical researches, yet he was the single most important architect of modern science. He was autocratic as warden of the Royal Mint and as president of the Royal Society, and suffered a mental breakdown in the early 1690s, perhaps poisoned by his alchemical experiments.

Pacioli, Luca (1445–1517). Renaissance mathematician, befriended by Piero della Francesca, and tutor to, and friend of, Leonardo da Vinci. Pacioli published a summary of 15th-century mathematics in 1494 that included an extensive description of double-entry bookkeeping and commercial arithmetic generally. His 1509 book, *On the Divine Proportion* (the famous Greek "golden ratio"), was written in Italian and illustrated by Leonardo. It describes the application of mathematical proportions to artistic depictions, for example, of the human body.

Parmenides (born c. 515 B.C.E.). One of the earliest and most influential Greek philosophers, in spite of the fact that his only work is lost, a poem of some 3000 lines, apparently, of which 150 are known because they are cited by other Greek philosophers. Parmenides's rigorously logical characterization of the concepts of being and becoming provoked atomistic theories of nature, in contrast to Heraclitus's process approach and influenced the view, dominant since Plato and Aristotle, that reality was timeless and unchanging and that knowledge and truth were universal, necessary, and certain.

Pascal, Blaise (1623–1662). A French mathematician and physicist, in 1654, Pascal had a vision that led him to cease almost all secular intellectual activity, although he designed a public transportation system for Paris that was built the year he died. He made important contributions to projective geometry and probability theory before turning to philosophical and theological themes. His *Pensées* has been in print since publication.

Pasteur, Louis (1822–1895). A French chemist, Pasteur became the very embodiment of the natural scientist, for the French at least. With Robert Koch, he formulated the germ theory of disease, but he also contributed to the creation of stereochemistry and established the value of chemical science to industry through his work on fermentation, pasteurization, vaccination, and silkworms.

Petrarch (1304–1374). An Italian poet, born in Arezzo, Petrarch was named Poet Laureate of Rome in 1341, largely because of an epic poem in Latin on the great Roman general Scipio Africanus, who defeated Hannibal. He was a great admirer of Dante, whose *Comedy* (called "divine" by Petrarch's admirer Boccaccio) was in Italian, not Latin. Petrarch instigated the Humanist movement and the collection of ancient manuscripts in order to recover models of the best writing, feeling, and thinking.

Planck, Max (1858–1947). The German physicist who initiated the quantum physics "revolution" with his 1900 solution to the black-body radiation problem. Planck remained in Germany in spite of his outspoken opposition to Nazi policies, and his only surviving son was gruesomely executed as an accomplice to an assassination plot on Hitler. After World War II, the Kaiser Wilhelm Institute was renamed the Max Planck Institute(s).

Plato (428–347 B.C.E.). The quintessential Greek philosopher from the perspective of the subsequent history of Western philosophy, Plato was one of Socrates's students and the teacher of Aristotle. "Plato" was his nickname—his given name was Aristocles—and he was initially a poet and, as a young man, a competitive wrestler. He was an elitist by birth and inclination, and the relationship between the "real" Socrates and the character in Plato's dialogues is, at best, loose.

Prigogine, Ilya (1917–2003). A Russian-born chemist who was raised, educated, and rose to fame in Belgium. He moved to the United States in 1961, first to the University of Chicago, then to the University of Texas, while retaining his Belgian academic affiliation. He demonstrated that many far-from-equilibrium physical and biological systems were self-organizing and stable and displayed adaptation.

Pythagoras (c. 572–c. 479 B.C.E.). A Greek philosopher and mathematician with a strong metaphysical/mystical bent. Pythagoras promoted a total lifestyle conception of wisdom and created schools and self-contained communities in which people could live in accordance with his teachings. His most enduring accomplishments are the idea of deductive proof, which essentially created mathematics as we know it, and the idea that mathematical forms are the basis of all natural order.

Quetelet, Adolphe (1796–1874). A Belgian astronomer-in-training whose lasting achievement was social statistics, especially the idea of statistical laws, which challenged the prevailing belief that laws were necessarily and exclusively deterministic.

Rumford, Count/Benjamin Thompson (1753–1814). A Royalist, Thompson fled the colonies to England in 1776, returning to the colonies as a British officer, then went to Europe after the war. He distinguished himself in Bavaria as minister of war and minister of police, becoming de facto prime minister, and was made count of the Holy Roman Empire in 1791. He instituted workhouses for the poor and new uniforms, marching formations, diet, and weapons for the army. In addition to his experiment in 1799, which proved that heat was motion, he founded the Royal Institution in London to teach science to the public, enjoyed a short-lived marriage to Lavoisier's widow, and endowed a science professorship at Harvard.

Rutherford, Ernest (1871–1937). Born in New Zealand, Rutherford went to Cambridge in 1895 to study with J. J. Thomson, then to McGill in Montreal as professor of physics, before returning for good to England in 1907. He was professor of physics in Manchester until 1919 when he moved to the Cavendish Laboratory at Cambridge as J.J. Thomson's successor. His 1908 Nobel Prize was in chemistry for his work on radioactivity, but he and his students made many fundamental contributions to atomic and nuclear physics.

Schleiden, Mathias (1804–1881). A German botanist who, with Theodor Schwann proposed the cell theory of life. Schleiden was originally a lawyer who turned to the study of botany after a failed suicide attempt. In 1838, he published an essay in a journal edited by Johannes Müller, proposing that cells are the basis of all plant life and are formed in a process that begins inside the nucleus of a progenitor cell. In an 1842 text, he argued that a single, mathematically describable physical force underlies all natural phenomena, including life.

Schrödinger, Erwin (1887–1961). Schrödinger was born in Vienna and received his Ph.D. there, in physics. He was an Austrian artillery officer during World War I and became a professor of physics in Zurich in 1921. It was at Zurich in 1925 that he developed his version of what was called "quantum mechanics," which unlike Heisenberg's version, was based on 19th-century deterministic wave physics and was interpretable as offering a conceptual "picture" of microphysical nature. Succeeding Max Planck as professor of theoretical physics in Berlin in 1927, he fled the Nazi takeover in 1933 for London; he returned to Vienna in 1936, only to flee again, this time, to Ireland until 1956 and yet another return to Vienna.

Schwann, Theodor (1810–1882). Schwann was born and educated in Germany and served from 1834–1838 as Johannes Müller's laboratory assistant in Berlin, but after a paper on yeast as a factor in fermentation was derided, he accepted a professorship in Belgium, where he spent his entire academic career. It was his 1839 book, *Microscopical Researches on the Similarity in the Structure and Growth of Animals and Plants*, that proposed the cell theory as the universal basis of both plants and animals, hence, of all life forms. Schwann thus extended Schleiden's cell theory of plant life, with which he was quite familiar; for this reason, the universal cell theory is attributed to them jointly.

Shannon, Claude (1916–2001). Shannon was born in Michigan and did his graduate work at MIT, receiving his master's and Ph.D. in mathematics in 1940 (with these in two different areas of applied mathematics). He joined Bell Labs in 1941. During the war, he worked on mathematical models for predictive antiaircraft firing. The technological applications of Shannon's theories in computer logic

circuit design, telephone switching circuits, computer networks, and electronic and optical information transmission and storage devices have had an incalculable social impact.

Shapley, Harlow (1885–1972). An American astronomer, Shapley originally planned to become a journalist after attending a new university journalism program in his home state of Missouri. He became an astronomer because the program was delayed and he chose to take astronomy courses while he waited! At Princeton from 1911 to 1914, Shapley did important observational work on double stars and variable stars and was, thus, well positioned, after his move to Mt. Wilson Observatory in 1914, to use Leavitt's variable-star–based cosmic "ruler" to estimate the size of the Milky Way and distances to the Magellanic Clouds.

Swift, Gustavus (1839–1903). Born and raised on Cape Cod, Swift dropped out of school after eighth grade and, at the age of 16, had his own butchering business, which prospered and expanded with each relocation. He and his partner moved to Chicago in 1875, and in 1878, he went his own way, commissioning the first successful refrigerated rail car. It was delivered in 1880, and a year later, he had 200 cars carrying 3000 dressed beef carcasses a week to New York City.

Tartaglia, Niccolò (aka Niccolò Fontana) (1499–1557). Tartaglia was a mathematician and engineer; as a boy, he was slashed through the cheek by a French knight, hence, his nickname, "stammerer" ("Tartaglia"). He discovered the general solution to the cubic equation (though Khayyam may have anticipated him, independently) and the parabolic trajectory of cannonballs. He made the first Italian translations of Euclid and Archimedes.

Thales (c. 624/620–c. 570/546 B.C.E.). According to Aristotle, Thales was the first Greek natural philosopher, speculating that water or some fluid was the universal "stuff" out of which all material objects were composed.

Thompson, Benjamin. See **Count Rumford**.

Thompson, Joseph John (1856–1940). Thompson was born near Manchester in England and planned on studying engineering, but because the family could not afford the apprenticeship fees for engineering training, he switched to physics, winning a scholarship to Cambridge—where he spent the rest of his life—and a Nobel Prize (in 1906). In 1884, he succeeded Lord Rayleigh, who had succeeded Maxwell, as Cavendish Professor of Physics and was succeeded in turn by Ernest Rutherford when he resigned in 1919 to become Master of Trinity College. His Nobel Prize was for discovering the electron and for studies of the conduction of electricity in gases, establishing the electron as a particle. (Thompson's son George won the Nobel Prize for physics in 1937 for showing that electrons behaved like waves!)

Thomson, William. See **Lord Kelvin**.

Virchow, Rudolf (1821–1902). A German biologist and another student of Johannes Müller's, Virchow focused his research on the cell, especially cellular pathologies, which he believed to be the basis of all disease. In the mid-1850s, he insisted on the principle that cells arise only from other cells by a process of division, utterly rejecting the possibility of spontaneous generation or other cell formation theories current at the time, among them, Schleiden's. His text *Cellular Pathology* was influential, and its ideas were the basis of his rejection of the Pasteur-Koch germ theory of disease. Like most biologists prior to the mid-1870s, Virchow defended the inheritance of acquired characteristics.

Vitruvius (fl. 1st century B.C.E.). Almost nothing is known about Vitruvius's personal life (even his full name is conjectural!), but the influence of his *On Architecture* since the Renaissance has been immense. The book was discovered in 1414 by the Humanist scholar Poggio Bracciolini and popularized by Leone Alberti in a major work on art and architecture, *On the Art of Building* (1452), that was dedicated to Pope Nicholas V, who initiated the construction of the Vatican complex.

Wallace, Alfred Russel (1823–1913). Wallace was born into a poor Welsh family and left school at 14 to become a surveyor under an older brother. Self-educated by local standards, he became a teacher at a workingman's school in 1844 when he met a young naturalist, Henry Bates, and discovered his true vocation. They traveled to Brazil together in 1848 to gather specimens for wealthy British collectors, and Wallace returned to England with crates' worth, all of which were lost when the ship sank approaching the English coast. He then spent 20 years, from 1842–1862, in the Malay Peninsula, collecting specimens and studying the distribution of plants and animals; this led to the essay proposing evolution by natural selection that he sent to Darwin in 1858 for his advice as to publication. Wallace became one of England's greatest naturalists, but he never accepted the extension of evolution to man. He was an aggressive supporter of radical social reform and of "scientific" spiritualism, believing in life after death.

Watson, James (1928–). Watson studied zoology at the University of Chicago and received his Ph.D. from Indiana University in 1950, where he was influenced by T.H. Morgan's former student Hermann Muller. Watson's Ph.D. thesis, under Salvador Luria, was on the effect of X-rays on bacterial cell division. In 1951, he met Maurice Wilkins, who had with him copies of X-ray diffraction patterns of DNA crystals, and Watson decided to spend time at the Cavendish Laboratory at Cambridge studying them. There he met Francis Crick and began their epochal collaboration.

Watt, James (1736–1819). A Scottish mechanic and instrument maker who opened a shop in Glasgow circa 1756 and began working for faculty members at Glasgow University. While repairing a Newcomen engine, Watt saw that the efficiency would be improved dramatically by separating the cylinder and the condenser. He built a crude working model in 1765, but a reliable engine for commercial application required solving problems involving valves, precision machining (for the day), and lubricants. Watt's partnership with Mathew Bolton from 1774 was heaven-sent, initiating the steam-power–based Industrial Revolution of the 19th century and freeing Watt to develop progressively more efficient and more useful designs that Bolton put into production.

Bibliography

Agricola, Georgius (Georg Bauer). *De Re Metallica*. Herbert Hoover, trans. New York: Dover, 1950. Bauer was a sort of chief medical officer for the Fugger mines in the 16th century, and this is a translation—by Herbert Hoover before he became president—of his survey of contemporary technologies related to mining, including medical technologies, of course.

Allen, Garland. *Life Science in the Twentieth Century*. Cambridge: Cambridge University, 1981. A solid history of biology in the first half of the 20th century.

Aristotle. *The Complete Works of Aristotle*. Jonathan Barnes, ed. Princeton: Bollinger, 1982. Aristotle's logical works include the *Prior* and *Posterior Analytics* and the *Rhetoric*. His scientific works include *On the Heavens*, *On Physics* (nature), *On the Soul*, *On Generation and Corruption*, and the *Generation of Animals*.

Augustine. *Confessions*. London: Penguin Books, 1961. Book 11 contains his penetrating analysis of time, and his style of writing reveals how intertwined his religious commitments were with his reasoning.

Bacon, Francis. *The New Organon*. New York: Bobbs-Merrill, 1960. Part 1 is the account of what we think of as the modern experimental method. Important and very readable.

Baeyer, Hans Christian von. *Information: The New Language of Science*. New York: Phoenix Press, 2004. A short, clear, current account of the emergence of information as a feature of reality on a par with matter or even superior to it as the "stuff" of reality.

Baird, Davis. *Thing Knowledge: A Philosophy of Scientific Instruments*. Berkeley: University of California Press, 2004. A provocative monograph on the connections among ideas, the artifacts we call instruments, and knowledge claims.

Barabasi, Alberto-Laszlo. *Linked: The New Science of Networks*. Cambridge, MA: Perseus, 2002. This book is a joy to read, and without having to confront an equation, you will learn a great deal about how mathematical forms can have properties that affect physical systems—here, networks, which are, of course, relational structures. Very highly recommended.

Barber, Elizabeth Wayland. *The Mummies of Urumchi*. New York: Norton, 1999. Barber is a historian of ancient textiles, and this analysis of what we can learn from the clothing on a mummified, 3200-year-old Caucasian family found in central Asia is fascinating. Highly recommended.

Barbour, J. Murray. *Tuning and Temperament*. New York: Dover, 2004. A clear and correct account of the responses of musicians, composers, musical instrument makers, and philosophers to Pythagoras's claim that musical harmonies are mathematical. Recommended.

Bernoulli, Jacob. *The Art of Conjecturing*. Edith Dudley Sylla, trans. Baltimore: Johns Hopkins University Press, 2006. Sylla's introductory chapter to Bernoulli's 1709 text is a wonderful essay on the early history of applying mathematics to real-world decision-making. Recommended.

Bernstein, Peter. *Against the Gods: The Remarkable Story of Risk*. New York: Wiley, 1998. A well-written and highly informative popular history of practical applications of probability theory. Recommended.

Bertalanffy, Ludwig von. *General Systems Theory*. New York: George Braziller, 1976. A reprint of Bertalanffy's pioneering text on the systems idea. Dated, of course, but reading it puts you in touch with original thinking.

———. *Problems of Life*. New York: Dover, 1952. Here, Bertalanffy focuses on applying the systems concept in biology but also makes connections to other sciences.

Billington, David P. *The Innovators: The Engineering Pioneers Who Made America Modern*. New York: Wiley, 1996. An easy-to-read, insightful series of vignettes about the commercialization of key technological innovations in the 19th century. Recommended.

———, and David P. Billington, Jr. *Power, Speed and Form: Engineers and the Making of the Twentieth Century*. Princeton: Princeton University Press, 2006. Billington and his historian son extend the earlier model to eight key 20th-century innovations.

Biringuccio, Vannoccio. *Pirotechnia*. New York: Dover, 1990. Like Agricola's book, this is a 16th-century survey of technologies available to "engineers" of the period, focusing on uses of fire, heat, and explosives but ranging more widely.

Bolter, J. David. *Turing's Man*. Chapel Hill: University of North Carolina Press, 1984. Bolter was a humanist scholar responding to the very early stages of the computer's penetration of society, but his book remains a valuable reflection on a socially transformative technology.

Braudel, Fernand. *The Wheels of Commerce: Civilization and Capitalism, 15th–18th Century*. New York: Harper and Row, 1979. This is the second volume of a magisterial three-volume work of social history. Highly recommended.

Buchwald, Jed Z., and Andrew Warwick, eds. *Histories of the Electron*. Cambridge, MA: MIT Press, 2001. A first-rate professional history of science, this collection of essays examines in detail the discovery of the electron in 1897, the response of physicists to that discovery, and the impact of the electron on physics theory.

Carroll, Sean B. *Endless Forms Most Beautiful: The New Science of Evo Devo*. New York: Norton, 2005. Evolutionary development, the *Evo Devo* of the title, is a leading expression of Darwinian theory today, and this book describes it very well.

Cercignani, Carlos. *Ludwig Boltzmann: The Man Who Trusted Atoms*. Oxford: Oxford University Press, 1998. A new, very good biography of Boltzmann by a physicist; describes his contributions to physics, among them, to the physical reality of atoms. Recommended.

Ceruzzi, Paul. *A History of Modern Computing*. Cambridge, MA: MIT Press, 2003. A good history by a professional historian of technology.

Chandler, Alfred D., and James W. Cortada. *A Nation Transformed by Information*. Oxford: Oxford University Press, 2000. The authors examine the impact of information technologies on U.S. society.

Cline, Barbara Lovett. *Men Who Made a New Physics*. Chicago: University of Chicago Press, 1987. Very readable, short intellectual biographies of a handful of physicists who fashioned relativity and quantum theory in the first half of the 20th century. Recommended.

Cohen, I. Bernard. *The Birth of a New Physics*. New York: Norton, 1985. Cohen was a great historian of early modern science; this short monograph is an account of mechanics emerging as the foundation of physics in the 17th century. Recommended.

Cohen, Jack, and Ian Stewart. *The Collapse of Chaos*. New York: Viking, 1994. This lively book focuses on the maturation of chaos theory into complexity theory, carrying James Gleick's earlier book *Chaos* into the early 1990s.

Coleman, William. *Biology in the Nineteenth Century*. Cambridge: Cambridge University Press, 1977. An excellent, short history of major ideas at the heart of 19th-century biological theories. Highly recommended.

Cooper, Gail. *Air-Conditioning America*. Baltimore: Johns Hopkins University Press, 1998. A good history of the co-evolution of air-conditioning technology and its commercial, industrial, and residential applications.

Copernicus, Nicolaus. *On the Revolutions of the Heavenly Spheres*. New York: Prometheus, 1995. You can—and should—read book 1 of this epochal work to experience Copernicus's revolutionary idea firsthand. (The rest of the book requires serious effort!)

Cortada, James W. *Before the Computer*. Princeton: Princeton University Press, 2000. An interesting history of calculator and tabulator technologies in the 19th and early 20th centuries and how they affected the conduct of business and business strategies.

Cutcliffe, Stephen H., and Terry Reynolds. *Technology and American History*. Chicago: University of Chicago Press, 1997. An excellent collection of essays from the journal *Technology and Culture* on how technologies have changed American society. Recommended.

Darwin, Charles. *On the Origin of Species*. Cambridge, MA: Harvard University Press, 1966. Reading Darwin's argument for what we call evolution is a powerful experience. Highly recommended, as is comparing it to Alfred Russel Wallace's essay "On the Tendency of Varieties to Diverge Indefinitely from Their Type" (download it from the Internet).

———. *The Descent of Man*. London: Penguin, 2004. The extension of evolution to mankind came 12 years after *Origin* (and Wallace rejected it!). Highly recommended.

Debus, Alan. *Man and Nature in the Renaissance*. Cambridge: Cambridge University Press, 1978. A classic monograph in a wonderful series of history-of-science monographs by Cambridge University Press. Recommended.

Dennett, Daniel C. *Darwin's Dangerous Idea*. New York: Simon and Schuster, 1996. Provocative, even controversial, but Dennett is a leading philosopher and a defender of a strict, strictly atheistical reading of Darwinism.

Descartes, René. *Discourse on Method* and *Rules for the Direction of the Mind*. London: Penguin, 1999. These two short works are Descartes' prescriptions for a deduction-based methodology as the foundation for modern science.

———. *The Geometry*. New York: Dover, 1954. Title notwithstanding, this long essay, published in 1637, proposes substituting algebra for geometry as the basis of mathematics.

Dohrn-van Rossum, Gerhard. *History of the Hour*. Chicago: University of Chicago Press, 1996. An excellent history of the weight-driven clock and its impact on late-medieval and Renaissance society. Highly recommended.

Drachmann, A. G. *The Mechanical Technology of Greek and Roman Antiquity*. Madison: University of Wisconsin Press, 1963. A scholarly monograph reviewing just what the title promises. Out of print but available used.

Drake, Stillman, and I. E. Drabkin. *Mechanics in Sixteenth-Century Italy*. Madison: University of Wisconsin Press, 1969. The authors, leading historians of early modern science, give a detailed account of the state of the art in which Galileo was trained. Modest mathematics required, but very informative.

Edgerton, Samuel Y., Jr. *The Heritage of Giotto's Geometry: Art and Science on the Eve of the Scientific Revolution*. Ithaca: Cornell University Press, 1994. Out of print, but a good introduction to the idea that Renaissance painting techniques contributed to the rise of modern science. Highly recommended. Edgerton's *The Renaissance Discovery of Linear Perspective* covers the same material.

Einstein, Albert. *Relativity: The Special and General Theory*. London: Penguin, 2006. In his own words, writing for a general audience, Einstein describes relativity theory, aiming at a broad conceptual understanding. Highly recommended.

Eiseley, Loren. *Darwin's Century: Evolution and the Men Who Discovered It*. New York: Anchor, 1961. Eiseley wrote beautifully about science, and the virtues of this book include its clarity and readability. Recommended in spite of many more recent works on this topic.

———. *The Firmament of Time*. New York: Atheneum, 1960. Here, the writing is center stage. The theme is the naturalization of time and man in the 19th century. Highly recommended.

Eisenstein, Elizabeth L. *The Printing Revolution in Early Modern Europe*. Cambridge: Cambridge University Press, 2005. An important scholarly study of the social impact of print technology—this is an abridged and illustrated edition of Eisenstein's two-volume *The Printing Press as an Agent of Social Change* (1984)—attributing that impact primarily to features of the technology. Adrian Johns's book (below) takes issue with this view.

Eldredge, Niles. *Darwin: Discovering the Tree of Life*. New York: Norton, 2005. Eldredge is an important evolutionary biologist. Here, he traces the development of the ultimate unity of all life forms in Darwin's thinking.

Elkana, Yehuda. *The Discovery of the Conservation of Energy*. Cambridge, MA: Harvard University Press, 1974. A very good, nontechnical history of the idea of energy and the foundation of thermodynamics. Recommended.

Euclid. *Euclid's Elements*. Dana Densmore, ed. T. L. Heath, trans. Santa Fe, NM: Green Lion Press, 2002. You probably hated it in high school, but this is one of the truly great works of the mind, exemplifying reason and knowledge for mainstream Western intellectuals right down to the present. Read it to appreciate the mode of reasoning it exemplifies. Highly recommended.

Galen of Pergamon. *On the Natural Faculties*. New York: Putnam, 1916; in the Loeb Classical Library series and reprinted by Kessinger in 2004. In this work, Galen pulls together many strands of Greek and Graeco-Roman medical thought and theory, as Euclid did for Greek mathematics and Aristotle for Greek logic.

Galilei, Galileo. *Dialogue Concerning the Two Chief World Systems*, 2nd rev. ed. Berkeley: University of California Press, 1962. This is the book that caused Galileo's trial for heresy. Did he advocate the view that the Earth moved around the Sun? Is this a "fair" scientific treatment of a controversial issue? Highly recommended.

Gamow, George. *Thirty Years That Shook Physics*. New York: Anchor, 1966. Gamow remains one of the least known of the great 20th-century physicists. This is a wonderful autobiographical memoir, often funny and somewhat irreverent, of the creation of quantum mechanics. Very highly recommended.

Gille, Bertrand. *Engineers of the Renaissance*. Cambridge, MA: MIT Press, 1966. Newer complement to Parsons (below) by a good French historian of technology; out of print but available used.

Gimpel, Jean. *The Medieval Machine: The Industrial Revolution of the Middle Ages*. New York: Holt, Rhinehart and Winston, 1976. Gimpel was an "amateur" historian in the best sense and an enthusiast for medieval and Renaissance technology as both beautiful and socially important. Easy to read yet packed with information. Highly recommended.

Gingrich, Owen. *The Book Nobody Read*. New York: Walker and Company, 2004. Gingrich is a leading historian of astronomy. Here, he traces the fate of copies of Copernicus's masterwork in the decades after its publication in 1543 as a way of assessing its influence.

Grafton, Anthony. *Leon Battista Alberti: Master Builder of the Italian Renaissance*. New York: Hill and Wang, 2000. Grafton is an intellectual historian, and this book, like his earlier biography of Jerome Cardan, gives an appreciation of the social-cum-intellectual context of a man who was at the center of art, business, and engineering in the late 16th century. Recommended.

Grant, Edward. *Physical Science in the Middle Ages*. Cambridge: Cambridge University Press, 1977. A very good, short monograph that surveys the major ideas, people, and places. A good source of leads to reading in greater depth about medieval nature philosophy as a seedbed of modern science.

Grattan-Guinness, Ivor. *The Norton History of the Mathematical Sciences: The Rainbow of Mathematics*. New York: Norton, 1997. Grattan-Guiness is the encyclopedic historian of mathematics, and this is a rich general reference to the subject.

Greene, Brian. *The Fabric of the Cosmos*. New York: Norton, 2004. A popular treatment of late-20th-century cosmology by a Columbia University physicist. Very well written. Recommended.

———. *The Elegant Universe*. New York: Norton, 1999. All you want to know about string theory and more at the turn of the 21st century. Well and clearly written.

Grendler, Paul F. *The Universities of the Italian Renaissance*. Baltimore: Johns Hopkins University Press, 2002. A scholarly study, narrow in scope, but this is the stuff of good history writing.

Ghiselin, Michael T. *The Triumph of the Darwinian Method*. Chicago: University of Chicago Press, 1984. A prize-winning monograph on the logic of Darwin's argument in the *Origin* and his methodology. Recommended.

Hacking, Ian. *The Taming of Chance*. Cambridge: Cambridge University Press, 1991. Very good social-intellectual history of probability theory. Well written and, like all of Hacking's books, insightful. Recommended.

Hall, Marie Boas. *The Scientific Renaissance, 1450–1630*. New York: Dover, 1994. For today's historians of science, this is a dated book, but it is enjoyable to read, highly informative without being stuffy, and not wrong. A good lead-in to Westfall's *Construction* (below).

Hankins, Thomas L. *Science and the Enlightenment*. Cambridge: Cambridge University Press. An excellent, short book on science in the 18th century, with an emphasis on science as an agent of social reform through its connection to the ideas of rationality and progress. Highly recommended.

Harman, P. M. *Energy, Force and Matter: The Conceptual Development of Nineteenth-Century Physics*. Cambridge: Cambridge University Press, 1982. A very good, tightly focused book. Highly recommended.

Harris, William V. *Ancient Literacy*. Cambridge, MA: Harvard University Press, 1989. A valuable, detailed study of literacy in ancient Greece and Rome; the spread of writing in law, politics, and daily life; and the emergence of a commercial book trade. Recommended.

Harvey, William. *On the Motion of the Blood in Man and Animals*. New York: Prometheus, 1993. This remains one of the most readable of all primary source works in early modern science, arguing in 1628 for the circulation of the blood driven by the heart. Recommended.

Haskins, Charles Homer. *The Renaissance of the Twelfth Century*. Cambridge, MA: Harvard University Press, 2005. A classic essay, now reissued, that remains a joy to read as a general introduction to a field now dominated by specialists. Highly recommended.

———. *The Rise of Universities*. New York: Transactions, 2001. Again, a reissued early study. Recommended.

Hero of Alexandria. *Pneumatica*. New York: American Elsevier, 1971. Always in print, this little book, written in the 2nd century, is a collection of ideas for machines. A fascinating insight into one facet of Graeco-Roman technology, but note that the illustrations are not original. Recommended.

Hesse, Mary. *Forces and Fields: The Concept of Action at a Distance in the History of Physics*. New York: Dover, 2005. A valuable and insightful historical study of recourse by natural philosophers and modern scientists to forces acting at a distance, as opposed to mechanical contact forces, in order to explain natural phenomena without invoking magic or spiritualism. Highly recommended.

Hodges, Andrew. *Alan Turing: The Enigma*. New York: Simon and Schuster, 1983. An excellent biography of Alan Turing and a clear treatment of the intellectual context out of which the idea of the computer emerged. Recommended.

Holland, John H. *Hidden Order: How Adaptation Builds Complexity*. Boston: Addison-Wesley, 1996. Short monograph on self-organization by a pioneer of complexity theory and creator of the computer program Life. Highly recommended.

———. *Emergence: From Chaos to Order*. New York: Perseus Books, 1999. Holland gives scientific content to the cliché that the whole is greater than the sum of its parts. Recommended.

Hughes, Thomas P. *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970*. Chicago: University of Chicago Press, 2004. Very good, very readable analysis of the relationships among technology, politics, and social values from the mid-19th through the mid-20th centuries. Recommended.

———. *Networks of Power*. Baltimore: Johns Hopkins University Press, 1983. Hughes is a dean of American historians of technology and this book shows why. It traces the relationships among invention,

innovation, commerce, politics, science, and society in the creation of America's electrical networks. Recommended.

Johns, Adrian. *The Nature of the Book*. Chicago: University of Chicago Press, 1998. Johns argues at length in this big book, with lots of supporting detail, that print technology enabled authoritative, uniform versions of a text only after an extended social struggle to create institutions that protected profit and reduced pirated editions and plagiarism. Recommended.

Jones, Richard A. L. *Soft Machines: Nanotechnology and Life*. Oxford: Oxford University Press, 2004. The commercial exploitation of nanotechnology and that of molecular biology in the early 21st century are converging; this popular account of the convergence is timely.

Kelley, Donald. *Renaissance Humanism*. New York: Twayne, 1991. A good introduction to the Humanist movement by a major scholar. Recommended.

Klein, Jacob. *Greek Mathematical Thought and the Origin of Algebra*. New York: Dover, 1992. An original analysis and survey of Greek mathematics, which was, after all, a decisive influence on modern science.

Kramer, Samuel Noah. *Sumerian Mythology*. Philadelphia: University of Pennsylvania Press, 1972. Kramer was one of the pioneers of the study of Sumerian texts. This book presents deciphered Sumerian religious texts.

Kuhn, Thomas. *The Copernican Revolution: Planetary Astronomy in the History of Western Thought*. Cambridge, MA: Harvard University Press, 1992. An excellent, important analysis of the intellectual legacy of Copernicus's astronomical ideas. Highly recommended.

Lamarck, Jean-Baptiste. *Zoological Philosophy*. Chicago: University of Chicago Press, 1976. Lamarck was a far more important figure than most 20th-century biologists are willing to allow. Read this for yourself and see that Lamarck is more than just the inheritance of acquired characteristics!

Landels, J. G. *Engineering in the Ancient World*. London: Chatto and Windus, 1978. Easier to find than Drachmann's book (above), though also out of print. Both are the real thing: Engineering-knowledgeable authors use surviving texts and artifacts to reveal what the Graeco-Romans knew how to do with machinery. Sounds stuffy, but it's fascinating detective work.

Lefevre, Wolfgang. *Picturing Machines, 1400–1700*. Cambridge, MA: MIT Press 2004. A collection of essays that survey the evolution of machine drawing during the Renaissance and its implications for machine design and construction and, more broadly, for technological innovation as a social force. Recommended.

Levere, Trevor. *Transforming Matter*. Baltimore: Johns Hopkins University Press, 2001. Histories of chemistry are rare, and readable ones (to non-chemists), rarer still; thus, Levere's book is recommended.

Lewontin, Richard. *The Triple Helix*. Cambridge, MA: Harvard University Press, 2000. Lewontin is a major figure in evolutionary biology, and in these four lectures, he describes what he thinks is wrong with the current linkage of evolution to molecular biology and genetics. Recommended (but be prepared for its relentless negativism!).

Lindberg, David C. *The Beginnings of Western Science*. Chicago: University of Chicago Press, 1992. A fine example of history-of-science writing and scholarship, surveying the Greek, Roman, Islamic, medieval, and early Renaissance antecedents of modern science. Recommended.

Lindley, David. *Boltzmann's Atom*. New York: Free Press, 2001. Where Cercignani's book focuses on Boltzmann and his scientific accomplishments, Lindley focuses on the idea of the atom in the 19th century and the context within which Boltzmann championed its reality.

Lloyd, Seth. *Programming the Universe*. New York: Knopf, 2006. Lloyd is a pioneer of the quantum computer and here describes, in nontechnical terms, his conception of the Universe as a quantum computational information structure. Recommended.

Lucretius. *On the Nature of the Universe*. London: Penguin, 1994. An important and, from the Renaissance on, influential statement of Epicurus's atomism that made the armature of a philosophy of nature and of man.

Mandelbrot, Benoit. *The Fractal Geometry of Nature*. San Francisco: W.H. Freeman, 1983. Mandelbrot pioneered the field of fractional dimensionality. This is a stimulating, accessible description of what fractals are and why they matter. Subsequently, they have become important tools in applied mathematics. Recommended.

Mann, Charles C. *1491: New Revelations of the Americas Before Columbus*. New York: Knopf, 2005. Mann is a journalist, synthesizing primary source material, and his claims are controversial, but they reflect the opinions of a growing number of scholars that the inhabitants of the Americas before 1492 were far more numerous and far more sophisticated than we have been taught.

Marenbon, John. *Later Medieval Philosophy*. London: Routledge, 1991. A good introduction to the knowledge issues in medieval philosophy, but this source also describes the rise of the universities and the translation of Greek and Roman texts from Arabic into Latin. Recommended.

Mayr, Ernst. *The Growth of Biological Thought*. Cambridge, MA: Harvard University Press, 1982. Mayr was one of the great evolutionary biologists of the 20th century and was still publishing as he approached 100! This is an excellent history of the great 19th-century ideas in biology. Recommended.

McClellan, James E., III, and Harold Dorn. *Science and Technology in World History: An Introduction*. Baltimore: Johns Hopkins University Press, 2006. Excellent social-historical interpretation of how technology and, later, science-through-technology have changed the world. Recommended.

Melsen, A. G. van. *From Atomos to Atom: The History of the Concept Atom* New York: Harper, 1952. A dated but charmingly literate monograph on the atomic idea from the Greeks to the 20th century. Out of print but available used. See Pullman below.

Misa, Thomas J. *A Nation Transformed by Steel*. Baltimore: Johns Hopkins University Press, 1995. An excellent example of the placement of history of technology in its social context. The displacement of iron by steel implicated science, technology, finance, industry, government, and society, and Misa does justice to them all. Highly recommended.

Morange, Michel. *A History of Molecular Biology*. Cambridge, MA: Harvard University Press, 1998. If you're going to read just one book about molecular biology, make it this one. Morange is a biologist, not a historian, so the focus is on the science, but the writing makes it very accessible.

———. *The Misunderstood Gene*. Cambridge, MA: Harvard University Press, 2001. Highly recommended critique of the still-prevalent view that genes do it all. What genes are and how they act is still being discovered.

Newton, Isaac. *The Principia*. I. Bernard Cohen and Anne Whitman, trans. Berkeley: University of California Press, 1999. This is one of the most influential science texts ever published, and in this new translation with extensive commentary, the general reader can learn directly from Newton! Highly recommended.

Nisbet, Robert. *A History of the Idea of Progress*. Piscataway, NJ: Transaction, 1994. Intellectuals have been critical of the idea of progress for most of the 20th century, but it remains a core public value and central to science and technology. Nisbet's book takes a positive view of progress and is a successor to J. B. Bury's classic *The Idea of Progress*. Recommended.

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*. New York: Twayne, 1996. A good short history of physical science as it became a driver of social change. Highly recommended.

Overbye, Dennis. *Lonely Hearts of the Cosmos*. Boston: Little, Brown and Co., 1999. A wonderful book that uses people, their ideas, and relationships as a means of describing the development of ideas about

the origin of the Universe since the 1950s. Highly recommended. (Read the revised 1999 edition or a later one.)

Parsons, William Barclay. *Engineers and Engineering in the Renaissance.* Cambridge, MA: MIT Press, 1968. A classic study of what the title promises. Still good enough after its original publication in the late 1930s to remain in print for decades, and now available used at reasonable prices. A big book.

Pesic, Peter. *Abel's Proof*. Cambridge, MA: MIT Press, 2003. Very short, very good (and nontechnical) account of how Niels Abel's proof of a negative about algebraic equations led to major innovations in 19th-century mathematics and in late-20th-century symmetry-based physics.

Plato. *Plato: The Collected Dialogues*. Edith Hamilton and Huntington Cairns, eds. Princeton: Bollingen, 1978. The dialogue *Phaedrus* contains Socrates's argument against writing; the dialogues *Thaeatetus* and *Timaeus* relate to knowledge of nature.

Porter, Roy. *The Rise of Statistical Thinking, 1820–1900*. Princeton: Princeton University Press, 1986. An excellent book; nicely complements Hacking (above), with a narrower focus.

Prager, Frank D., and Gustina Scaglia. *Brunelleschi: Studies of His Technology and Inventions.* New York: Dover, 2004. Brunelleschi not only reintroduced perspective drawing, but his dome for the cathedral in Florence was an epochal technological achievement, and he invented numerous machines to enable its construction. Recommended.

Prigogine, Ilya. *Order Out of Chaos*. New York: Bantam, 1984. A philosophical reflection on the challenge of process thinking to atomistic thinking. Highly recommended. (His later *From Being to Becoming* is more challenging technically.)

Provine, William. *The Origins of Theoretical Population Genetics*. Oxford: Oxford University Press, 2003. Ignore the forbidding title: This is an excellent book that exposes how Darwinian evolutionary theory was resurrected in the 1920s. Highly recommended.

Pugsley, Alfred, ed. *The Works of Isambard Kingdom Brunel*. Cambridge: Cambridge University Press, 1976. Brunel, typically for engineers, is unknown in spite of being one of a small community of men (including his father, Marc) responsible for making the world "modern." This is a collection of short essays (search for it used online) that reveal how much one of these men accomplished while knowing so little theory!

Pullman, Bernard. *The Atom in the History of Human Thought*. Alex Reisinger, trans. Oxford: Oxford University Press, 2001. A history of the atom from the Greeks to the 20th century. Given that the author was a professor of chemistry at the Sorbonne, this is a scientist's view of the history of a core scientific idea.

Raby, Peter. *Alfred Russel Wallace: A Life*. Princeton: Princeton University Press, 2001. A good biography of Wallace, who is still damned with faint praise by biologists. A leading scientist, a social reformer, and a spiritualist, Wallace deserves our attention. Recommended.

Randall, Lisa. *Warped Passages*. New York: Harper, 2005. If you're interested in learning about string theory, this is one breezily written option by a string theory researcher. I prefer Brian Greene's *The Elegant Universe* on this subject.

Ratner, Mark, and Daniel Ratner. *Nanotechnology: A Gentle Introduction to the Next Big Idea*. Upper Saddle River, NJ: Prentice Hall, 2002. Nanotechnology research, development, and commercialization, along with safety and health issues, are evolving at a breakneck pace, so consider this a good introduction to the underlying ideas and read the newspaper.

Robb, Christina. *This Changes Everything: The Relational Revolution in Psychology*. New York: Farrar, Straus and Giroux, 2006. Robb is a Pulitzer Prize–sharing journalist; this book describes how acknowledging the reality and causal efficacy of relationships affected clinical and theoretical psychology.

Rocke, Alan J. *Chemical Atomism in the 19th Century: From Dalton to Cannizaro.* Columbus: Ohio State University Press, 1984. An in-depth study of the early history of the atomic theory of matter, when it was mostly a theory for chemists.

Rudwick, Martin J. S. *The Meaning of Fossils*. Chicago: University of Chicago Press, 1985. All of Rudwick's books are excellent, and his most recent, *Bursting the Limits of Time*, is most relevant to the reconceptualization of time in the 19th century, but it is massive. This book is a gentler yet still highly informative study of the same subject. Highly recommended.

Scaglia, Gustina. *Mariano Taccola and His Book* De Ingeneis. Cambridge, MA: MIT Press, 1972. This is a very good edition, with scholarly commentary, of a Renaissance-era machine design book, symptomatic of the emergence of modern engineering. See Prager and Scaglia (above) and Scaglia's *Francesco di Giorgio*, a beautiful collection of Renaissance machine drawings with extensive commentary by Scaglia. Recommended.

Seife, Charles. *Decoding the Universe*. New York: Viking, 2006. A very readable account by a science journalist of how information has become physically real for many scientists. Recommended.

Shapin, Steven and Simon Schaffer. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life*. Princeton, New Jersey: Princeton University Press, 1985. A modern classic that exposes the equivocal character of experimental research using newly devised instruments by way of Thomas Hobbes' criticism of Robert Boyle's "discoveries" and the Royal Society as an institution. Recommended.

Singleton, Charles. *Art, Science, and History in the Renaissance*. Baltimore: Johns Hopkins University Press, 1968. An alternative to Edgerton (above); also out of print but available used at more reasonable prices.

Smolin, Lee. *The Trouble with Physics: The Rise of String Theory, the Fall of Science, and What Comes Next*. Boston: Houghton Mifflin, 2006. One of several recent attacks on string theory by physicists who claim that it is a dead end and bad science. I admire Smolin's earlier books, especially *Three Roads to Quantum Gravity*, and his criticisms are legitimate, but the book's primary value is as one skirmish in a "war" within physics.

Sorabji, Richard. *Matter, Space and Motion: Theories in Antiquity and Their Sequel*. Ithaca: Cornell University Press, 1988. A survey by a philosopher of materialist theories of nature from the earliest Greek philosophers through the 6th century. This complements Lindberg's book, above.

Stachel, John. *Einstein's Miraculous Year*. Princeton: Princeton University Press, 1998. Stachel is the editor of the Einstein papers and here offers the historic 1905 articles in translation with enough commentary for anyone to follow their arguments. Highly recommended.

Stephenson, Bruce. *The Music of the Heavens: Kepler's Harmonic Astronomy*. Princeton: Princeton University Press, 1994. Here, you can see the authority given to the Pythagorean idea that mathematical form was the indwelling order of nature underlying its expression in matter and that this order was fundamentally musical. Recommended.

Strogatz, Steven. *SYNC: The Emerging Science of Spontaneous Order*. New York: Hyperion, 2003. A readable book for a general audience on self-organization, bringing Prigogine's early ideas up-to-date. Strogatz is himself a researcher in this field.

Susskind, Leonard. *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design*. Boston: Little, Brown and Co., 2006. As if to counter Smolin's rant against string theory, one of its architects describes the theory as if its triumphant completion and confirmation were imminent! Stranger than science fiction. Recommended.

Swade, Dorn. *The Difference Engine*. London: Penguin, 2002. An excellent book that makes reading about Charles Babbage's failed quest to build a computer in the mid-19th century fun. The effort and its failure reveal much about the science-technology-society relationship. Highly recommended.

Taylor, George Rogers. *The Transportation Revolution*. New York: Harper, 1968. A solid history of the 19th-century transportation technology innovations that literally changed the world.

Travis, Anthony. *The Rainbow Makers*. Bethlehem, PA: Lehigh University Press, 1983. The fascinating story of how a teenager discovered the first synthetic dye and triggered the first "Silicon Valley" phenomenon, in which chemical science, industry, and government created enormous wealth and power. Recommended.

Uglow, Jenny. *The Lunar Men: Five Friends Whose Curiosity Changed the World*. New York: Farrar, Straus and Giroux, 2002. Wonderful account of the interactions of a group of thinkers and doers at the turn of the 19th century whose members included James Watt and Mathew Boulton, Erasmus Darwin and Josiah Wedgwood (both of them Charles Darwin's grandfathers!), and Joseph Priestley. Highly recommended.

Vitruvius. *The Ten Books on Architecture*. New York: Dover, 1960. More than 2000 years old, still in print, and still worth reading!

Watson, James D. *The Double Helix*. New York: Signet, 1968. No scientist had written such a tell-it-all account of how his research was done before this book. Highly recommended.

———. *DNA*. New York: Knopf, 2003. Now an honored senior, Watson describes the state of our understanding of how DNA works for a general audience. Recommended.

Webster, Charles. *The Great Instauration*. London: Peter Lang, 2002. Webster describes the social context of 17th-century England—especially the religious, political, social reform, and medical contexts—in which early modern science took root.

Weinberg, Steven. *Dreams of a Final Theory*. New York: Pantheon, 1992. Weinberg shared a Nobel for the first step in the unification of the four fundamental forces of nature and here anticipates the implications of full unification. Not dated because there has been little progress since 1992!

Westfall, Richard S. *Never at Rest: A Biography of Isaac Newton*. Cambridge: Cambridge University Press, 1980. The definitive personal and intellectual biography of Newton. Highly recommended.

———. *The Construction of Modern Science*. Cambridge: Cambridge University Press, 1989. Short, excellent introduction to the ideas at the heart of 17th-century science and its accomplishments. Highly recommended, as are all the monographs in the Cambridge History of Science series.

White, Lynn. *Medieval Technology and Social Change*. Oxford: Oxford University Press, 1966. White describes the social impact of the stirrup, wind power, and agricultural innovations, overstating the case but calling attention to technology as a force driving social change when most historians ignored it.

Williams, Trevor. *A History of Invention*. New York: Checkmark Books, 1987. It looks like a coffee table book, but Williams is a scholar and the book is filled with lots of valuable information without reading like an encyclopedia.

Wilson, Catherine. *The Invisible World: Early Modern Philosophy and the Invention of the Microscope*. Princeton: Princeton University Press, 1995. An important study of the interaction of ideas and instruments, theories of nature and observations. Recommended.

Worboys, Michael. *Spreading Germs: Disease Theories and Medical Practice in Britain, 1865–1900*. Cambridge: Cambridge University Press, 2000. An account of the response of the British medical community to the germ theory of disease as that theory evolved. Recommended.

Zachary, G. Pascal. *Endless Frontier: Vannevar Bush, Engineer of the American Century*. Cambridge, MA: MIT Press, 1999. A good biography of the man who was the "czar" of harnessing science and technology to the World War II effort and who promoted the postwar policy of federal support for scientific research.

Zagorin, Perez. *Francis Bacon*. Princeton: Princeton University Press, 1998. A very good biography of Bacon, doing justice to him as a social reformer, political opportunist, and philosopher of nature. Recommended.

Internet Resources:

Stanford Encyclopedia of Philosophy. A superb resource for the history of philosophy, of uniformly high quality, guaranteed to illuminate and please. Includes outstanding entries on many science topics—try advanced search. http://plato.stanford.edu.

University of Delaware Library. *Internet Resources for History of Science and Technology*. A "super" site for exploring the history of technology and of science from antiquity to the present. www2.lib.udel.edu/subj/hsci/internet.html.

Ancient Languages and Scripts. An informative site on the history of writing. www.plu.edu/~ryandp/texts.html.

The Labyrinth: Recourses for Medieval Studies. A "super" site listing resources for exploring Medieval culture. http://labyrinth.georgetown.edu.

The Art of Renaissance Science. A rich, multi-disciplinary site created by Joseph Dauben on the relationships among art, mathematics and science in the Renaissance. www.mcm.edu/academic/galileo/ars/arshtml/arstoc.html.

The Galileo Project. An excellent resource site for everything to do with Galileo's life, works and ideas. http://galileo.rice.edu.

The Newton Project. A similar, and similarly excellent resource, for the life, works and ideas of Isaac Newton. www.newtonproject.ic.ac.uk.

University of St. Andrews School of Mathematics and Statistics, *The MacTutor History of Mathematics Archive*. A very good resource for the history of mathematics; the Biographies on the site offer a comprehensive history of mathematicians and their accomplishments. www-history.mcs.st-and.ac.uk/.

Selected Classic Papers from the History of Chemistry. An outstanding collection of the full text of classic papers in the history of chemistry. http://web.lemoyne.edu/~giunta/papers.html.

The Nobel Foundation. Official web site offering access to all Nobel Prize winners, their biographies and accomplishments, and their acceptance addresses; a rich and fascinating history of science resource. http://nobelprize.org.

The History of Computing. An excellent collection of materials and links for exploring the history of computers and computing. http://ei.cs.vt.edu/~history/.

NASA History Division. A central site for aerospace history. http://history.nasa.gov.

The Official String Theory Website. The "home page" for accessible accounts of string theory. http://superstringtheory.com.

Sunny Y. Auyang. “Scientific convergence in the birth of molecular biology.” Very good essay on the history of molecular biology. Other articles available on this idiosyncratic yet interesting website by a respected scientist address engineering, including a useful history of engineering, biomedicine, and physics. www.creatingtechnology.org/biomed/dna.htm.

National Nanotechnology Initiative. The official Web site for federally funded nanotechnology research and development. www.nano.gov.