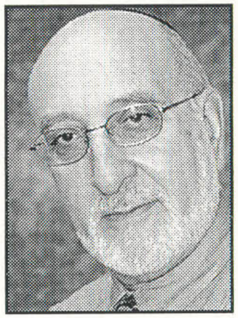

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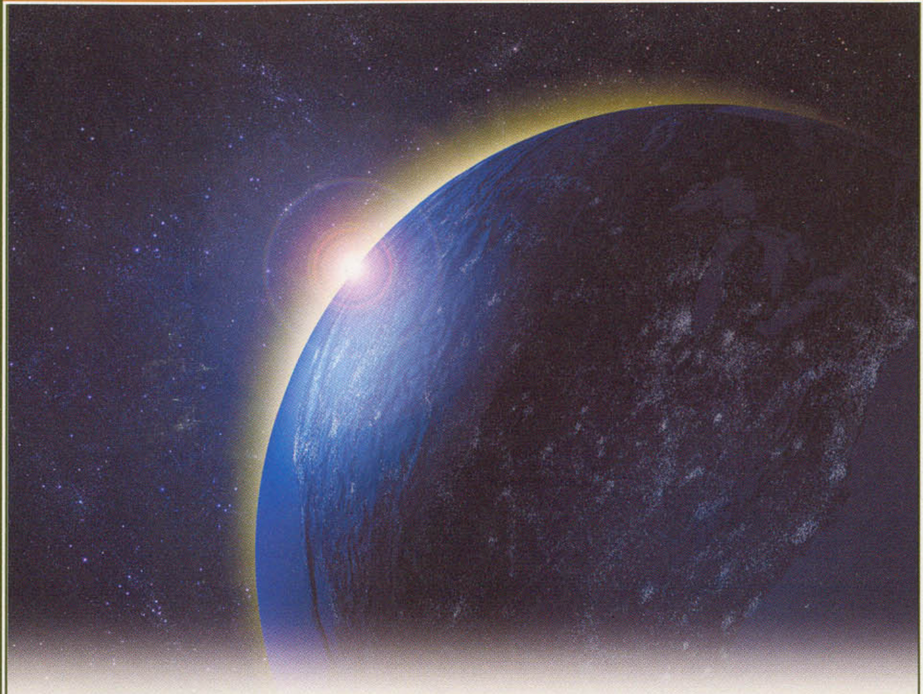

Science in the Twentieth Century:
A Social-Intellectual Survey

Taught by: Professor Steven L. Goldman,
Lehigh University

Part 2

Course Guidebook

THE TEACHING COMPANY®

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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.

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Science in the Twentieth Century: A Social-Intellectual Survey

Scope:

In the course of the 20th century, the practice of science, professionally, intellectually, and in relation to society, increased in scope, scale, and complexity far beyond what had been anticipated at the end of the 19th century. All of the sciences became inextricably entangled with social, political, and commercial forces and values. From the perspective of society, at least, this erased the distinction between pure and applied science, between knowledge and its "fruits," which had been passionately espoused by many leading 19th-century scientists. As scientists created increasingly powerful theories, people—often scientists themselves—applied those theories to develop technologies whose exploitation created new wealth, new forms of power and control, new ways of life…and new dependencies on more science to create newer technologies!

Concurrently, the practice of science became increasingly formalized, institutionalized, and professionalized. This professionalization reflected and was driven both by the rise of a large number of people who made a living as scientists, in comparison with the comparatively modest community of mostly gentlemen scientists in the 19th century, and by the steadily increasing significance of science to society from the last third of the 19th century through the 20th century. Two hundred and fifty years after the pioneering work of Descartes, Francis Bacon, and Galileo, science suddenly mattered—not just to intellectuals, but to everyone and in profoundly existential ways.

Intellectually, too, the discoveries and theories of 20th-century physical, life, and social scientists exceeded anything that had been anticipated, even by the greatest of 19th-century scientists. As 1900 approached, leading physicists claimed that, apart from the details, the task of science was nearing completion; however, by the end of the 20th century, effectively every 19th-century theory of natural and social phenomena would be overthrown or superseded.

The first lecture in this course establishes its objective: to trace an intellectual history of the physical, life, and social sciences in the 20th century, organized around an evolving scientific understanding of matter and energy, the universe, Earth, life, and humanity, subsuming under the last category theories of culture, society, and mind.

Complementing this survey of a century of science from the "inside," in terms of its ideas and discoveries, will be an account of the evolution of 20th-century science from the "outside," that is, of its evolving relationship with society. It is this reciprocal relationship between science and society that makes an understanding of the sciences as a whole in the 20th century important, and not simply as history, because science is implicated in all of our 21st-century prospects, the threats no less than the promises.

Lectures Two though Eleven describe our evolving understanding of matter and energy, the foundations of the physical and life sciences. We begin with the special and general theories of relativity and how they redefined what we mean by space, time, matter, energy, and motion: in short, what the framework of reality is for the physical sciences.

Given that quantum theory is the most important and intellectually revolutionary scientific theory of the 20th century, eight lectures are devoted to it. Lectures Three and Four trace the early history of the theory, from the tentative introduction of the quantum hypothesis in 1900 to the formulation of quantum mechanics in 1925 and its radical Copenhagen interpretation in 1929. Our goal is a qualitative appreciation of the innovative ideas underlying the theory and of the bizarre microworld underlying ordinary experience that it revealed. Lectures Five through Eight describe the creation and application of the second stage of quantum theory's development, quantum electrodynamics (QED), from 1929 to 1965. Lectures Nine and Ten describe the transition from QED to quantum chromodynamics (QCD) and the unification of all known fundamental forces of nature.

Lecture Eleven concludes the discussion of matter and energy by highlighting major events in the evolution of chemistry, emphasizing the transformation wrought by its assimilation of quantum theory and its growing power to create molecules by design.

The obscurity of the theories of 20th-century physical science from the perspective of the non-scientist public is overwhelmingly a consequence of the forbidding mathematics that has become the language of science. Lectures Twelve and Thirteen discuss controversies in the first half of the 20th century over the relationship between mathematics and truth, and between mathematics and reality, as well as the astonishing fertility of abstract mathematics for the sciences, even if the source of that fertility is not understood.

What we mean by the *universe* has changed, from 1900 to 2000, far more dramatically than anything else in the history of science, more even than the change wrought by Copernicus. Today, the universe is unimaginably more vast than it was thought to be in 1900, and the stories of its origin, constitution, and fate, discussed in Lectures Fourteen through Sixteen, are beyond science fiction!

Lectures Seventeen through Nineteen focus on our knowledge of planet Earth, especially the shift from a geology of static continents to plate tectonic theory. We also discuss the growing recognition of the Earth as a complex system, integrating a dynamic, evolving, physical Earth with its biosphere, oceans, atmosphere, and external and internal magnetic fields, the whole interacting with the solar system in general and the Sun in particular.

Lectures Twenty and Twenty-One address the "outside" of science, especially the rise of techno-science (science-based technology) and its connections to government, industry, and society.

Lectures Twenty-Two through Twenty-Six address our understanding of life, treating the history of evolutionary biology, human evolution, genetics, molecular biology, and science-based medicine.

Lectures Twenty-Seven through Thirty-Four focus on our knowledge of humanity. This group includes three lectures on the evolution of anthropological theories of human culture, the field and theoretical work of archaeologists, important developments in linguistic theory, and changing conceptions of history as a science. Three lectures describe theories of society, the state, and economies, theories that have had profound implications for national and global political agendas and actions in the course of the 20th century. Two lectures describe changing theories of the human mind, our most intimate attempt at self-understanding, from the enormously influential theories of the unconscious by Freud and Jung early in the century, through the equally influential behavioral psychology that dominated the mid-century, to the cognitive psychology that came to the fore in the late century, especially cognitive neuroscience allied to artificial intelligence research.

Lectures Thirty-Five and Thirty-Six review the major concepts of 20th-century science and discuss their broader cultural and intellectual significance, survey the leading edges of the sciences at the close of the 20th century, and look ahead to the continuing evolution of science in the 21st century.

Lecture Thirteen
Mathematics and Reality

Scope: Although more difficult to communicate qualitatively, the development of mathematics in the 20th century was every bit as breathtaking as the development of theories of matter, energy, life, the Earth, and the universe. David Hilbert's challenge to mathematicians was highly technical and esoteric, but it provoked surprising consequences. Kurt Gödel's 1931 proof that the logical consistency and completeness of mathematics could not be proven was a philosophical bombshell on a par with Heisenberg's uncertainty principle, announced five years earlier. Five years later, in 1936, Alan Turing's extension of Gödel's work proved that no rule-based procedure, or algorithm, could exist, even in principle, that would guarantee a solution to every mathematical problem, though Hilbert's formalist interpretation of mathematics required that it should. The means by which Turing established this led directly to the theory of computing and underlies modern computer science. At the same time, developments in mathematics during and after World War II led to game theory, cybernetics and information theory, network theory, fractal geometry, chaos theory, systems and complexity theories, and the discovery of self-organization.

Outline

I. Regardless of the confusion among mathematicians in the early 20th century, mathematicians continued to generate new mathematical knowledge at an astonishing rate.

- **A.** In general, it is fair to say that mathematicians live with a peculiar, unresolved problem: What is the nature of mathematical objects? Do they exist independently of the human mind or not?
- **B.** Most mathematicians will privately assert that mathematical objects do exist independently of the mind. That is to say, we *discovered* the triangle and its properties; we didn't *invent* them. But if that is the case, how do we learn about mathematical objects?

II. In 1931, Kurt Gödel demonstrated that the consistency and completeness of any axiomatic system as simple as ordinary arithmetic could not be proven.

- **A.** Using tools of mathematical logic developed by Frege, Russell, and others earlier in the century, together with a technique derived from the set theory of George Cantor, Gödel created an ingenious proof that any axiomatic system necessarily generated statements that could not be proven to be either true or false within that system.

- **B.** Gödel's proof was a major event in the 2500-year-long history of mathematics in Western culture, on a par with the shock caused by non-Euclidean geometries. The proof showed that the formalist interpretation of mathematics was not possible, as the logicist wasn't. Most mathematicians do not believe that intuitionism is correct either, so we are left with the question: What is the nature of mathematical truth?
- **C.** In 1936, Alan Turing built on Gödel's proof to solve David Hilbert's problem of the effective procedure. Turing proved that no effective decision procedure existed for solving all problems in arithmetic.
  1. Turing constructed his proof around an imaginary machine, now called a *Turing machine*, that acted on itself in accordance with a fixed set of instructions built into it.
  2. This simple conceptual machine allowed Turing to solve the negative of Hilbert's problem. Turing also recognized that a corollary of his proof was that such a machine could solve any logical or mathematical problem for which an algorithm *could* be specified.
  3. Turing was unaware, in 1936, that his theoretical work paralleled work in the United States that reached the same conclusions he had and that World War II would make his imaginary machines real, leading in 1949 to the first electronic, stored-program digital computer.
  4. During the war, Turing used a kind of analog computer to break the Enigma Code. After the war, he worked on the first generation of electronic, stored-program digital computers in England. Turing was found dead under mysterious circumstances shortly after his conviction for homosexuality in the late 1950s.

III. We will focus on two aspects of the use of computing that are particularly interesting for science and mathematics: the use of computer simulations in science and the use of computer capabilities in mathematical proofs.

- **A.** Computer simulations have become essential research tools in all of the sciences. In this, we again see an ultimately mathematical structure becoming a surrogate for reality. We seem to have an almost intuitive notion that mathematics somehow captures features of reality.
  1. Geologists, for example, use computer simulations to predict the processes that take place beneath the crust of the Earth. Predictions of the simulations then become the hypotheses of experiments.
  2. In this way, computers have influenced the practice of all physical, life, and social sciences.
  3. The very availability of computers causes us to identify new kinds of problems and to attempt to solve them in new ways. We can also

avoid simplifying problems because of the availability of computing power.

- **B.** Since the 1980s and the Four-Color Map problem, mathematicians have used computers as part of mathematical proofs.
  - **1.** Part of a proof may read, for example: "Input to a computer… output from a computer."
  - **2.** Does this "shortcut" meet the definition of a *mathematical proof*; that is, to show a line of reasoning to demonstrate that a conclusion is true?

IV. Despite the philosophical questions surrounding the discipline, new forms of mathematics continue to provide fertile areas of exploration for science.

- **A.** For example, *game theory*, the mathematical modeling of rational choice in either competitive or cooperative situations of partial or no information, attracted attention during World War II and quickly became a staple of tactical and strategic military planning, political science, and economic theory.
- **B.** Early in the 20th century, several mathematicians studied a peculiar property of certain algebraic curves: self-similarity. In 1951, Benoit Mandelbrot synthesized these ideas, along with his own, into what became a new branch of mathematics, *fractals*, the geometry of self-similar shapes.
- **C.** No account of science in the second half of the 20th century can omit the influence of mathematics-based *chaos*, or *complexity*, *theory*.
  - **1.** *Chaos theory* is the application of mathematical tools to describe the underlying order of apparently disorderly natural phenomena, such as the weather.
  - **2.** In particular, scientists use chaos theory to model the behavior of non-linear systems, which over time, display an exquisite sensitivity to minute differences in initial conditions.
  - **3.** Throughout the 20th century, we have become increasingly sensitive to such non-linear, non-equilibrium systems. We have moved away from the 19th-century notion that equilibrium is the norm; we now recognize that many systems can remain in a non-equilibrium state through self-organization.
- **D.** Finally, especially for the Internet generation, it is necessary to note the development of the mathematical theory of *complex networks*.
  - **1.** Just after World War II, the Hungarian mathematicians Paul Erdos and Alfred Renyi created a mathematical model of a randomly connected network. Networks can have different kinds of structures—random connection is just one—and these structures have distinctive properties, quite independent of what they connect.

  - **2.** This theory is another example of 20th-century relationalism at work in science. The network of neural cells in the brain, the network of proteins determining cell metabolism, and the network of genes determining the self-organization of amino acids into proteins are all areas of exploration as complex networks.

Essential Reading:

John Casti, *Five More Golden Rules: Knots, Codes, Chaos, and Other Great Theories of 20th-Century Mathematics.*

John Holland, *Emergence: From Chaos to Order.*

Ernest Nagel and J. R. Newman, *Gödel's Proof.*

Supplementary Reading:

Andrew Hodge, *Alan Turing: The Enigma.*

Questions to Consider:

1. Does it matter that, logically at least, mathematics is incomplete and cannot be proven consistent?
2. Do mathematicians explore the properties of mathematical "objects" that exist independently of our experience of them, or do they invent these objects?
3. If the latter, how can mathematics be so fertile in science, which is about experience if not reality; but if the former, how can we know these objects?

Lecture Fourteen

The Universe Expands

Scope: It was only in the early 1920s that other galaxies were discovered. Suddenly, the *universe* was no longer synonymous with the Milky Way, which was no more central to the great scheme of things than the Earth had been thought to be before Copernicus. Five years later, analysis of star light suggested that the universe was expanding. Ten years after that, the Big Bang theory of the origin of the universe, supported by new developments in atomic physics and theories of the life and death of stars, was proposed as an explanation of that expansion. This theory implied a temporal beginning to the universe, however, and was challenged after World War II by the Steady State theory, which explained expansion without a beginning. Observational astronomy later swung support to the Big Bang approach.

Outline

I. Our understanding of the universe in the year 2000 contrasts dramatically with our understanding in 1900.

  A. The difference in these two views is not just a matter of scaling up the universe; by the end of the 20th century, we have completely reconceptualized the universe.

  B. We have used the term *evolution* in describing this survey of 20th-century science. This term applies not merely to the content of the sciences but also to our thinking about nature. Indeed, our brief overview of mathematical thought revealed the evolution of our thinking about thinking.

II. In 1900, the universe was "homey."

  A. In 1543, Copernicus argued that the Sun was the center of the universe and that the known planets rotated around the Sun. The "fixed stars" were far from Earth but close together in space. Copernicus did not know the scale of the universe.

  B. Between the time of Copernicus and the mid-19th century, astronomers had worked out the scale of the solar system. They knew, for example, that the Moon was about 200,000 miles from Earth and the Sun was about 93 million miles from Earth.

    1. In 1838, Friedrich Bessel used the principle of *parallactic displacement* to calculate the distance from Earth to a star.

    2. He determined that a star in the constellation Cygnus was 6.2 light years from Earth. (Remember that a light year is about 6 trillion miles.) The distance to this star, 38 trillion miles, gave astronomers some sense of the scale of the universe.

  C. By the early 1900s, the Milky Way was considered to be synonymous with the universe; it was the only galaxy. Nebulae, seen as fuzzy, glowing clouds, were believed to be clouds of gas within the Milky Way.

  D. In 1900, George Ellery Hale, a world-class solar astronomer, received funding from the Carnegie Institution of Washington to build a 60-inch reflecting telescope and an observatory on Mt. Wilson in southern California. Hale installed Harlow Shapley as director of the observatory.

    1. Fortunately for Shapley, a woman at Harvard University, Henrietta Leavitt, recognized that the brightness of certain stars varied with regular periods that were correlated with their observed luminosity. These *Cepheid stars* are distributed throughout the universe and can be used as "yardsticks" to calculate distances.

    2. Shapley used Leavitt's techniques, together with a technique for correlating the brightness of stars with their distinctive light spectra, to estimate the distance to the Large Magellanic Cloud at 100,000 light years. Suddenly, the universe had a scale and, for 1916, a jaw-droppingly immense one at that!

    3. Shapley also used this technique to estimate the size of the Milky Way and the location of Earth within it. These advances catapulted Shapley to fame, and he left Mt. Wilson to become director of the Harvard University Observatory.

    4. In 1919, a 100-inch telescope became operational at Mt. Wilson, and Edwin Hubble became director of the observatory there.

    5. In a public debate in New York City in 1920, Shapley aggressively defended the identity of the universe with the Milky Way against recent speculations that nebulae were other galaxies.

    6. In 1924, Hubble, using the 100-inch telescope, observed individual stars in the Andromeda "nebula," revealing that it, too, was a galaxy composed of hundreds of millions of stars and about a million light years from the Milky Way. Hubble could also see thousands more galaxies beyond Andromeda and, soon, millions more. The scale of the universe exploded!

  E. Hubble was far from done.

    1. In 1914, a little-known American astronomer named Vesto Slipher had reported a puzzling fact about the light he had analyzed from about a dozen nebulae: The frequencies were shifted from laboratory-based expectations, as if the stars were moving. Slipher's observations did not receive serious attention.

    2. In the mid-1920s, Hubble revisited Slipher's thinking and collected his own spectra from about 250 of the many galaxies he had discovered. He observed that, except for the nearest, all these galaxies were shifted toward the red end of the frequency spectrum. Applying the principles of the *Doppler effect*, Hubble concluded that all these galaxies were moving away from Earth.

   3. The Doppler effect is a wave phenomenon. Sound waves will seem to be of a higher frequency when traveling toward a listener and a lower frequency when traveling away from the listener, as if the waves are being stretched. In the same way, a light wave traveling away from an observer will be shifted toward the lower frequency, or red end of the spectrum.
   4. Hubble also noted that there was a direct relationship between the size of the shift in the spectra and the distance of the galaxy from Earth: the greater the distance, the greater the shift.
   5. In 1929, Hubble announced that the universe was expanding!

III. In 1917, Willem de Sitter had informed Einstein that the equations of the general theory of relativity entailed an expanding universe.

- **A.** Given that Einstein knew of no astronomical evidence to support this conclusion, he modified his gravitational equations to cancel this "spurious" expansion.
   1. In the mid-1920s, the Russian Alexander Friedmann worked out the expanding universe consequences of the general theory of relativity.
   2. Einstein was impressed with Friedmann's papers, but it was only after Hubble's announcement that he re-evaluated the general theory of relativity and removed his clumsy modifications.
   3. Georges Lemaître, a Belgian physicist and a Catholic priest, speculated that the expansion implied that the universe had a beginning in time and space from a single point of matter, consistent with Genesis.
- **B.** Hubble also traced the expansion backwards and estimated the age of the universe at about 2.5 billion years. Estimates of the age of the Earth, based on radioactivity, had put it at about 1.5 billion years.
- **C.** In 1938, Hans Bethe proposed that stars generated their energy by fusing hydrogen atoms into helium atoms, which gave us some understanding of the evolution of the universe. A year or two later, George Gamow began to build his first formulation of what came to be called the Big Bang theory that the universe originated in a cosmic explosion of matter.
   1. Gamow continued to develop this idea with collaborators, publishing important papers in 1946 and 1948, but the theory could not explain, in a manner that was consistent with quantum theory, *nucleosynthesis*, that is, the synthesis of heavy elements in stars.
   2. At the same time, Fred Hoyle, Hermann Bondi, and Thomas Gold rejected the idea that the universe had a beginning, although they acknowledged its expansion; they proposed, instead, a *Steady State theory*.
   3. The Steady State theory requires the regular creation of hydrogen atoms to maintain constant density as the universe eternally expands. Except for local variations, the universe is essentially uniform in space and time. But this theory, too, requires an explanation of how all the elements are synthesized from hydrogen atoms.
   4. Hoyle, with physicists William Fowler and Geoffrey and Margaret Burbridge, worked out a solution to this problem in the mid-1950s, but in the end, the solution reinforced the Big Bang theory! How this development came about is the subject of our next lecture.

Essential Reading:

Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory.*

Helge Kragh, *Cosmology and Controversy.*

Dennis Overbye, *Lonely Hearts of the Cosmos: The Story of the Scientific Quest for the Secret of the Universe.*

Supplementary Reading:

Timothy Ferris, *The Whole Shebang: A State-of-the-Universe(s) Report.*

Questions to Consider:

1. Why do we think that everything there is constitutes a uni-verse, that is, an ordered whole, as opposed to a mere collection of things?
2. How do modern optical telescopes differ as complex instruments from particle accelerators or electron and quantum mechanics–based microscopes?
3. Is the universe expanding, or is expansion merely one way to interpret astronomical data so that the data fit a number of accepted physical theories?

Lecture Fifteen

What is the Universe?

Scope: In the 1960s, the discovery of a universal cosmic background radiation, together with developments in the relativity and quantum theories, resurrected the Big Bang theory of the universe. Pursuing this approach to cosmology has led to increasingly detailed, but often controversial and speculative, accounts of the constitution, age, size, and origin of the universe. For example, after a late-20th-century modification of the Big Bang hypothesis called *inflation theory*, the universe suddenly became far more vast than anyone had imagined and perhaps not unique. It may have been the offshoot of literally no "thing" at all, but of the energy of the vacuum, according to quantum theory. Furthermore, to everyone's surprise, in 1998, astronomers found evidence, subsequently strengthened, that far from slowing down as had been supposed, some force was causing the expansion of the universe to accelerate.

Outline

I. We ended the last lecture in the 1950s with the rivalry between the Big Bang theory and the Steady State theory. At about the same time, George Ellery Hale had been aggressively seeking funding to build a 200-inch telescope.

- **A.** Hale secured funding from the Rockefeller Foundation to build another observatory in southern California on Mt. Palomar. The 200-inch telescope became operational there in 1949. Hubble was director of this observatory briefly before his retirement and was succeeded by Alan Sandage.
- **B.** Sandage inherited privileged access to the 200-inch telescope, along with the "mantle" of Hubble, that is, Hubble's view of the universe and his techniques for estimating distances in the universe. Sandage also inherited Hubble's brilliant assistant, Milton Humason.
- **C.** Sandage refined and extended Hubble's methodology, correcting the estimated age of the universe to approximately 11 billion years. Eventually, Sandage would estimate the age of the universe at 18–20 billion years, which put him in rivalry with a younger generation of astronomers who argued that Hubble's techniques for measuring galactic distances were incorrect.
- **D.** Finally, in 1999, a team of astronomers led by Wendy Freeman established the age of the universe at about 13.7 billion years.

II. We now pick up the story of the Steady State theory, which had been poised to triumph over the Big Bang theory in the early 1960s.

- **A.** In 1958, Geoffrey Burbridge reported radio signals from distant galaxies that seemed to have the energy of a million or more stars.
  - **1.** Between 1958 and 1960, a Dutch physicist, Maarten Schmidt, studied these energy sources and gave them the name *quasars*, for "quasi-stellar radiators." These objects are relatively compact, yet they have tremendous energy. They also seemed to be associated with the centers of the most distant galaxies.
  - **2.** The discovery of quasars was perceived as a blow to the Steady State theory, which asserts that the universe is, on a large scale, uniform at all distances and in all directions. Because of their great distance, quasars seemed only to have formed long ago, implying that the Earth was not uniform.
  - **3.** Astronomers later determined that quasars are massive black holes and that every galaxy, including ours, has a black hole at its core, though not a massive one.
- **B.** The second blow to the Steady State theory was the discovery of microwave background radiation.
  - **1.** In 1949, Gamow and his collaborators claimed that their theory implied that the universe should be uniformly filled with the aftermath of the Big Bang in the form of microwave frequency radiation and that the temperature of the universe should be about 5 degrees above absolute 0 (5 degrees Kelvin).
  - **2.** In the early 1960s, with Fowler's solution to nucleosynthesis available, Princeton physics professor Robert Dicke began to re-examine the universe's "birth" as if the Big Bang theory were true. He challenged his graduate students, among them Jim Peebles and Dave Wilkinson, to work out its consequences.
  - **3.** Peebles filled in a gap in the Fowler nucleosynthesis program and predicted a microwave background afterglow of about 10 degrees Kelvin. The team at Princeton then began to plan an experiment to search for this afterglow but they were "scooped" by two industry scientists at Bell Labs.
  - **4.** There, Arno Penzias and Robert Wilson were developing an antenna that could exchange microwave frequency radio signals with the first communications satellite, Telstar. Penzias and Wilson used an extremely sensitive antenna that had been developed for an earlier project.
  - **5.** In attempting to calibrate this antenna, Penzias and Wilson could not eliminate a background hiss that seemed to come from every direction. Happening upon Peebles's paper, Penzias and Wilson calculated the temperature equivalent of the background noise at

about 3 degrees Kelvin. They called Dicke with the news, and suddenly, the Big Bang theory was resurrected!

C. Research into the microwave background radiation since that time has given us our oldest picture of the universe. In particular, two satellites launched by NASA, in 1992 and 2002, have enabled us to "see" the universe as it was approximately 380,000 years after the Big Bang.

D. Theory required that the background radiation be almost perfectly uniform. By the mid-1960s, however, scientists realized that if that were true, matter would never have clumped together to form stars, let alone galaxies. There must be some non-uniformity in the cosmic microwave background.

  1. From the late 1960s, Dave Wilkinson played a central role in the detailed measurement of the non-uniformity of this radiation, termed *anisotropy*.

  2. Data from the NASA satellites has revealed minute variations in the background radiation temperature in the range of 10^{-5} degrees Kelvin, and this is consistent with the clustering of matter into stars and galaxies.

III. Quantum theory strongly suggested that although the Big Bang and cosmic expansion were real, the visible evidence of these phenomena could not be extrapolated back to the event in which the universe originated. We need to use quantum mechanics to understand the origin event at a much deeper level than Gamow's theory allowed.

A. In 1980, Alan Guth proposed what he called *inflation theory* to explain why the visible evidence of Gamow's Big Bang takes the form it does.

  1. The quantum theory of the vacuum suggests that a *false vacuum* can exist that contains a tremendous amount of pent-up energy. This energy is "stalled," initially, but can be triggered and released.

  2. Building on this idea, Guth proposed that at 10^{-35} seconds after the Big Bang, the universe underwent an instantaneous inflation in which its size doubled 100 times. In the process, the universe cooled dramatically, from 10^{28} degrees Kelvin.

  3. This inflation pulled the universe into a uniform mode with very modest non-uniformities. In that universe, the breaking of symmetries took place that led to the emergence of photons and matter.

B. The inflationary moment was powered by a false vacuum. At the time of this occurrence, the universe was about the size of a softball; it then expanded by a factor of 2^{100}. Thus, even the vast observable universe of the late 20th century is only a minute fraction of the entire inflated universe.

C. Since 1980, inflationary theory has become the orthodoxy in astrophysics and cosmology. All available empirical evidence is consistent with this theory.

D. In the past two decades, two comparably dramatic developments have taken place that require reconceptualizing the inflated universe.

  1. The first of these was the realization, in the 1980s, that galaxies rotate too fast to hold together. Some other force must hold galaxies together and, indeed, must hold clusters of galaxies together. The consensus view at the end of the 20th century is that *dark matter* is responsible for this stability and that dark matter accounts for more than 90% of the total matter in the universe.

  2. The second dramatic development took place in 1998, when two teams of physicists announced that the expansion of the universe is accelerating. The so-called *dark energy* associated with this acceleration would be the dominant form of energy in the universe. In the next lecture, we'll discuss how we know these mind-boggling facts about the universe.

Essential Reading:

Alan Guth, *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*.

Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*.

Supplementary Reading:

Helge Kragh, *Cosmology and Controversy*.

Questions to Consider:

1. Why would scientists prefer the Steady State to the Big Bang theory as a model of the universe?
2. Did Penzias and Wilson discover the microwave background radiation, and what does their experience, and the 1998 "discovery" of the universe's acceleration, reveal about the relation between theory and experiment in science?
3. Can we truly comprehend a universe such as that described in inflation theory, and what value is a scientific theory that is not comprehensible?

Lecture Sixteen

How Do We Know What's Out There?

Scope: Ideas and theories tend to dominate histories of science, but the fact is that from the beginning of modern science, instruments have played a fundamental role in stimulating ideas and theories and in determining which ideas and theories survive. Successful theories are those whose predictions are borne out by observations, but discoveries are made by instruments. In the 20th century, newly invented instruments disclosed utterly unanticipated cosmic realities. Beginning in the 1930s, with the unexpected discovery of radio-wave emissions from outer space, the array of Earth- and space-based instruments available to astronomers expanded: radio telescopes; infra-red, ultraviolet, X-ray, cosmic ray, and gamma ray telescopes; orbital satellites and interplanetary space probes; radical new optical telescope designs; neutrino telescopes; and gravity wave telescopes. All these revealed a universe vastly more varied and complex than anyone had imagined in 1900.

Outline

I. How do we know about the universe? Just as we saw in QED and the transition to QCD and in chemistry, we will see that the development of instruments in astronomy has played a substantial role in our theories of the universe.

II. Before we begin looking at these instruments, we will briefly review the chronology of the universe in the framework of the Big Bang model, adjusted for inflation theory.

- **A.** Approximately 13.7 billion years ago, an origin event took place. Only 10^{-43} seconds later, the loops or strings manifested themselves in their full 10-dimensional generality. At 10^{-36} seconds, supersymmetry broke, separating gravity and the Higgs field; the loops or strings contracted down to 3 dimensions. At 10^{-35} seconds, the universe underwent inflation, doubling in size 100 times.
- **B.** When the universe was 10^{-20} seconds old, the first photons appeared. At 10^{-10} seconds, matter appeared, first in the form of quarks and leptons, then at 10^{-4} seconds, as protons and neutrons. At 100 seconds, the first elements appeared: hydrogen, helium, and a very little lithium.
- **C.** At one month of age, the universe filled with what physicists call *blackbody radiation*, the echo of which was detected by Penzias and Wilson in 1964 as the microwave background radiation. At about 400,000 years of age, photons separated from matter. However, the universe was dark, because the average energy of the photons was below the visible range.

- **D.** At about 900,000 years, there was light! The first stars formed, and by a billion or so years, there were galaxies. The matter in galaxies evolved into a mix of 90% hydrogen, 9% helium, and 1% everything else, which is what we observe today.

III. The main instruments for studying the universe were, from the time of Galileo until the mid-20th century, all based on light, including optical telescopes, photographic equipment, and spectrometers.

- **A.** In 1935, two AT&T engineers were assigned to investigate static on long-distance telephone lines. In the course of their work, they discovered radio signals coming from the Sun and from the center of the Milky Way. This discovery led to the birth of radiotelescopy.
  1. After World War II, this became a major branch of astronomy, from which we have gained a great deal of information.
  2. In the early 1950s, for example, Harvard University Observatory invested in a small radiotelescope, which was enough to discover the frequency radiated by interstellar hydrogen.
  3. Over the next decade, radio astronomers discovered hundreds of atoms and molecules in space, including organic molecules and hydroxyl molecules. These findings have significant implications for understanding the origin of life.
  4. By the 1960s, astronomers were using a 250-foot steerable parabolic dish at Jodrell Bank in England and a 1000-foot non-steerable dish in Arecibo, Puerto Rico. These huge instruments offered a critical new window on the universe and revealed that it was different from what we thought it was.
  5. In the 1970s, the United States built a massive radiotelescope in New Mexico. This *Very Large Array* links 27 eighty-foot-wide telescopes in a Y-shaped configuration over miles of the desert. These 27 telescopes are connected using the interferometry principle. The configuration is the equivalent of a single radiotelescope dish that is 20 miles in diameter.
- **B.** Cosmic rays were a surprise and radiotelescopy opened truly new windows on the universe, but they were just the beginning of discovering the richness of the non-visible universe.
  1. Only in the 1960s was it discovered that there were X-ray and gamma ray sources in outer space, as well as sources of neutrinos. The same period of time saw renewed interest in the general theory of relativity, which had predicted gravity waves and, by extension, the existence of a particle called the *graviton*.
  2. These discoveries prompted the development of instruments that could help us explore new aspects of the universe.
- **C.** The first X-ray satellite, the X-Ray Explorer, was launched in 1970 and immediately validated the prediction of the existence of *pulsars*, or

neutron stars, dense concentrations of matter remaining after the death of a star.

1. Neutron stars had been discovered by Jocelyn Bell, a graduate student, in the output of radiotelescope observations. Bell noted an extraordinary repeated pattern of pulsed signals.
2. The X-Ray Explorer confirmed the existence of pulsars.

D. The X-Ray Explorer also validated the existence of black holes. The satellite observed a star in the constellation Cygnus, Cygnus X-1, which orbits around an invisible companion.

E. Further improvements in telescopy resulted in NASA's Great Observatories series, which put four major satellite telescopes in orbit in the last decade of the 20th century and the first decade of the 21st: the Hubble Space Telescope, the Compton Gamma Ray Observatory, the Chandra X-Ray Observatory, and the Space Infra-Red Telescope Facility. This complex of telescopes has enabled us to observe the earliest stars, galaxies, and galactic clusters.

F. Another instrument in this arsenal of telescopes is the neutrino telescope.

1. As you recall, the existence of neutrinos was postulated by Wolfgang Pauli during the controversy over the nature of beta decay that took place in the 1930s.
2. In 1955-1956*, Department of Energy scientists at the Savannah River Complex observed the neutrino for the first time. A few years later, neutrinos were detected using a large tank of chlorine installed deep underground in an abandoned gold mine. Evidence in the 1960s suggested that solar neutrinos changed their character in ways that implied that they had mass.
3. Subsequently, more sophisticated directional neutrino detectors were constructed, including the Super Kamiokande Detector in Japan and two built by the United States in Antarctica.

G. Finally, we turn to the gravity wave telescope, which uses the interferometry principle and is capable of detecting a change in the shape of space on the order of 10^{-16} centimeters. NASA and the European Space Agency are planning a project to put three gravity wave telescopes in orbit above Earth; this configuration will be able to detect even smaller changes in the shape of space and may validate the existence of the graviton.

H. We close this discussion of instrumentation by returning to optical telescopes. Despite advances in other areas, optical telescopes have developed extraordinary new capabilities.

1. Very large, single-mirror, glass-lens telescopes pose almost insuperable mechanical problems. One solution to these problems is a computer-controlled, multiple-mirror design, such as the two 6-segment, 10-meter telescope mirrors for the Keck Observatory on top of Mauna Kea volcano in Hawaii. Twice each second, computers adjust the shape of the mosaic mirror to within 4 nanometers of the perfect shape of a single 10-meter-diameter mirror.
2. In 1999, an adaptive optics system for the Keck configuration virtually eliminated the distorting effects of the atmosphere. In addition, the two main telescopes, plus two smaller 2-meter-wide "satellite" telescopes, are linked by the interferometry principle.
3. In 2000, the Keck telescope observed the transit of a planet across the face of a star 153 light years away at exactly the time predicted by theory!
4. The Keck Observatory technologies are representative of world-class practice at the close of the 20th century. Other facilities with comparable equipment include the European Southern Observatory and the Inter-American Observatory in Chile, high above the Atacama Desert.

Essential Reading:

Walter McDougall, *The Heavens and the Earth: A Political History of the Space Age.*

Wallace Tucker and Karen Tucker, *The Cosmic Inquirers.*

Questions to Consider:

1. Should the proliferation of new types of telescopes other than optical ones make us feel confident that *now* we are receiving all the signals that the entities that make up the universe are emitting?
2. Is there a limit to the development of new instruments, and how will we know when we've reached it, or is this a self-perpetuating research "industry"?
3. How can the public better share in the beautiful and important knowledge continually being created at its expense but now in the possession of small communities of experts?

* *Erratum*: On the tape, the professor inadvertently stated that Department of Energy scientists first observed the neutrino in 1965-1966. The correct date is 1955-1956.

Lecture Seventeen

From Equilibrium to Dynamism

Scope: In 1900, the dominant view of the Earth among geologists was that the continents had formed as they were, where they were, when the Earth cooled from its initial molten state and that the surface of the continents was the result of those forces, and only those forces, currently acting. American geologists, especially, remained tenaciously committed to this view even as European geologists began to favor a view that the continents had been in motion since they formed, colliding, merging, separating, and migrating around the world over the course of eons. Finally, in the 1960s, empirical observations provided compelling support for what had been called *continental drift*, as well as a mechanism to explain how and why the continents drift. The story of the resulting, now dominant, theory of plate tectonics offers fascinating insight into the process of theory creation and gives us a very different account of the Earth than the one we had in 1900.

Outline

I. Conceptually speaking, the change in our understanding of the Earth between 1900 and 2000 is comparable to the change in our understanding of the universe in the same period.

- **A.** In 1900, the Earth was considered to be stable, at or approaching equilibrium as it cooled from its initial molten state.
- **B.** By 2000, the Earth was conceived to be a violent, dynamic *system.*
  - **1.** Its interior is roiled by convection currents of lava, driven by the 6000-degree heat of its solid iron core.
  - **2.** The continents are a mosaic of colliding "plates," pushed apart by magma welling up from the ocean floor.
  - **3.** The Earth's magnetic field is continually shifting and episodically reversing.
  - **4.** Its daily rotation is slowing as the moon spirals outward.
  - **5.** Massive open-ocean currents affect the biosphere and the atmosphere.
- **C.** We also now know that the Earth is a working part of a larger system, encompassing the solar system and the universe.

II. In 1900, American geologists were unanimously committed to a theory that explained the surface features of the Earth as the result of contraction, as the Earth steadily cooled from its initial molten state, together with erosion and sedimentation.

- **A.** At the time, the British physicist Lord Kelvin had convinced many biologists and geologists that the Earth was, at most, 100 million years old and was steadily losing heat. But this notion turned out to be wrong and profoundly misleading.
  - **1.** The discovery of radioactivity by Becquerel in 1896 and, in 1903, the announcement by Marie Curie of the enormous amount of energy released by radioactivity, had major consequences for biology and geology.
  - **2.** In 1913, Arthur Holmes published the first absolute dating scale in geology, putting the age of the oldest known rocks at 1.5 *billion* years. This implied that the Earth had an internal energy force that acted to sustain a non-equilibrium state.
- **B.** Accumulating evidence challenged the *isostasy theory*, which assumed that the Earth's major formations—oceans, continents, and mountains—were at or approaching equilibrium.
  - **1.** For instance, the region of Scandinavia was found to be rising, which was attributed to the melting of glaciers. This finding revealed that continental masses were capable of some vertical motion.
  - **2.** Further, geologists studying the Alps noted that the "folding" of the rock strata strongly suggested some lateral force pushing on the continents as mountains formed.
- **C.** In 1915, a German physicist, Alfred Wegener, proposed a theory called *continental drift* based on three observations: (a) the jigsaw-puzzle fit of the continents, suggesting that they had, at one time, been joined; (b) the fact that rock strata matched up across continents; and (c) identical plant and animal fossils that were found across ocean barriers. With very few exceptions, American geologists strongly opposed Wegener and his theory.
- **D.** In 1928, Arthur Holmes published a paper explaining continental drift as the result of convection currents deep below the continents, which brought magma up through the mid-ocean floor, forcing the ocean floor apart, and in turn, causing the movement of the continents.
  - **1.** One major objection to this line of thinking came from the study of earthquakes. Such studies suggested that seismic waves propagated through the Earth as if the Earth were rigid.
  - **2.** Increasing evidence, however, showed that a fluid that flows very slowly could behave like a rigid body. One example is glass.
- **E.** In 1923, a Dutch geologist, Felix Vening Meinesz, invented a shipboard instrument that was capable of accurately measuring the strength of the Earth's gravity.
  - **1.** Meinesz circled the globe in a Dutch submarine and found that the ocean floors were not in equilibrium, as isostasy required; he

confirmed this finding in 1928 on a cruise aboard a U.S. submarine.

   2. When World War II broke out, the Navy turned to geologists for help in submarine warfare. The Navy also supported further research on the strength of the gravitational and magnetic fields under the ocean.

F. Immediately after the war, attention was focused on mapping the magnetic field strength of the Earth.

   1. Holmes's idea that magma was constantly pushing up out of the ocean floor suggested that geologists should be able to find evidence of magnetic field "stripes" in the ocean floor.
   2. In the 1930s, scientists had begun to seriously consider the idea that the Earth's magnetic field had changed. After World War II, studies of geological strata confirmed this idea.
   3. In the 1950s–1960s, the U.S. Navy collected enormous amounts of data on the magnetism of the ocean floor. In 1962, an American geologist, Harry Hess, who had gained access to the Navy's data, published the pioneer version of what came to be called *plate tectonics*.
   4. Hess himself discovered the eroded remains of undersea volcanoes, which supported his theory. Others found valleys and volcanoes along the mid-ocean ridges, revealing that the ocean was geologically active.

III. We now know that the continents and oceans are about 60–80 miles thick, and they both rest on a layer of material on top of the Earth's mantle that is not quite solid, yet not quite viscous.

A. The magma welling up from the mid-ocean floor cools and creates new ocean floor, which pushes the old ocean floor outward. The old floor moves over a period of tens of millions of years, pushing on the edges of the continents.

B. Through a process called *subduction*, the old ocean floor material is pulled under the continental crust. The continent itself is moved at about the rate of an inch a year.

C. The ocean crust is pulled through the semi-solid/semi-viscous layer into the mantle. There, the crust is melted into mantle material and wells back up through the mid-ocean floor. This cycle takes 100–200 million years.

D. In 1968, Hess's qualitative theory of plate tectonics was given a mathematical formulation. In the 1970s, plate tectonics became the orthodox opinion of the state of the Earth.

Essential Reading:

Naomi Oreskes, *The Rejection of Continental Drift: Theory and Method in American Earth Science.*

———, *Plate Tectonics: An Insider's History of the Modern Theory of the Earth.*

Questions to Consider:

1. What was so threatening about the hypothesis of continental drift that it provoked decades of opposition in spite of considerable supporting evidence?
2. Why does the assumption of equilibrium have such a powerful hold on our thinking about natural processes?
3. How is our sense of the rationality of science affected by recurring episodes like the discovery of radioactivity, in which fundamental changes in concepts, principles, and theories are triggered by accidents?

Lecture Eighteen

Subterranean Fury

Scope: The Earth as described by plate tectonics is in turmoil beneath a comparatively placid surface, a turmoil driven by a solid iron core almost as hot as the surface of the Sun. But 20th-century earth science also began to view the planet as a system. To understand any part required understanding the relationships among the constantly changing atmosphere, global ocean current circulation, evolving biosphere, moving crust, churning mantle, and rotating liquid and solid cores, as well as the Sun, the Moon, and the solar system as a source of gravitational forces, electromagnetic fields, charged particle streams, and material objects, collision with which has profoundly altered the Earth's evolution.

Outline

I. The story of the rise of plate tectonic theory is fascinating for the insight it offers into the evolution of scientific thinking over the period from 1900–2000, but the picture of the Earth that emerges is even more fascinating.

- **A.** By the end of the 20th century, every aspect of the Earth, from its solid core to the uppermost reaches of its atmosphere, was viewed as "alive," continuously driven by the play of awesome forces.
  - **1.** By the 1990s, the core of the Earth was determined to be a solid sphere, at least 90% iron and about 1400 miles in diameter, under a pressure more than 3.5 million times that of atmospheric pressure, and at a temperature of almost 6000 degrees Kelvin, the same as the surface temperature of the Sun!
  - **2.** The temperature of the core is largely the primordial heat from the Earth's initial formation. It is what maintains the Earth in a non-equilibrium condition, drives the turbulence beneath the surface of the Earth, and serves as the engine of the Earth's surface geological activity.
- **B.** The solid core is surrounded by a liquid iron shell about 1400 miles thick, roiled by convection currents that carry heat from the inner core below through to the mantle above.
  - **1.** Scientists speak of a "meteorology" of the liquid core, as if it had weather systems, including constant "storms," that can be detected through global networks of seismic detectors.
  - **2.** Above the liquid core is the mantle, which is approximately 1800 miles thick.

II. We will return to the interface between the liquid core and the mantle, but first, we will explore the surface features of the Earth.

- **A.** The continents and the ocean floor are made of rock and are, essentially, rigid. The continental crust tends to be formed of silicate rock types, and the oceanic crust is largely basalt. Both the continental and ocean crusts "sit" on top of a 70- to 80-mile-thick band of rock that is not quite solid but not quite molten, called the *asethenosphere*.
- **B.** As we discussed in the last lecture, the ocean crust is constantly pushed outward by the upward flow of lava from the mid-ocean ridges. It is then pulled under the continental crust and back into the mantle by a process called *subduction*. This crust is significantly cooler than the mantle material and, thus, sinks.
- **C.** The mantle extends 1800 miles down to the Earth's outer core of liquid iron, but it is divided into two parts: the upper mantle, which is 400 miles thick, and the lower mantle, which is 1400 miles thick.
  - **1.** Most of the subducted ocean crust becomes molten in the upper mantle and begins the process of re-circulating.
  - **2.** Some crust material continues through the upper mantle unmelted until it reaches the boundary between the lower mantle and the liquid core.
- **D.** The interface between the lower mantle and the liquid iron core is about 120 miles thick and is considered by geologists to be the most dynamic and chemically reactive place on Earth.
  - **1.** No material can move from the liquid iron core to the mantle; thus, the heat from the liquid core can be transferred across this interface only by *conduction*.
  - **2.** This heat creates convection currents in the mantle, which in turn, cause the upwelling of magma at the mid-ocean ridges.

III. In the past 10 years, geologists have learned that mantle "jets" are created when some of the ocean crust material sinks to the boundary of the lower mantle and the liquid iron core before melting.

- **A.** These jets shoot all the way to the surface, erupting in volcanoes or, in the case of Yellowstone National Park, hot springs.
- **B.** Keep in mind that these jets are fixed in place even as the continental plates move. The hot springs in Yellowstone were, at one time, in Oregon.
- **C.** Another illustration of this phenomenon is found in the Deccan Traps, a vast area of India covered by the remains of molten lava. A hot spot under Reunion Island today was once under the Deccan Traps.

IV. The 20th-century systemic view of the Earth embraces, in an integrated way, interactions among the oceans, the biosphere, the atmosphere, and the body of the planet.

- **A.** The study of the deep ocean had to await technologies that became available only in the course of the 20th century.
- **B.** With the aid of satellite observing platforms and research vessels, massive ocean currents have been observed that affect the planet's climate and life cycles.
    1. Open-ocean currents transport huge quantities of water, up to 50 million cubic feet per second, typically bringing deep Antarctic water to the Arctic, where it sinks and returns in a constant circulation across the equator.
    2. These currents generate in their wake vast eddies, which generate smaller eddies in a hierarchy, mixing cold water that is rich in nutrients with warm water, transporting heat along with water, and affecting the climate and ecologies.
    3. The atmosphere, too, has only begun to be understood dynamically and as a single, evolving global whole in the 20th century, in continual interaction with the oceans, land, and Sun.
    4. In the late 1970s, marine geologists observed hydrothermal venting along the mid-ocean ridges and, to their amazement, discovered hundreds of new species and hundreds of new genera of plants and animals.
    5. In 1991, the research submersible *Alvin* observed and monitored an undersea volcanic eruption at the East Pacific Rise and found that as soon as the murderous lava flow eased, plants and animals swiftly recolonized the area, creating a dense, diverse ecology. More recently, it has been discovered that this life returns at temperatures of over 250 degrees.
    6. Some scientists believe that life may have originated deep in the ocean surrounding hydrothermal vents, not in water near the surface.
- **C.** Atmospheric studies have also changed dramatically since John Dalton began studying the physical mixing of oxygen, nitrogen, and carbon dioxide in 1806.
    1. As with open-ocean currents, only in the late 20th century was it realized that global atmospheric currents routinely transport across continents and oceans, not just precipitation, but seeds, insects, dust, sand, pollutants, bacteria, and viruses.
    2. The atmosphere is driven by the heat engines from below and above and is affected by ocean currents, as well as our own activity. Thus, the atmosphere links the world in a complex network.

- **D.** Because of these interconnections among the oceans, the biosphere, the atmosphere, and the planets, science has been pushed toward a systems perspective of the Earth.
    1. What we have said about the Earth also applies to the general theory of relativity and quantum theory; each of those theories told us about interrelationships that we had not appreciated earlier. The general theory of relativity, for example, told us that space, time, matter, and energy are intimately interconnected.
    2. The idea of the Earth as a system became a central theme of 20th-century science and was manifested in the environmental movement.
    3. The widespread reaction to ozone-layer damage is one illustration of systems thinking in the public consciousness, as is the current issue of global warming.
    4. As we'll see in the next lecture, the Earth itself is just one node in a much larger, extraterrestrial system.

Essential Reading:

John McPhee, *Annals of the Former World.*

Naomi Oreskes, *Plate Tectonics: An Insider's History of the Modern Theory of the Earth.*

Questions to Consider:

1. Does plate tectonic theory imply that we are doomed to being helpless victims of episodic calamities caused by the churning mantle?
2. What happens to the Earth's climate zones as the continents move? Are they permanent or do they move, too?
3. Is the total geosphere-ocean-biosphere-atmosphere system so massive that human activity can be dismissed as too puny to affect it, or might human activity upset a delicate balance, with catastrophic consequences?

Lecture Nineteen

Solar System Citizen

Scope: The exploration of space from the 1960s on deepened our understanding of the Earth immeasurably by embedding Earth science in the broader sciences of the Sun, the solar system, and the cosmos. The contrast between system-based Earth science in comparative planetary perspective and 1900-style geology captures many essential features common to the evolution of the physical, life, and social sciences in the 20th century. As with cosmology and quantum theory after 1930, an appreciation of the instruments used to gain knowledge is as important to understanding science as is an appreciation of the knowledge gained.

Outline

I. By the end of the 20th century, our conception of the Earth had changed dramatically, in the direction of a dynamic terrestrial system.

- **A.** The dynamism and the system concept are core innovative features of 20th-century Earth science.
    - **1.** Energy inputs from the Sun and from the Earth's extremely hot core maintain the terrestrial system in a nonequilibrium state, characterized by constant dynamic interactions among the geosphere (the crust-mantle-core subsystem), the oceans, the atmosphere, and the biosphere.
    - **2.** The word *ecology* was invented in the 1880s by Ernst Haeckel but not employed in its current sense until the 1920s. In the 1930s, the term *ecological system* was introduced, and the first plant *and* animal interactive environmental studies were published.
    - **3.** The last piece of the puzzle was acceptance that human behavior was also a factor in local and global ecologies. Rachel Carson's 1962 *Silent Spring* was a watershed in this regard, as reflected in the rise of a popular environmental movement.
- **B.** Recognition that the terrestrial system was itself a subsystem within a cosmic extraterrestrial system is a major 20th-century achievement.
    - **1.** Recognition in the 19th century of the extraterrestrial origin of meteorites followed a long and bitter controversy.
    - **2.** Beginning with cosmic rays in the 1930s, it was discovered that the Earth is bathed in matter and energy from the Sun, the solar system, and distant sources inside and outside the Milky Way.
    - **3.** Besides cosmic rays, the Earth receives charged particles from the solar winds and neutrinos, the most numerous particles in the universe.

    - **4.** In addition to the obvious solar radiation and starlight, the Earth is bathed in radio frequency waves, X-rays, gamma rays, and very likely, gravity waves.
    - **5.** In 1958, America's first satellite discovered the Van Allen radiation belts that buffer the Earth from the Sun's violent eruptions of charged particles.

II. If the Earth is conceived as an evolving, dynamical system, then the system must include elements beyond the Earth.

- **A.** The Sun and the Moon exert subtle, though vital, influences on the Earth. The solar system, too, has played a critical role in the Earth's history and fate.
    - **1.** In 1930, Sidney Chapman proposed that the ozone layer was created by chemical reactions in the upper atmosphere driven by ultraviolet radiation from the Sun that blocked much of that life-damaging radiation from reaching the surface.
    - **2.** The planet Jupiter has shielded the Earth through much of its history from asteroid-like particles and comets that rained toward the Sun from the Kuiper Belt. The gravitational field of Jupiter attracted many of these rocky objects, preventing them from hitting the Earth.
    - **3.** In 1979, Luis Alvarez proposed that a collision with a comet or asteroid caused the mass extinction that ended the dinosaur era and made possible the evolution of mammals. This suggested that the four other known mass extinctions in the 600-million-year-history of multi-cellular life on Earth also were triggered by such collisions.
    - **4.** The Moon's presence stabilizes the Earth's rotation on its axis, and the event that created the Moon may have thinned the Earth's early atmosphere so that life evolved as it has.
- **B.** Finally, the universe as a whole played, and plays, a determining role in the Earth's fate.
    - **1.** This idea is consistent with the Big Bang theory, which links the chemical composition of the Earth to the broader evolutionary history of the universe as a whole.
    - **2.** The formation of the solar system may have been triggered by the shock wave from a nearby supernova.
    - **3.** In 2003, it has been suggested that one of the five mass extinctions of life on Earth was triggered by the radiation from a distant supernova explosion, which caused the Sun to flare and changed Earth's atmosphere in a way that shut down photosynthesis.

III. Understanding the Earth thus entails understanding the network of its extraterrestrial relationships, which is what space science is about.

A. Less than 10 years after a RAND Corporation report affirmed the possibility and desirability of artificial satellites, a new era in space science began, in October and November 1957, with the launch of Sputniks 1 and 2, followed in 1958 by the first U.S. satellites, Explorer and Vanguard.

1. In 1960, the Transit, Tiros, and Echo satellites were launched, pioneering accurate Earth surface position location, weather monitoring, and satellite-based communications, respectively. Landsat 1, relaying color and multi-spectral images of the Earth from orbit, was launched in 1972.
2. By the 1990s, Transit had evolved into the Global Positioning System; Tiros, into continuous global satellite-based weather forecasting; and Echo, into global, satellite-based radio, TV, telephone, and data communication systems.
3. The Russians put the first space station, Salyut, into orbit in 1971, and the Americans followed in 1973 with the short-lived Skylab. In 2000, the International Space Station went into operation, rounding out a century in which the possibility of space exploration began as the stuff of science fiction.

B. Research scientific satellites and space probes, with no practical applications, have expanded our understanding of the Earth's place in the solar *system* and the universe. These include the astronomical satellites discussed in earlier lectures, culminating with the Satellite Infrared Telescope Facility, which gave us a glimpse of the earliest stars and galaxies formed after the Big Bang.

C. Finally, we have launched space probes that have left Earth's orbit and explored the inner planets all the way out to the Kuiper Belt.

1. The Apollo manned lunar landings were the most dramatic expression of the first phase of space exploration, which included numerous earlier probes launched to the Moon beginning in 1959 and successful launches to Mercury (1973, Mariner 10), Venus (1978, Pioneer; 1983–1984, Venera 15/16; and 1990–1994, Magellan radar-mapping mission), Mars (1976, Viking Landers 1 and 2), and the outer planets (1977, Voyagers 1 and 2).
2. The Mars Global Surveyor in 1996 and the Pathfinder Rover mission of 1997 paved the way for the 2003 Mars Express of the European Space Agency (ESA) and 2004 NASA Mars Odyssey missions, both with orbiters and air- and soil-science–packed landers.
3. The Galileo probe, launched in 1989, arrived at Jupiter in 1996 and, for years, collected data about Jupiter and its moons Europa, Io, Callisto, and Ganymede. In 1997, the joint NASA-ESA Cassini mission to Saturn was launched for a close-up study of that planet and its moons, including landing a probe on Titan, with its orange atmosphere suggesting oceans of hydrocarbons beneath an icy crust.
4. Voyagers 1 and 2 sailed past Uranus and Neptune to Pluto, and now, Voyager 1, still transmitting data, is moving beyond Pluto through the Kuiper Belt and into interstellar space.

D. This range of accomplishment—and in less than 50 years from the first unmanned orbit of the Earth—has been supplemented by the collection or sampling of material from the Moon, Mars, Venus, Jupiter, an asteroid, and the tail of a comet, as well as particles from the interstellar wind and solar wind.

E. What have we learned for our NASA dollars?

1. First, we have gained a much greater understanding of the universe. Without the satellites that showed us the microwave background radiation, we would not have had the detailed development of the Big Bang theory that we have.
2. We have learned that the Earth's history is its evolutionary history as a part of the solar system, and that its future will be determined at least in part by the future of the solar system.
3. We have learned that we *can* explore space, directly and indirectly, and that without understanding what is beyond the Earth, we cannot understand what is on and within the Earth.

F. Our investment in space exploration has been substantial, and it was only made possible by government programs operating with the long-term support of the public. In our next two lectures, we will explore the relationships among science, technology, and society that are reflected in this kind of government commitment and public support.

Essential Reading:

Luis Alvarez, *Alvarez: Adventures of a Physicist*.

Peter J. Bowler, *The Earth Encompassed: A History of the Environmental Sciences*.

J. R. McNeill, *Something New under the Sun: An Environmental History of the Twentieth Century*.

Supplementary Reading:

Rachel Carson, *Silent Spring*.

An excellent resource for the history of space exploration is the web site maintained by NASA: www.spaceflight.nasa.gov/history.

On comparative planetology, see the web site maintained (in English) by the Institute for Planetology at the University of Muenster in Germany: http://ifp.uni-muenster.de/links/worldlnk.phtml.

American Scientist, the magazine of Sigma Xi, the Scientific Research Society, is an outstanding source of excellent, professionally prepared articles for non-specialist readers on all aspects of science.

Questions to Consider:

1. How does recognizing the dependence of the Earth's fate on its status in a hierarchy of extraterrestrial systems affect our sense of the position of life in the universe? Of human life in the universe?
2. Does making the Earth a part in a greater whole diminish or enhance its status? On what grounds?
3. What is the value to society of our exploration of space, and using what criteria can it be said to be "worth" the financial expenditure?

Lecture Twenty

Science Organized, Adopted, Co-opted

Scope: The practice of science, its scale and its scope, changed dramatically in the course of the 20th century, as did the relationship of science to government, industry, and society. In the United States, by mid-century, the university had become the primary setting for scientific research. The gifted "gentleman" pursuer of knowledge of nature had virtually disappeared, displaced by people who practiced science for a living, either at a university or at a government-, industry-, or foundation-funded research laboratory, but even then, only after acquiring appropriate credentials at a university. First in the physical sciences, then in the life and social sciences, the cost of doing science grew exponentially. Along with this increase came an increasing dependence on external funding and, inevitably, a concomitant influence on science of the goals and values of its funding sources—after World War II, primarily the federal government. In the context of mass anti-establishment protests in the 1960s and 1970s, this led to an attack on the very concept of objective knowledge that ballooned into what was called the *Science Wars* of the 1990s.

Outline

I. Particle accelerators, fusion research, orbital observatories, and space exploration add up to serious money, perhaps a trillion dollars over the second half of the 20th century. Where did this money come from, why was it spent, and what impact did it have on the practice and content of science?

- **A.** In the United States in the 19th century, prevailing opinion held that science was an elitist pursuit and that spending public funds on scientific research was inappropriate. Of course, in a capitalist society, applied science should be funded by industry.
- **B.** The U.S. government supported science in a limited number of activities in the 19th century, including mapping the country, conducting research into infectious diseases, and setting regulatory standards for industry.
- **C.** At the same time, the United States rapidly made the shift from a primarily agricultural economy to a primarily industrial one.
  - **1.** In 1862, with the South in secession, Congress passed the Morrill Land Grant Act, rewarding states that created engineering colleges with gifts of large tracts of public land.
  - **2.** The impact over the next half century was dramatic: The number of engineering colleges increased from 13 in 1862 to 126 in 1917, and enrollment increased from a few hundred to more than 30,000.

3. The nature of engineering education was an issue of some controversy, ultimately won by those who believed that engineering should be based on science, rather than those who saw the basis of engineering in the workshop.
4. This new model of engineering education, in turn, created a significant demand for physicists, mathematicians, and chemists as faculty at engineering colleges. Further, American universities were, increasingly, requiring research as a condition of employment for their faculty members.
5. Driving this trend was, of course, industry, now organized around the corporations that dominated electrification, transportation, communication, and mass production.

D. Shortly before U.S. entry into World War I, George Ellery Hale, who was largely responsible for the private funding of four world-class telescopes between 1897 and 1949, tried to convince the U.S. government to organize the nation's academic scientists as a resource for the war effort.

1. Hale failed in this political effort, however, in the face of reluctance to give public monies to academics. Instead, technical knowledge for military needs was organized around engineering, under industrial leadership.
2. In the 1920s and early 1930s, a second effort by Hale to create a national research council funded jointly by government and industry also failed.

II. The situation in Europe was substantially different from that in the United States.

A. In Germany, government-funded research institutions in "pure" and applied science had been established by Bismarck and were flourishing, together with industry-funded laboratories.

1. In 1900, Germany was the world leader in technology-based industries and in physical scientific research and mathematics. Germany was also the world leader in harnessing scientific knowledge for military applications.
2. The United States, Britain, and France resisted this model and, as a consequence, were grossly unprepared for World War I.

B. A nation that did not resist the German model was Japan, which became a world military and industrial power in less than 100 years.

III. World War II transformed the conduct and organization of science in the 20th century.

A. The German persecution of Jews and socialists resulted in a massive shift of technical expertise from Germany to the United States and Britain. The scientists and mathematicians who came to the United States trained their students in the style and techniques of research that they had developed in Europe.

B. Further, in 1940, Vannevar Bush, president of the Carnegie Institution, a former MIT professor, and a pioneer of analog computers in the 1920s, did what Hale had been unable to do a decade earlier. Bush convinced Roosevelt to organize the nation's academic scientists in the interests of national security.

1. Roosevelt created the National Defense Research Council, with Bush as its head; within in a year, that organization had become the Office of Scientific Research and Development (OSRD).
2. Bush began to organize a network of the finest scientists in the country into committees to address specific problems with military applications.
3. The most famous of these efforts was the Manhattan Project, which resulted in the atomic bomb. Perhaps of even greater significance for the war was the research conducted at MIT's radiation laboratory, where radar and electronic countermeasures were developed and improved.
4. Operations research, what we now call *systems analysis*, was applied to military tactics and planning under the aegis of the OSRD. The OSRD was also involved in developing techniques for manufacturing penicillin in large volumes and at low cost.

IV. The legacy of Vannevar Bush lay in his focusing of scientific expertise to solve problems for the government and the military.

A. Bush also authored a report, entitled "Science: The Endless Frontier," outlining his vision for America's science policy in the wake of World War II. This report asserted that America's future was critically dependent on technological innovation, which was itself dependent on sustaining basic science. We could not return to the prewar policy.

B. One result of Bush's report was the creation of the National Science Foundation (NSF), despite a vicious political battle from 1946–1950, again, over the issue of using public funds to support basic science. Since the organization's inception, the budget of the NSF has not been a significant factor in the total post-World War II federal budget for scientific research.

C. The federal government currently supports approximately 600 laboratories that are largely focused on applied science. Of course, the Department of Defense, Department of Transportation, Department of Energy, Department of Agriculture, National Institutes of Health, and NASA distribute billions of dollars, overlapping areas of applied and basic research.

D. One other consequence of the government's investment in scientific research is that universities have become dependent on federal funding to maintain their integrity as institutions.

E. Finally, in the 1960s, with widespread anti-establishment sentiment, scientists, too, became a focus of attack, because they were perceived to be in league with government and industry. Concurrently, science experienced an intellectual critique, which had been absent in the past, that questioned its absolute objectivity. In the 1980s, this questioning led to the Science Wars, which will be the subject of our next lecture.

Essential Reading:

Mario Biagioli, *The Science Studies Reader*.

Stephen H. Cutcliffe, *Ideas, Machines and Values: An Introduction to Science, Technology, and Society Studies*.

Ian Hacking, *The Social Construction of What?*

Questions to Consider:

1. What should the relationship be between government institutions and scientific research?
2. In a democracy, who should determine how public monies should be distributed to support what kinds of research?
3. Given the profound social impact of scientific knowledge and its applications, what role can the public play in influencing the direction of research?

Clarification: On the tape, the professor states that the Japanese navy sank the Russian Pacific fleet. The Russian fleet destroyed in the Pacific by the Japanese at the Battle of Tsushima Straits in 1905 was the Baltic fleet, transferred to the Pacific to engage the Japanese.

Lecture Twenty-One

Techno-Science and Globalization

Scope: The entanglement of 20th-century science with society is exemplified in the rise of what came to be called "techno-science," that is, science-based technological innovation. This alliance among science, engineering, and industry resulted in marketplace success that drove the need for more new science in order to generate further innovations in what sometimes seemed to be an endless cycle of wealth creation. Early-20th-century innovations were primarily engineering achievements, loosely indebted to scientific theory. But the growing power of chemistry and of physics to create commercial (and military) value created a whole new dynamic, not just in the relationship between science and engineering, but in the relationship between technical knowledge and innovation, correctly understood as the selective exploitation of technical knowledge driven by social and market values. Innovation, by the 1970s, was widely accepted as necessary for economic growth and quickly became a global phenomenon. The social, political, cultural, and economic implications of this globalization, in turn, provoked political and cultural responses to innovation and its social infrastructure.

Outline

I. One of the most important of all scientific developments in the 20th century was not a theory or a discovery, but the new relationship between science and society.

A. This change is not merely external to science. The organization, practice, and content of science all changed dramatically, especially in the second half of the 20th century, as the scale of science grew. This increasing scale was associated with the shift of dominance in scientific research to the United States in the post-World War II period.

B. One of the elements behind this shift was the notion, especially in the United States, that post-secondary education was a natural expectation for everyone. The G.I. Bill of Rights played a role in creating this expectation.

C. The shift of dominance to the United States spawned a new, large-scale approach to science, engendering what has been called "Big Science." The resulting capital-intensive projects transferred the OSRD wartime experience to peacetime.

D. After World War II and under the influence of the United States, science also went global to a greater degree than it ever had before. The so-called "Science Wars" of the 1970s–1990s* were between the view that science incorporated culturally specific intellectual and value prejudices and thus was only an interpretation of experience and the view that science is universal and an account of reality.

E. When President Eisenhower left office, he warned the nation that we had created a military-industrial complex that could easily result in the pursuit of self-serving initiatives by either party. Eisenhower's warning should have included the universities.

  1. Increasingly in the 1960s–1970s, federal funding from the Department of Defense and Department of Energy for direct and indirect military applications was flowing into the universities and transforming them.

  2. Universities were forced to become dynamic in science, engineering, and the social sciences.

  3. Not surprisingly, 40–50 research universities emerged as dominant in terms of federal funding.

F. The relationship between government and science also became politicized.

  1. In the wake of Sputnik, Eisenhower recognized the need for a Presidential Science Advisory Committee (PSAC), which Kennedy implemented and used extensively for science policy advice.

  2. Because of its support for the Nuclear Test Ban Treaty and opposition to the Anti-Missile Defense Plan, PSAC was disbanded by Nixon during his administration.

  3. In one of his last acts as president, Gerald Ford formed the Office of Science and Technology Policy, which became operational under Carter.

  4. Given these political aspects of the government-science relationship, it is often difficult to separate scientific advice from political positions. A perfect example of this difficulty is seen in the attitude of the U.S. government toward global warming.

G. The suspicion that science has a political dimension is one of the issues that kept the federal government from funding scientific research up until the mid-20th century.

II. In the 20th century, the public began to broadly identify science in general with truth.

A. In World War I, for example, psychology received a boost when the army turned to this science for assistance in testing recruits. The Stanford-Binet IQ test was developed initially to screen out those who were intellectually incapable of serving in the military.

B. In the 1920s–1930s, U.S. universities saw a tremendous increase in the study of social science, political science, economics, and management science. This is indicative of the shift in the American economy from an industrial base to a service base.

  1. This shift was already manifest in the 1920s. As government and corporations grew, the demand for managers and bureaucrats grew.

  2. The universities were given the social task of broadening the student base to produce these middle managers. Again, this required more faculty in various specialties, who were, in turn, required to do original research.

C. To appreciate science as an intellectual and social phenomenon in the 20th century, we must look at the sciences as a whole. The study of social science was also caught up in this broad identification of science with knowledge and truth.

III. We conclude this lecture with a discussion of the progressive intensification of the role of science in technological innovation.

A. The question of what the relationship between science and society should be was not an issue for the public at large before World War II. Until that time, science was primarily an intellectual activity with a few applications associated with engineering.

B. After World War II, questions were raised about the proper place of an industrial corporation in society and, in turn, about the proper place of science, which provided industry with its technological innovations.

C. Before World War II, even radical thinkers had privileged science, setting it apart from their political agendas. After World War II, these thinkers saw that science could not be separated from the impact it had on society.

  1. In the early 1960s, the first academic program in this area, called "Science, Technology and Society," was created at Cornell University.

  2. One of the goals of this program was to study the ways in which scientific thinking reflects the social environment. Technology was seen as the channel through which scientific thinking is transmitted to society and vice versa.

  3. Such programs spread rapidly at the end of the 20th century in the United States, Europe, and Japan.

D. One of the most interesting findings of this approach to looking at the relationship between science and society is the recognition that technological innovation is not synonymous with invention.

  1. The internal combustion engine, for example, is the *invention* of a late-19th-century workshop. It becomes an *innovation* when it is transferred to society.

2. The key lies in what happens to an invention before it is accepted into society; that is, the invention is *selectively* implemented.
3. Technological innovation is a social process in which the knowledge of scientists, engineers, and inventors is selectively exploited by corporate managers and government bureaucrats in pursuit of corporate or government agendas.
4. Which inventions are translated into products, how rapidly they are developed, and how they are introduced are all functions of political and social values. This has nothing to do with the mechanisms or theories underlying how an invention works.
5. We should also note that this process is not a one-way street. Society is also responsible for modifications to corporate and government plans for how technology will develop. Society's response to the Internet is one example of its impact on corporate and government thinking.

Essential Reading:

Louis Galambos and J. E. Sewell, *Networks of Innovation: Vaccine Development at Merck, Sharp and Dohme, and Mulford, 1895–1995.*

Steven L. Goldman, *Science, Technology and Social Progress.*

Thomas Hughes, *Networks of Power: Electrification in Western Society, 1880–1930.*

Supplementary Reading:

Thomas Hughes, *American Genesis: A History of the American Genius for Invention.*

Questions to Consider:

1. What is the relation between progress in science and technology and social progress? Does the former always lead to the latter?
2. Have science and technology changed the relationships of power in society?
3. Is the marketplace an effective mechanism for public influence on the innovation process?

* *Erratum*: On the tape, the professor inadvertently stated that the "Science Wars" were in the 1960s–1970s (the correct date is 1970s–1990s) and that by 1927, employment in the service sector exceeded employment in the manufacturing sector (the correct date is 1947).

Lecture Twenty-Two

The Evolution of Evolution

Scope: The "big ideas" in 20th-century life science are associated with evolution, genetics, and molecular biology, and these ideas were intertwined in their own evolution from 1900 to 2000. In 1900, evolution was firmly established among biologists, but natural selection had fallen into disfavor. One problem was time. Based on the prevailing chemical theory of the heat generated by the Sun, the Earth could be only 80–100 million years old, not nearly enough for evolution by natural selection. A second problem was the absence of a mechanism for transmitting to posterity new characteristics "spontaneously" acquired by an organism. The discovery of radioactivity and the recognition that the Earth was billions of years old, the rediscovery of Mendelian genetics, and the invention of population genetics led, by the late 1920s, to a revival of evolution by natural selection and, in the 1930s, to the rise to dominance of neo-Darwinian theory.

Outline

I. Darwin's concept of evolution, his "dangerous idea," was one of the most powerful and radical ideas in all of science.
  A. Darwin and Alfred Russell Wallace redefined the term *evolution*, which until the mid-19th century, had been used to describe a deterministic development, similar to what a fetus undergoes.
  B. What did Darwin mean by *evolution*?
    1. It is a process—the continuous, spontaneous, minute variation of offspring from parents, together with natural selection—by means of which, over vast periods of time, all of the multifarious forms of life on Earth have diverged from a common ancestor.
    2. What makes it radical is its contingency, its explanation of design without a Designer, its nominalism, and its assertion of the emergence of true novelty in time.
  C. These four consequences of Darwinian evolution deserve explication.
    1. Darwinian evolution is contingent in being driven by "spontaneous," that is, by random, variation.
    2. Natural selection acting on this variation does not merely root out the "unfit"; it leads to structures in organisms that look designed but aren't.
    3. The category *species* is just a name for Darwin, not a feature of reality. The reality is individual organisms.

        4. Because of its contingency, the evolution of life is, in principle, unpredictable: Novelty emerges in time. This stands in sharp contrast to the materialistic determinism of 19th-century science.

    D. Initially embraced by scientists and intellectuals, by 1900, Darwin's version of evolution was in deep trouble.

        1. In 1900, almost all biologists accepted some notion of evolution. At issue was the process by which organisms become as differentiated as they are.
        2. At the same time, the prevailing view that the Earth was only 80–100 million years old made evolution by natural selection alone effectively impossible.
        3. In the absence of an adequate theory of discrete inheritance, spontaneous variation seemed doomed to being "swamped."
        4. Darwin's insistence that evolution was driven by continuous, small variations rather than by "jumps" was judged by many biologists to be incapable of leading to truly new life forms.

II. Darwinian evolution was "rescued" by geology and genetics, and its fate in the 20th century became intertwined with both and with the rise of molecular biology.

- **A.** The discovery of radioactivity in 1896 led to Arthur Holmes's 1913 absolute geological time scale of an Earth billions of years old, which revived natural selection as a candidate process for evolution.
- **B.** Further, as Darwin realized all too well, evolutionary theory is critically dependent on a coordinate theory of inheritance, one that will preserve variations in only a very few members of a mating population.
    1. Gregor Mendel's work was rediscovered in the 1880s-1890s, by scientists looking for the discrete theory of inheritance. Between 1910 and 1930, the Mendelian theory of genetics developed along lines that blurred the distinction between it and Darwinism.
    2. In the 1920s, the genetics community began to look at gene patterns in large populations and to develop mathematical models to predict how genes would spread.
    3. In the 1930s, an explicit synthesis of evolution by natural selection and Mendelian genetics, applied to populations, was effected, and by 1942, Darwinism was the dominant evolutionary theory again.
- **C.** The history of evolution in the 20th century is, thus, intertwined with the history of genetics and molecular biology, each of which we will take up shortly.

III. The theory of evolution presented a paradox: It displaced the notion of spontaneous generation of life, but if the theory of evolution were correct, then there must have been a time on Earth when life did spontaneously appear.

- **A.** In the 1920s, A. I. Oparin and J. B. S. Haldane, proposed that organic molecules spontaneously formed on the young Earth and, under the circumstances then prevailing, formed more complex molecules, until a primitive form of life emerged that was subject to evolution by natural selection.
- **B.** In 1953, Stanley Miller produced self-replicating amino acid chains in his University of Chicago lab. Analysis of the 1969 Murchison meteorite revealed the presence of the same amino acid sequences that Miller had produced.
- **C.** In the 1950s, radio astronomers discovered clouds of organic molecules floating in interstellar space, suggesting that the early Earth already contained the ingredients for life.
- **D.** The discovery in 1977 of mid-ocean thermal vents gave biologists their first glimpse of one form early life took.
    1. At least 3.2 billion years ago, microbial life based on iron and sulfur existed at such vents at temperatures of at least 250° Fahrenheit.
    2. By the late 1990s, experience with self-organizing chemical systems and self-assembling molecular structures led to the suggestion that autocatalytic reactions under such conditions led to the first self-replicating organisms.
- **E.** Evolution is one interpretation of developmental sequencing. It is a dynamic interpretation, that is, driven by forces that result in a nonequilibrium condition. It is also fundamentally historical; without understanding the history of the system, we cannot understand how we arrived in the present and we cannot predict the future with unlimited accuracy.

IV. We now take a quick look at what evolutionary biologists think actually happened.

- **A.** In the 1950s, 3.5-billion-year-old fossil bacteria called *prokaryotes* were found. These are single-celled organisms without a nucleus that lived in watery environments, perhaps in large mats or webs, in an overwhelmingly carbon dioxide atmosphere.
- **B.** A mutant prokaryote developed photosynthesis and, over a period of hundreds of millions of years, feeding on the CO_2-rich atmosphere of the early Earth, converted it to an oxygen-rich atmosphere.
- **C.** A second mutant, *mitochondria*, stored energy in a molecule, ATP, and could power more complex metabolic processes.

D. Complex bacteria called *eukaryotes* evolved that captured the mitochondria and developed a nucleus within which the self-replication "machinery" was packaged. Eukaryotes flourished in the now oxygen-rich atmosphere and became the ancestors of all plants and animals, which is why their biochemistry is virtually identical.

E. About 600 million years ago, during the Cambrian geological period, the first multi-celled fossils are found.

V. By 1960, Darwinism had become a "fact" for biologists, but it remained controversial both within biology and within society.

A. The 1923 *Scopes* trial in Tennessee may have seemed a lamentable manifestation of ignorance to some in the post–World War II era, but even at the turn of the 21st century in America, there are a dozen states that prohibit or severely regulate the teaching of evolution in high school biology classes.

B. In 1975, Edward O. Wilson published *Sociobiology*, in which he applied the concept of evolution to human culture and values. This approach, too, provoked a tremendous political response. As we can see, evolution is still a rich and controversial idea.

Essential Reading:

Garland Allen, *Life Science in the Twentieth Century*.

Daniel Dennett, *Darwin's Dangerous Idea: Evolution and the Meanings of Life*.

E. O. Wilson, *Sociobiology: The New Synthesis*.

Supplementary Reading:

Stephen Jay Gould, *Wonderful Life: The Burgess Shale and the Nature of History*.

Hilary Rose and Steven Rose, *Alas, Poor Darwin: Arguments against Evolutionary Psychology*.

Questions to Consider:

1. Why is evolution such a powerful idea, across the sciences?
2. What are the implications of biological evolution for the meaning of life in general and human life in particular?
3. What is the relation between biological evolution and cultural evolution?

Clarification: Bateson called for the public adoption of the term *genetics* to describe discrete inheritance theory in 1905, but used the term privately earlier. He and others quickly adopted the term *gene* from 1909 on, but it seems first to have been used by Wilhelm Johannsen at a lecture at Columbia University that year.

Lecture Twenty-Three

Human Evolution

Scope: The discovery of fossil human bones in 1856 in the Neander Valley above the Dussell River in what is today Germany sparked a vicious controversy that, even at the close of the 20th century, was still alive. Recognition that these and other fossil bones found in Africa and Asia were the remains of ancient humans and their evolutionary predecessors was slow in coming. Even slower was a consensus on the ancestral "tree" of modern humans. Are we lineal descendants of Neandertal Man or a rival branch of the hominid tree? Did Neandertals die out because they could not compete with *Homo sapiens*; did we aggressively destroy them or, perhaps, mate with them? Meanwhile, discoveries in east Africa put the Neandertal controversies in the context of a multimillion-year evolution of hominids, strongly suggesting that all modern humans originated in and radiated out of Africa.

Outline

I. As evolutionary theory is deeply intertwined with genetics and both with molecular biology, we *should* turn now to the rise of genetic theory, but the story of our own evolution is too fascinating to defer.

A. Darwin was cautious about extending the idea of evolution to man. Not until 12 years after *The Origin of Species*, with the publication of *The Descent of Man* in 1871, did he extend the scientific application of the idea of evolution to human beings and their history.

B. Alfred Russell Wallace, the co-discoverer of evolution, never accepted that the theory applied to humans. He believed that cultural evolution was not characterized by the same processes that characterized biological evolution and that the nature of human intelligence was beyond any mutation or variation that could have been associated with a survival advantage.

C. Nevertheless, by the end of the 19th century, most scientists believed that humans had evolved, but the consensus was that we had evolved *once*. In other words, at a certain point in the history of life on Earth, human beings emerged. Humans have gotten "better," but we did not evolve out of a series of creatures that were less human than we are.

1. Further, different populations of humans on the planet were different because they had become "better" at different rates.
2. The prejudice was strong that the Europeans were the most advanced. This view underlay and was used as a rationale for 19th-century racism.

3. For the same reason, the overwhelming consensus was that man had evolved on the Eurasian land mass, not in Africa or South America.

D. In 1856, quarry workers discovered old-looking bones in a cave overlooking the Neander Valley. They called in the local schoolteacher, who recognized the bones as human but not-quite-"us"-human.

1. Over the next 30 years, an often-vicious debate erupted over whether these were the bones of a diseased "modern" human or of a precursor to modern humans and, if the latter, whether an ancestor or an inferior "cousin."
2. Thus was born the Neandertal-versus-*Homo sapiens* controversy, still not fully resolved by 2000, a controversy that reveals a good deal about scientific prejudices.

E. After 1908 and the recovery of an almost complete skeleton, Neandertal Man was depicted as a brutish, cave-dwelling ape-man, not an ancestor of *H. sapiens* but a failed branch on the primate evolutionary tree.

F. Neandertal bones from a growing number of European sites were soon complemented by fossil remains from Java (1890), southern Africa (1921 and 1924), China (1929 and 1935), and Palestine (1932–1939) that were clearly *not* Neandertal. A minority view began to grow that an ancestral sequence, either linear or branching, was encoded in these confusing fossil clues and, after 1940, that genetics and natural selection might be useful to the decoding.

G. After the 1940s, neo-Darwinist biologists began to apply their methodologies to human fossils, reclassifying them into two genera, *Australopithecus* and *Homo*, each with numerous species.

H. The neo-Darwinists focused on geographically distributed human populations adapting in different ways to diverse environmental selection pressures that altered their genetic makeup.

II. The work of Louis Leakey answered several of the remaining questions with the *out-of-Africa hypothesis*.

A. Louis Leakey began collecting human fossils in the Olduvai Gorge in Tanganyika in the early 1930s, continuing into the 1970s. His wife, Mary, was a partner and their son Richard (following his older brother, Jonathan) carried on to the end of the century.

1. From the 1960s, the Leakeys, with collaborators, peers, and rivals, unearthed a wealth of fossils that made a case for the African origins of mankind.
2. In addition to recovering early hominid fossils, in 1966, Mary Leakey established tool-making styles as a characteristic feature of hominids and revealed tool-making as a "proto-industry" that she named *Oldowan*, once again tying biology and culture together in the study of human evolution.

B. In 1974, Donald Johanson, digging in Hadar, Ethiopia, uncovered fragments of a female hominid who, after a short but bitter controversy, was accepted, under the name *Australopithecus afarensis*, as the ancestral type of all subsequent hominids. This female, named Lucy, was dated to be about 3.5 million years old.

1. *Australopithecus afarensis* evolved between 4 and 5 million years ago. In the 1980s, a consensus grew that the genus *Homo* branched off some 2 million years ago as *H. erectus*.
2. Almost immediately, *H. erectus* migrated out of Africa to Asia and then to Europe. In 1991 and again in 1999, fossil remains of *H. erectus* 1.7 million years old were found in the Republic of Georgia.

C. These findings indicate the following sequence: Hominids emerged about 2 million years ago. For 2–3 million years before hominids, there were various species of *Australopithecene* creatures. These creatures existed millions of years after what became the hominid line had diverged from the common ancestor of gorillas, chimpanzees, orangutans, and humans. About 170,000–180,000 years ago, *H. sapiens* evolved in eastern Africa, and they, too, began to migrate.

D. This sequence was speculative reconstruction until 1987, when two biochemists, Rebecca Cann and Mark Stoneking, applied an insight from genetics and revolutionized paleoanthropology.

1. Every cell contains mitochondria with their own DNA that is inherited through the mother only and, except for mutations, are replicated exactly generation after generation. Cann and Stoneking realized that this provided an absolute marker for matrilineal genealogy.
2. There is an analogous segment on the Y chromosome for males, and by 2000, a strong case had been made that all current humans descend from just three lineages within a breeding population of, perhaps, 2000 *H. sapiens* living in eastern Africa some 150,000 years ago. (In 2002, three skulls found in Ethiopia reinforced this claim.)
3. Two of these lineages remained in Africa, but one migrated out to Asia about 65,000 years ago, then to Europe about 45,000 years ago, and to the Americas in two waves, approximately 25,000 and 12,000 years ago.
4. The Y chromosome dates are a little lower than this but are close, and both imply that all non-Africans descend from a common ancestor about 140,000 years ago.

E. What happened to the non-*H. sapiens* descendants of *H. erectus*? *H. sapiens* coexisted with *H. neandertalis* in Europe until 30,000–50,000 years ago and with descendants of *H. erectus* in Asia until much more recently. How *H. sapiens* displaced the others is unclear, but it was probably not through interbreeding.

F. We are also still left with the mystery of what happened between 10,000 and 20,000 years ago that accelerated the cultural development of *H. sapiens*.
   1. The record is clear that *Australopithecus* existed for millions of years and did not evolve hominid culture.
   2. Hominids evolved 2 million years ago but show little cumulative cultural development until about 175,000 years ago, when *H. sapiens* emerged.
   3. The pace of cultural development for both *H. sapiens* and Neandertals was extremely slow, until—astonishingly—civilization suddenly was "there," some 12,000 years ago. In 9000 B.C.E., organized settlements existed with walled towns, trade, and mass production.
   4. What triggered this evolution of human culture? There is some speculation that a mutation leading to the acquisition of speech was the basis of *H. sapiens'* rise to dominance and the sudden, nonlinear evolution of human culture, especially after the last glacial period.

Essential Reading:

Kurt Lewin, *Bones of Contention: Controversies in the Search for Human Origins*.

Pat Shipman and Erik Trinkaus, *The Neanderthals: Changing the Image of Mankind*.

Supplementary Reading:

Thomas Gossett, *Race: The History of an Idea in America*.

Questions to Consider:

1. Given the cumulative and growing fossil and biological evidence that all humans share a common ancestry, why is racism so persistent a social phenomenon?
2. Considering the slow pace of cultural change over the first 140,000 years of *H. Sapiens*' existence, how can we explain the rapidity with which "civilization" emerged as the last Ice Age ended some 10,000 years ago?
3. As the out-of-Africa theory of human origins becomes more deeply rooted as a scientific fact, how might it be used to influence global political institutions generally and Africa policies in particular?

Lecture Twenty-Four

Genetics—From Mendel to Molecules

Scope: Gregor Mendel's 1865 paper on the discrete inheritance of certain plant characteristics had been recovered by 1900 by at least four researchers already seeking discrete mechanisms of heredity. A substance in the nucleus of the cell was linked to heredity early in the 20th century, and in the 1940s, this substance was identified as DNA. After Watson and Crick's 1953 discovery of the structure of DNA, exactly what DNA did and how it did it became the preoccupation of biologists studying inheritance and metabolism at the cell and molecular levels. But identifying the double-helix structure of DNA was not the end of the quest; it was barely a beginning. Understanding the replication process, the transfer of instructions from the nucleus to the cell, and the direction of metabolic processes through protein synthesis was yet to be accomplished, and drawing a map of the detailed internal structure of the DNA molecule for individual organisms became a "Holy Grail" for many.

Outline

I. Between 1900 and 1910, genetics emerged as the dominant theory of inheritance. The story of its rise and development is entangled with the restoration of Darwinian evolution in the 1930s, with the role of biochemistry in biology, and with the rise of molecular biology.
   A. From the beginning, Darwin recognized that his version of evolution required a complementary theory of inheritance.
      1. How could natural selection alone cause continuous, random, small variations in individuals to accumulate over many generations into new life forms? Why weren't these variations "swamped"?
      2. Meanwhile, a discrete theory of inheritance had been published in 1865 by Gregor Mendel, but it received little attention until the 1890s.
      3. Mendel had concluded that something in the seeds of his pea plants contained the determinant for such properties as skin color and texture. When we speak of *genes*, we mean this kind of discrete determination and transmission of properties.
   B. In 1900, four individuals in four countries independently recovered Mendel's work in the course of developing their own discrete theories of inheritance.
      1. In 1903, one of these scientists, William Bateson, gave the name *genetics* to such a theory, and in 1909, the name *gene* was given to the discrete unit of inheritance by Wilhelm Johannsen*. The gene is analogous in biology to the atom in chemistry.

2. A vicious controversy developed between "loyal" Darwinists, who rejected Mendelianism and developed mathematical models of inheritance patterns to support natural selection acting on continuous, small, individual variations, and the Mendelians, who emphasized mutations, downplayed natural selection, and rejected the heritability of individual variations.
3. By 1910, evidence accumulated that genes were physically distributed along nuclear structures called *chromosomes*. In the course of cell division, chromosomes divide and recombine (*genetic recombination*), introducing opportunities for new characteristics to appear.
4. Of particular importance was the creation in 1910 by T. H. Morgan at Columbia University of a genetics research program based on the study of mutations in fruit flies. Morgan found that he could exactly correlate eye color in fruit flies with a particular chromosome.

C. Note the evolving similarity of gene theory to the atomic and quantum theories in physics, primarily the acceptance of both the gene and the atom as physical realities, along with the use of mathematical models without concern for the underlying mechanisms.

1. In 1908–1909, G. H. Hardy and Wilhelm Weinberg independently developed an equilibrium "law" for genetic inheritance patterns, an equilibrium that would be disturbed by natural selection and selective breeding.
2. In 1915, H. T. J. Norton extended this, publishing tables of the rate of spread or removal of genes based on selection pressures.
3. By 1918, natural selection was widely accepted as fundamental, as was the compatibility of evolution and genetics. In 1927, H. J. Muller's induction of mutations by X-rays convinced most of the reality of genes.

D. A distinctive feature of genetics research from 1918 to 1930 was a shift of focus from individuals to populations. There is a similarity here to the adoption of statistical descriptions in late-1920s quantum mechanics.

1. By the early 1930s, the work of three men, R. S. Fisher, Sewall Wright, and J. B. S. Haldane, put *population genetics* on a foundation consistent with evolution by natural selection, thereby establishing what Julian Huxley in 1942 called the "modern synthesis" of evolution and genetics.
2. What is especially interesting in this is that, in another echo of contemporary physics, Fisher, Wright, and Haldane formulated functionally equivalent mathematical models of population genetics from very different assumptions.

II. Once biologists understood that genes are real, they turned to the question: What are genes?

A. In 1900, many biologists believed that the basis of life was enzymes, which seemed to be proteins. In 1907, the German chemist Emil Fischer established that proteins were composed of combinations of amino acids.

1. Amino acids are a particular kind of molecule; there are 20 different amino acids, which combine to form the 10,000 different proteins in the human body.
2. Fischer was able to synthesize near-proteins by linking amino acids together, reinforcing a growing conviction that life was ultimately a matter of chemical interactions.

B. By the next decade, proteins were being promoted as the key to cell processes, and geneticists were identifying genes with the production and action of proteins. The idea that proteins had a fixed structure was established only with the acceptance of Staudinger's macromolecule theory.

1. Proteins, however, work in the body of the cell, not the nucleus, and genes were associated with chromosomes, which are in the nucleus. The relationship between proteins and genetics was unclear throughout the 1920s–1930s.
2. In the 1860s, Friedrich Miescher claimed a role in heredity for nucleic acids. In the 1930s, DNA was identified, but it was dismissed as uninteresting, because it seemed to be merely a mix of four different types of bases.
3. DNA was set aside in favor of the theory of George Beadle and Edward Tatum that genes make enzymes and enzymes do the work in the cell. This *one-gene/one-enzyme theory* linked biology and biochemistry, but it was wrong.
4. In 1944, Oswald Avery and collaborators established DNA in the nucleus of the cell as the carrier of inheritance.

C. Between 1925 and the late 1940s, a number of technical developments in biology and chemistry played critical roles in enabling the discovery of the structure of DNA in 1953. As we have seen, the instruments that are available to science have a profound influence on the theories that are formulated.

1. In the 1920s, scientists had reached a consensus that large molecules had a precise chemical and spatial structure. At that time, X-ray crystallography became available and was in use by physicists to study the structure of crystals.
2. By the early 1950s, biologists learned how to crystallize biological molecules without warping them, which enabled the use of X-ray crystallography to study the structures of these molecules.

3. In 1950–1951, Linus Pauling used this technique to study proteins and discovered that all proteins have the same structure, which he called an *alpha helix*.
4. In 1953, Pauling and, independently, Watson and Crick used X-ray crystallography to study DNA. Of course, Watson and Crick were the first to announce the double-helix structure of the molecule that is central to genetics.
5. Four years later, Mathew Meselson and Frank Stahl showed that DNA reproduces when the two helices separate and each creates a complementary helix. From that point on, the dominant model in biology was that genes were carried by DNA.

Essential Reading:

Frederic L. Holmes, *Meselson, Stahl and the Replication of DNA: A History of "The Most Beautiful Experiment in Biology."*

William Provine, The Origins of Theoretical Population Genetics.

James D. Watson, *The Double Helix: A Personal Account of the Discovery of the Structure of DNA.*

Supplementary Reading:

Garland Allen, *Life Science in the Twentieth Century.*

Questions to Consider:

1. Do genes *determine* what we are, let alone who we are?
2. After 100 years of Mendelianism, is *gene* the name of a specific molecular thing or of a specific function physically distributed across the DNA molecule and even beyond it?
3. How can structure be so important in determining function, not only in physics and chemistry but also in biology? Is it as important at the level of society, as well?

* *Clarification*: Bateson called for the public adoption of the term *genetics* to describe discrete inheritance theory in 1905, but used the term privately earlier. He and others quickly adopted the term *gene* from 1909 on, but it seems first to have been used by Wilhelm Johannsen at a lecture at Columbia University that year.

Biographical Notes

Alvarez, Luis Walter (1911–1988): American physicist; created an artificial mercury isotope whose emitted light wavelength became the basis for the U.S. standard of length; discovered tritium; developed new types of radar during the war; built the first linear accelerator for protons, discovering scores of "elementary" particles; proposed the asteroid/comet collision theory to explain the mass extinction at the end of the Cretaceous (65 million years ago).

Bacon, Francis (1561–1626): British jurist, educational reformer, and philosopher who articulated a rigorously empirical-inductive method for identifying the covert causes responsible for natural phenomena.

Beard, Charles (1874–1958): American historian; his 1913 history of the writing of the American Constitution, which emphasized the economic motives of the Founders of the Republic, not their political ideals, was the opening salvo in his lifelong war against objectivist history-writing.

Berg, Paul (1926–): American biochemist; developed the basic techniques of recombinant DNA and organized the 1975 Asilomar Conference, at which researchers debated the ethics and hazards of genetic engineering and defined research safety standards.

Bethe, Hans (1906–): German-American physicist, a major contributor to nuclear physics, quantum physics, the fusion theory of stellar energy, and the life cycle of stars; after World War II, he was active in attempts to limit the possibility of nuclear war.

Bohr, Niels (1885–1962): Danish physicist; with Einstein, the leading architect of the "old" (1905–1925) quantum theory of matter and energy and the leading philosopher-interpreter of quantum mechanics in its formative years (1925–1935); with Heisenberg, creator of the Copenhagen interpretation of quantum mechanics as a fundamentally probabilistic theory describing experience, not an independently existing reality.

Bush, Vannevar (1890–1974): American engineer-scientist, architect of America's post-World War II policy of public support for scientific research as the seedbed of technological innovation. Pioneer of mechanical analog computers in the 1920s and 1930s, he served as president of the Carnegie Institution, then as head of the Organization of Scientific Research and Development throughout World War II.

Chomsky, Noam (1928–): American linguist; the most influential linguist of the second half of the century, dismissing all earlier theories of language in favor of his view that language is a fundamentally neuro-anatomical phenomenon, hence, universal in its "deep structure."

Crick, Francis (1916–): British physicist-turned-molecular-biologist after World War II who, with James Watson, discovered the double-helical structure of the DNA molecule in 1953. In the 1960s, Crick played an important role in uncovering how the base sequences in the DNA molecule translate into instructions for protein synthesis, later focusing his research on neurobiology and a materialistic theory of consciousness.

De Broglie, Louis (1892–1987): French physicist whose 1923 doctoral dissertation extended early quantum theory by arguing that, just as waves behaved like particles, particles must behave like waves. His prediction was confirmed three years later.

Derrida, Jacques (1930–): French philosopher; Derrida dramatically extended de Saussure's theory of language, developing the methodology called *deconstructionism*, which makes the determination of meaning an open-ended, dynamic phenomenon to be explored by way of networks of relationships that are the sole source of meaning.

Dewey, John (1859–1952): American philosopher, educator, and social reformer; known for developing into a comprehensive system the philosophy called *pragmatism* introduced by Charles Sanders Pierce in the 1870s and championed by William James.

Dirac, P.A.M. (1902–1984): British electrical-engineer-turned-physicist, creator of the relativistic theory of the electron, and the founder of what became quantum electrodynamics. His prediction of the positron was a startling instance of the fertility of abstract mathematics for revealing physical reality.

Domagk, Gerhard (1895–1964): German chemist; in the mid-1930s, he created the first synthetic antibiotic, Prontosil, and subsequently, the family of drugs called sulfonamides, based on the chemistry of synthetic dyes.

Durkheim, Emile (1858–1917): French sociologist, the founder of modern sociology and of a relational theory of society and of the "forces" that a society exerts on its members.

Einstein, Albert (1879–1955): German-born physicist, creator of the special and general theories of relativity, and arguably, the founder of quantum physics.

Fermi, Enrico (1901–1954): Italian physicist; he played a central role in nuclear physics in the 1930s, especially the physics of fission, and in 1942, as a prelude to the Manhattan Project, built the first nuclear reactor as a demonstration that the abstract physics actually worked.

Feynman, Richard (1918–1988): American physicist; with Julian Schwinger and the Japanese physicist Sin-Itiro-Tomonaga, founder of quantum electrodynamics; influential teacher and author of an irreverent autobiography.

Fischer, Emil (1852–1919): German chemist; a major contributor to turn-of-the-century organic chemistry, especially the detailed structure and synthesis of complex sugars, Fischer pioneered the study of enzymes, establishing the number of amino acids used by the human body to build proteins and the relationships among the amino acids and successfully synthesizing peptides (protein-like amino acid chains).

Foucault, Michel (1926–1984): French philosopher, one-time mentor-collaborator of Derrida, flamboyant critic of cultural orthodoxy, and author of very influential histories of Western cultural institutions that exposed their underlying logics of power.

Fowler, William (1911–1995): American physicist; with Fred Hoyle and Geoffrey and Margaret Burbridge, explained how all the elements could be synthesized by stars, then disseminated into interstellar space when stars ended their lives explosively.

Frege, Gottlob (1848–1925): German mathematician; almost single-handedly founded modern mathematical logic and, through his interpretation of concepts, launched a fundamental reorientation of 20th-century philosophy.

Friedman, Milton (1912–): American economist; opponent of Keynesian economics in favor of his own monetarist economic theory based on money-flow models.

Freud, Sigmund (1856–1939): Austrian psychologist; founder of psychoanalysis as a methodology, of the unconscious as the dominant factor in human behavior, and of the sexual trauma theory of neurosis/psychosis; creator of the theory of repression, the Oedipus complex, and the Ego-Id/Libido-Superego model of the mind.

Gamow, George (1904–1968): Russian-American physicist; best known for his Big Bang theory of the origin of the universe and prediction of the microwave background radiation. He made important contributions to 1930s quantum physics, including predicting the quantum tunneling phenomenon, and informed Watson and Crick how the sequence of bases in their DNA molecule could "code" for the synthesis of proteins out of amino acids.

Geertz, Clifford (1923–): American cultural anthropologist; initially an objectivist, Geertz became a leading expositor of the view that a culture was a symbol system, the meaning of whose material remains could not be understood without understanding the underlying symbols of that culture.

Gell-Mann, Murray (1929–): American physicist; he formulated the *Eightfold Way* of organizing the hundreds of so-called elementary particles known by 1960 into families and, concurrently with George Zweig, created the quark theory of matter, which he called *quantum chromodynamics*.

Gödel, Kurt (1906–1978): Austrian mathematician and mathematical logician; his proof that Hilbert's requirement that mathematics be consistent and complete could not be met was an intellectual tour de force that also led to Turing's follow-on proof of the unsolvability of another of Hilbert's problems, which led to the first computers.

Guth, Alan (1947–): American physicist; founder of inflation theory, which made the universe unimaginably vast and the result of a quantum vacuum fluctuation phenomenon.

Hale, George Ellery (1868–1938): American astronomer; eminent solar astronomer but best known for his tireless promotion of private support for scientific research—resulting in the Yerkes, Wilson, and Palomar Observatories, each housing in its time the world's largest telescope—and of organizing academic scientists as a national resource in peacetime, as well as in war.

Hawking, Stephen (1942–): British physicist; best known as a theoretician of space, time, gravity, and black holes; his work, along with that of Jakob Bekenstein, which Hawking initially rejected, is fundamental to the search for a quantum theory of gravity.

Heisenberg, Werner (1901–1976): German physicist; one of the giants of quantum physics through his 1925 formulation of matrix mechanics and his collaboration with Bohr on the physical meaning of quantum mechanical theory, especially the Uncertainty Relations/Principle of 1927 and the 1929 Copenhagen interpretation of quantum mechanics.

Hilbert, David (1862–1943): German mathematician and philosopher of mathematics; eminent as a mathematician and founder of the formalist interpretation of mathematics, Hilbert is best known for his 1900 and 1929 challenges to the world's mathematicians to solve a series of problems he formulated. The solutions have proven to be enormously fertile, scientifically, technologically, and mathematically.

Hoyle, Fred (1915–2001): British astrophysicist; best known for dismissively rejecting what he called the Big Bang theory of the origin of the universe in favor of his own Steady State theory, in which there is no origin and no end. With William Fowler and the Burbridges, worked out how stars could synthesize all the natural elements.

Hubble, Edwin (1889–1953): American astronomer; Hubble discovered that there were other galaxies besides the Milky Way and that galaxies were all moving away from the Earth as if the universe as a whole were expanding; he developed the first techniques for estimating the age and size of the universe.

James, William (1842–1910): American psychologist and philosopher, early proponent of experimental psychology, author of a text that remained influential for decades, and a champion of pragmatism.

Jung, Carl (1875–1961): Swiss psychologist; noted for his anti-Freudian approach to psychoanalysis based on his theory of the collective unconscious.

Kahneman, Daniel (1934–): Israeli-American social scientist; with Amos Tversky, built a compelling empirical case for the non-rational character of human decision-making with major implications for philosophy, psychology, and social science generally, but rational choice theory–based economic models in particular.

Keynes, John Maynard (1883–1946): British economist; perhaps the single most influential economic theorist of the century in terms of government policy.

Kuhn, Thomas (1922–1996): American historian of physical science; his 1962 *Structure of Scientific Revolutions* triggered a relativism-based critique of objectivity that transformed history, philosophy, and sociology of science, in part, causing the Science Wars of the 1980s and 1990s.

Lawrence, Ernst O. (1901–1958): American physicist; from the day he arrived at Berkeley in 1930, his focus was on building ever-more-powerful cyclotron-style charged-particle accelerators that exploited the resonance principle as tools for atomic physics research.

Leakey, Louis (1903–1972): Kenya-born British paleoanthropologist; with his wife, Mary, and later, his son Richard, Leakey transformed our understanding of human evolution through his fossil discoveries in east Africa, especially Olduvai Gorge, laying the foundation for the *Out-of-Africa theory* of humanity.

Lévi-Strauss, Claude (1908–): French anthropologist; founder of structuralism, which in the 1960s and 1970s, was broadly adopted as a methodology by social scientists and literary theorists.

Maxwell, James Clerk (1831–1879): Scots physicist; founder of classical electromagnetic theory and electrodynamics, simultaneously the basis for quantum electrodynamics and superseded by quantum chromodynamics.

Mead, George Herbert (1863–1931): American sociologist; founder of social behaviorism, an interactional-relational theory of the self and of society with pragmatist overtones.

Minsky, Marvin (1927–): American computer scientist; one of the founders of artificial intelligence research, creator of MIT's AI Laboratory, and champion of the view that thinking is calculating with symbols, thus, a strong opponent of neural net models.

Oppenheimer, J. Robert (1904–1967): American physicist; Oppenheimer is best known for having been the director of the Manhattan Project and for the loss of his security clearance for having opposed developing the hydrogen bomb, but in the 1930s, he was an important contributor to quantum theory.

Pareto, Vilfredo (1848–1923): Italian sociologist and economist whose theories of society and the economy, based not on objective reason but emotion and will, were taken up in the 1930s and became central to one strand of modern economic, and welfare state, theory.

Pauli, Wolfgang (1900–1958): Austrian physicist; his 1924 Exclusion Principle provided the first systematic explanation of the periodic table and opened the way to Schrödinger's and Heisenberg's versions of quantum mechanics. Pauli also solved the problem of beta decay in 1930 and predicted the existence of what became known as the neutrino.

Pauling, Linus (1901–1994): American chemist; formulated the definitive theory of chemical bonding in his 1940 text employing quantum physics to explain inter-atomic bonds and new physics-based technologies, including X-ray crystallography to determine the molecular structure of biochemical molecules, thus paving the way for Watson and Crick.

Prigogine, Ilya (1917–2003): Belgian chemist; championed the study of irreversible processes, self-organizing systems, nonequilibrium thermodynamics, and nonlinear dynamics, enriching our understanding of entropy and laying the foundation for the study of complex systems.

Russell, Bertrand (1872–1970): English mathematician, mathematical logician, and philosopher; Russell demolished Frege's project to reduce arithmetic-based mathematics to logic, then collaborated with Alfred North Whitehead on an attempt at reducing all of mathematics to logic.

Rutherford, Ernst (1871–1937): New Zealand–born British physicist; Rutherford's Cambridge University laboratory was, for decades, a remarkably fertile source of important experimental and theoretical developments. Rutherford formulated the modern, so-called solar system model of the atom, which stimulated Bohr to propose a quantum theory of orbital electrons that launched quantum physics and chemistry.

Samuelson, Paul (1915–): American economist; perhaps the greatest influence on the adoption of sophisticated mathematical analysis by post-World War II economists and an architect of dynamic economic theory.

Sanger, Frederick (1918–): English biochemist, received two Nobel Prizes for chemistry (1958 and 1980) for having determined the complete molecular structure of insulin and for working out the basic techniques for determining the sequence of bases in DNA.

Saussure, Ferdinand de (1857–1913): Swiss linguist; best known for his very influential theory of language as a closed system of relationships.

Schrödinger, Ernst (1887–1961): Austrian physicist; one of the giants of quantum mechanics, especially in the period 1924–1934. His wave mechanics of 1925 became the basis of Dirac's relativistic theory of the electron, which evolved into quantum electrodynamics.

Shannon, Claude (1917–2001): American mathematician; with Warren Weaver, he laid the foundation for modern communication and information theory, which became important resources for the new fields of systems analysis and computer science.

Simon, Herbert (1916–2001): American social scientist but not an economist by training, Simon received the Nobel Memorial Award in Economics for his studies of organizational decision-making, emphasizing the concepts of *bounded rationality* and *satisficing*. With Alan Newell, he was, in the 1960s, a pioneer of artificial intelligence research.

Skinner, B. F. (1904–1990): American psychologist; in the 1930s, Skinner revived John Watson's crude stimulus-response behaviorism and made reinforcement-based behavioral psychology the dominant paradigm until the rise of cognitive psychology in the 1970s.

Turing, Alan (1912–1954): English mathematician; his 1936 proof that, contrary to Hilbert's challenge, there could be no mechanical decision procedure in mathematics led to the conceptual design of the modern computer.

Von Neumann, John (1903–1957): Hungarian-American mathematician of enormous influence in mathematics, physical science, computer science, and social science. Founder of game theory, established the basic software and hardware architectures for stored-program electronic computers, pioneer of the theory of automata, and an important contributor to set theory and quantum mechanics.

Watson, James (1928–): American biochemist; received his Ph.D. at age 22 and, shortly thereafter, with Francis Crick, discovered the double-helix structure of DNA, launching molecular biology.

Weber, Max (1864–1920): German sociologist; best known for arguing that the roots of capitalism lie in the Protestant ethic and that the human and social sciences necessarily require an interpretive, rather than an inductive or deductive, method.

Wegener, Alfred (1880–1930): German meteorologist and geologist who, in 1915, proposed a theory of continental drift that, after initial ridicule, evolved into plate tectonics.

Wheeler, John (1911–): American physicist; with Gamow and Oppenheimer, one of the most eminent physicists of the century not to have been awarded a Nobel Prize. Wheeler made major contributions to gravitation theory and coined the name *black hole*.

Wiener, Norbert (1894–1964): American mathematician and scientist, founder of cybernetics, pioneer of mathematical modeling of mechanical and biological systems, and an important contributor to information theory and system theory.