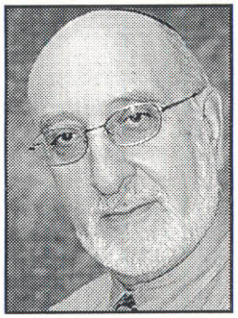

Professor Steven L. Goldman is Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University, where he has taught for over 25 years. He received his Bachelor of Science degree in Physics at Polytechnic University of New York and his M.A. and Ph.D. in Philosophy from Boston University. Professor Goldman has received Lehigh's Lindback Distinguished Teaching Award. He has authored or edited eight books and many scholarly articles and reviews.

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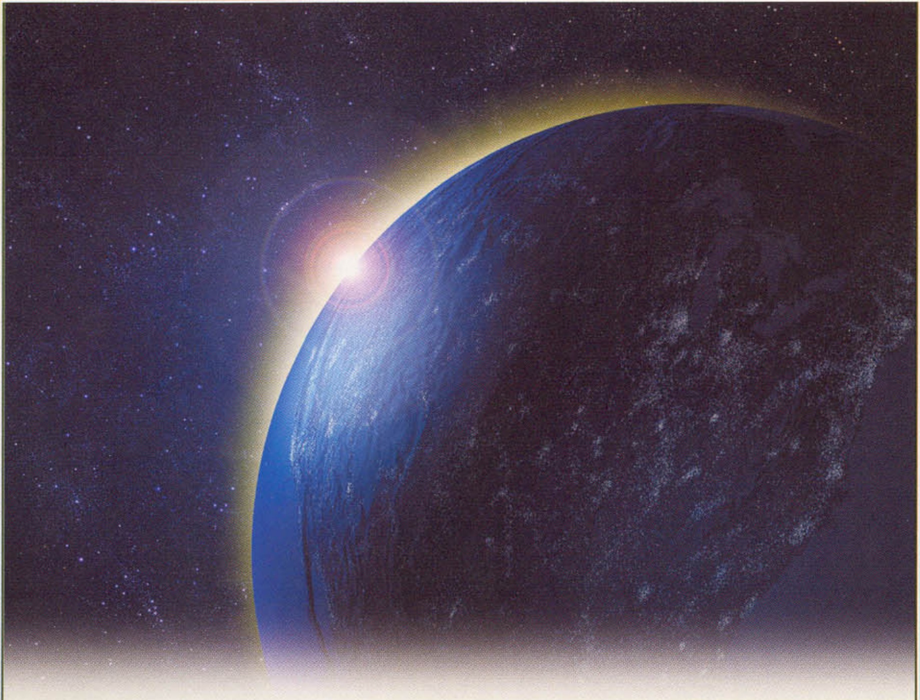

Science in the Twentieth Century:
A Social-Intellectual Survey

Taught by: Professor Steven L. Goldman,
Lehigh University

Part 1

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 One
The Evolution of 20th-Century Science

Scope: Twentieth-century science is an *evolutionary* outgrowth of 19th-century science: intellectually, in terms of the theories scientists created and the new ideas underlying them; in its organization and conduct as a professional practice; and in its relationship to society. As powerful and innovative as 19th-century science was by comparison with 17th- and 18th-century science, it is dwarfed by the scale, scope, and power of 20th-century science. Our goal is a rounded appreciation of what science became in the course of the 20th century: a cultural force in virtue of its reality-defining worldview and a force driving social change through its relation to industry and government.

From its 17th-century birth, modern science has had two mutually influential "sides": an "inside," intellectual dimension, and an "outside," social relationship dimension. The inside, the outside, and the relationship between them all changed character in the course of the 20th century. Our exploration of the inside of science will be organized around the evolving 20th-century understanding of Matter and Energy, the Universe, Earth, Life, and Humanity. The outside will be organized around the relationship of science to society-transforming technological innovation, to government, and to public institutions and values.

As 20th-century physical, life, and social science are built on 19th-century science, identifying developments in 19th-century science that played key roles in 20th-century science is a precondition for appreciating the innovativeness of 20th-century science. A preview of the major theories and the core ideas that cut across the scientific disciplines will help orient us as we begin tracing the rise of these innovative theories and ideas.

Outline

I. This course will take us on an intellectual odyssey, as we explore the evolution of the sciences and of the relationship between science and society in the course of the 20th century.

- **A.** Our study will span the physical, life, and social sciences without distinguishing between the "hard" sciences of, for example, physics and chemistry, and the "soft" sciences, such as economics and sociology.
- **B.** We apply the term *evolution* to our study of 20th-century science in the sense that it was used by Charles Darwin and Alfred Russell Wallace; that is, *evolution* is the emergence of novelty by the introduction of discontinuity into an underlying continuity.

- **C.** Our exploration will be organized around five broad themes: Matter and Energy, the Universe, the Earth, Life, and Humanity. We will also look at several seminal developments in mathematics that profoundly influenced the practice and application of science in the 20th century.
- **D.** Our survey, then, has a dual structure. We will look at the intellectual "inside," that is, the ideas and theories of 20th-century science, as well as its "outside," seen in its relationship to society.

II. We begin by identifying the core ideas of 19th-century science that underlie the evolution of 20th-century science.

- **A.** In the 19th century, the *atom* came to represent the view that natural phenomena consisted of fundamental building blocks that could be configured to produce the vast number of forms we find in nature. The atom in physics and chemistry is an example of that conception, as are the gene in the theory of heredity and the germ in the germ theory of disease.
- **B.** In the 19th century, a science of *energy* was created, called *thermodynamics*, which identified energy as a new dimension of reality. This science recognized that energy was a phenomenon in nature parallel to matter.
- **C.** The 19th century also saw the development of the idea of *fields* of energy and force. A field is an immaterial phenomenon obeying natural laws and capable of exercising forces on material objects.
- **D.** Chemists in the 19th century discovered that *structure* is the feature that differentiates one substance from another, as opposed to the fundamental constituents of substances and the properties of these constituents.
- **E.** The fifth core idea of the 19th century that would influence 20th-century science was the discovery of *non-Euclidean geometry*. For approximately 2,300 years before the mid-19th century, Western philosophy, science, and mathematics were based on the confident assumption that deductive reasoning was closely linked to truth. In the mid-19th century, mathematicians discovered deductively perfect geometries that contradict Euclidean geometry, raising the question of which form of geometry is true of space and severing the uncritical connection between reasoning and reality.
  1. Another important development in mathematics in the 19th century was the invention of symbolic logic. From this development, we learned that notation can have a significant impact on our thinking. Simply replacing words with symbols can lead to new insights.
  2. Further, symbolic logic undermined the notion that subjects had priority over predicates, that is, that things were the ultimate reality and relationships were a secondary consequence of the

organization of things. Through the use of symbolism, relationships were found to have properties of their own.

F. The 19th century also saw the replacement of Newton's particle, or corpuscular, theory of light with the *wave theory of light* and the subsequent expansion of this theory with James Clerk Maxwell's *electromagnetic theory of energy*.

G. *Probability* and *statistics* became important in the 19th century, specifically, the idea that natural processes exist that require probability to describe them.

H. Finally, the 19th-century theory of *evolution* was a foundational idea of 20th-century science.

III. We also need to mention three of the many instruments that were invented in the 19th century that will reappear throughout the course.

A. The first of these is the *color-corrected microscope*, which enabled high-power magnification without blurring.

B. Another important scientific device of the 19th century was the *spectrometer*, which identifies the frequencies of a beam of light.

C. Finally, the invention of the *interferometer* allowed scientists to measure extremely small distances and would be integral to the development of 20th-century astrophysics.

IV. What features of the 19th-century social context were critical in the evolution of 20th-century science?

A. In the 19th century, technological innovation emerged as the primary agent of social change, displacing the dominance of religion and politics.

B. This development was reinforced by the invention of the industrial research laboratory, the emergence of the university as a center for scientific research, and governments' use of scientific research in pursuit of military, economic, and social policies.

V. Certain ideas that cut across disciplines emerged as distinctive features of 20th-century science.

A. The first of these is the idea that reality is ultimately describable in terms of *relationships*.

B. Connected to the first idea are the concept of *systems* and analysis of natural phenomena from the top down, rather than a building up of reality from elementary parts.

C. Another important idea of the 20th century is *dynamism*; that is, the notion that change is a normal state.

D. Also, *information* is understood as a feature, or category, of reality, similar to matter or energy.

E. The 20th century also finds that unlimited complexity can emerge out of simplicity.

F. Over the course of the century, the distinction between subjectivity and objectivity, between mind and world, becomes blurred.

G. Finally, in the 20th century, scientific research becomes increasingly cross-disciplinary and collaborative.

Essential Reading:

William Coleman, *Biology in the Nineteenth Century: Problems of Form, Function, and Transformation.*

P. M. Harman, *Energy, Force and Matter: The Conceptual Development of Nineteenth-Century Physics.*

Mary Jo Nye, *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940.*

Questions to Consider:

1. Why did Western societies become so much more receptive to science in the 20th century?
2. How is it that a public so uneducated in science can be so influenced by scientific theories and ideas?
3. Granted that the conduct of science is influenced by the social context in which it is practiced, can that context also influence the content of science, and how does it do that?

Lecture Two

Redefining Reality

Scope: The special theory of relativity (STR) undermined 200 years of physics. How did Einstein come to formulate STR, the subject of just one of three papers he published in 1905 that moved physics in new directions? What problem was Einstein trying to solve and how did his solution entail nothing less than a reinterpretation of space, time, motion, causality, energy, and matter: thus, a reinterpretation of physical reality? Why is it called the "special" theory of relativity and what is relative about it? As late as 1921, when Einstein was awarded the Nobel Prize in physics, relativity theory was still suspect in conservative scientific circles, and he was awarded the prize for another 1905 paper: a pioneering contribution to quantum theory. STR was, for a time, not susceptible of empirical validation, but beginning in the late 1920s, its validity became inescapable and its utilization necessary for both theoreticians and experimentalists.

In the general theory of relativity (GTR), Einstein extended STR into a new, anti-Newtonian, universal theory of gravity in which space, time and motion, matter, energy and force became types of relationships and not the absolute entities they were in Newtonian science. At the same time, GTR entailed a wholly unexpected revision in our conception of the universe, as unlimitedly large but finite and, incredibly, expanding, implying temporal finitude as well. Especially after 1960, experimental testing of GTR became possible and astronomical observations have confirmed long-ignored predictions of the theory, including the existence of neutron stars, galactic lenses, and black holes.

Outline

I. In 1905, Einstein published three papers, each one influential in changing the history of 20th-century science.

A. The first of these was a paper on *Brownian motion*. In this phenomenon, small particles suspended in fluid are observed to move around at random. In the course of explaining Brownian motion, Einstein convinced many of his fellow physicists of the existence of atoms.

B. The second paper, which we will discuss in the next lecture, was on the *photoelectric effect*. Einstein explains the phenomenon that certain materials, typically metals, when exposed to light, give off electrons. Einstein won the Nobel Prize for this paper, which is one of the foundations of quantum theory.

C. Of course, Einstein's third paper was on the *special theory of relativity*.

II. What were the problems that Einstein's special theory of relativity was trying to solve?

A. The first problem was one that the physics community shared: Using the wave theory of light, physicists tried to measure the motion of the Earth in absolute space, but every attempt resulted in a measurement of 0. Further, every measurement of the speed of light in a vacuum resulted in a constant, a result exhibited by no other form of motion in nature.

B. The second problem was a seemingly simple one that troubled Einstein personally: What does it mean to say that two events, one at a distance from an observer and one close to the observer, occur simultaneously? In fact, the event that occurs at a distance must take place earlier, because it takes time for the light signal from that event to reach the observer.

C. Einstein solved both problems in the special theory of relativity, which rests on two principles.

1. The first principle is one that had been accepted by physicists for 300 years, that is, the principle of the relativity of motion. For two observers who are traveling at a uniform speed and subject to uniform forces, the laws of physics identified by both will be the same.
2. The second principle was to accept as an axiom that the speed of light in a vacuum is a constant for all observers, regardless of their motion.
3. What follows from taking these two principles together is the special theory of relativity, which includes a new view of space and time as relationships, not things.

D. Until 1905, space and time were accepted by scientists as Newton had defined them.

1. Space had a Euclidean character that existed independently of anything in space; in other words, space was an absolute, infinite, and uniform container for matter. Time was an absolute, uniform "clock" ticking in the background at a constant rate.
2. According to the special theory of relativity, all spatial and temporal measurements are, instead, relative to an observer's frame of reference; space and time are not absolute and uniform.

E. The special theory of relativity required rethinking our definitions of space and time, but perhaps more dramatically, it resulted in the equation $E = mc^2$. Matter and energy, which were considered to be two distinct categories of nature throughout the 19th century, were, in fact, interconvertible.

III. Between 1905–1917, Einstein was working to further develop his contributions to quantum theory and to generalize the special theory of relativity.

   A. In the wake of the special theory of relativity, Einstein was concerned with a peculiar feature of Newtonian science that had been unquestioned until the early 20th century. This feature of physics is that *gravitational mass* (weight) and *inertial mass* (the resistance of matter to motion) are identical. Einstein wondered why this is true.

   B. Again, Einstein proposed to make this equivalence a new principle of nature. What emerged was a new universal theory of gravity, in which space, time, matter, and energy are intimately related.

      1. *Space* and *time* are now names of relationships, and so is *matter*. The mass of an object is, in some way, dependent on the total distribution of mass in the universe.

      2. When a star explodes and its mass is dispersed in space, that event has implications for the shape of space throughout the universe.

      3. Space and time, then, are relationships. They have no reality apart from their connections with matter and energy.

      4. Further, space has a shape; it is not featureless in all directions. The shape of space is a function of the distribution of matter and energy in space.

      5. Finally, space is not infinite.

   C. The first experimental confirmation of this general theory of relativity came in 1919, when Sir Arthur Eddington observed that light rays passing close to the Sun during an eclipse were "bent" almost exactly as predicted by the theory.

IV. The general theory of relativity has dramatic consequences that are still being played out.

   A. The general theory of relativity is explicitly *ontological*; that is, it describes reality. The special theory of relativity can be interpreted *metrologically*, that is, as a statement about what we can measure.

   B. The general theory of relativity predicts gravity waves, which have not yet been detected. According to the theory, a change in the distribution of matter in the universe should cause waves to ripple through space and affect the shape of space; we should be able to detect these waves.

      1. At the end of the 20th century, NASA funded America's first gravity wave telescope, which is based on the interferometer invented in the 19th century.

      2. This device is several miles long and is capable of detecting a change in the distance between two fixed points as small as the diameter of a proton.

   C. The most amazing prediction of the general theory of relativity is that the universe is expanding at an accelerating rate, which Einstein himself initially did not believe could be correct.

   D. We will return to the cosmological implications of the general theory of relativity in a later lecture; in the next lecture, we'll turn to quantum theory and the attempts to unify it with the general theory of relativity.

Essential Reading:

Albert Einstein, *Relativity: The Special and General Theories.*

Abraham Pais, *Einstein Lived Here: Essays for the Layman.*

John Stachel, *Einstein's Miraculous Year.*

Supplementary Reading:

Ronald Clark, *Einstein: The Life and Times.*

Questions to Consider:

1. How is it that theories like STR and GTR that are based on rethinking existing ideas can reveal absolutely unthought-of aspects of reality?
2. If matter and energy are interconvertible, as Einstein's equation correctly predicted, then what is the reality of which they are complementary expressions, or is this not a legitimate question?
3. Intuitively, we grasp calling "things" real, but how can relationships be what reality ultimately is made of?

Lecture Three

Quantum Theory Makes Its Appearance

Scope: The special and general theories of relativity were the unanticipated offspring of what the eminent British scientist Lord Kelvin called one of "two small clouds" in the otherwise blue sky of late-19th-century science. The other was the failure to solve what came to be known as the *blackbody radiation problem*. In December of 1900, Max Planck announced a solution to this problem but only by assuming that the emission and absorption of electromagnetic energy, at the time believed to be continuous waves, could be only whole multiples of a discrete unit, or *quantum*, of energy. Thus was born *quantum theory*, but for the next 10 years, its "father" tried to smother it! In 1905, however, Einstein argued that light behaved as if it really *were* a stream of particles, characterized by a quantized amount of energy. In 1906–1908, he extended this quantum hypothesis to problems in physical chemistry, and others, too, found the quantum hypothesis valuable. In 1912, Niels Bohr rescued Ernest Rutherford's so-called solar system model of the atom by quantizing the orbital energy of the electrons circling the atom's central, positively charged nucleus. Suddenly, a wide range of puzzling phenomena could be explained but only by abandoning 19th-century conceptions of matter and energy.

Outline

I. Radical as they were, the special and general theories of relativity are deterministic theories that use modes of reasoning and explanation, as well as forms of mathematics, that would have been familiar to 19th-century scientists.

- **A.** The special and general theories of relativity leave in place the greatest achievements of 19th-century physics: the atomic theory of matter, the wave theory of light, and Maxwell's electromagnetic theory of energy.
- **B.** Quantum theory was far more radical than the special or general theories of relativity; it overturned the conceptual structure of 19th-century science. Quantum theory is important to examine because it changed both our ideas about physical reality and our conception of rationality itself.
- **C.** We will look at the development of quantum theory in three stages.
  1. From 1900–1929 is the "heroic" period of quantum theory, encompassing Einstein's 1905 paper to the formulation of quantum mechanics in 1925 and, after four years, to a radical interpretation of the physical meaning of quantum mechanics.

  2. From 1930–1964 is the "working" stage, during which quantum theory was extended to a far more powerful theory, quantum electrodynamics (QED).
  3. Since 1964, quantum theory has been in its "mature" stage. This period has seen the replacement of QED with an even more powerful theory of matter, quantum chromodynamics (QCD), and the beginnings of the unification of all known forces of nature into a single theoretical framework.
  4. Running through all three stages is a foundational principle: that at the most fundamental level of natural processes, nature is discrete, not continuous. This principle applies even to space and time.

II. Quantum theory begins with a problem that had puzzled physicists for two decades around the turn of the 20th century.

- **A.** A body that absorbs all the electromagnetic energy that falls on it, for example, all frequencies of light, is called a *blackbody*. As it absorbs this radiation, it becomes hotter, and the body itself begins to radiate. The question is: How is the energy radiated by the blackbody distributed among all the frequencies of electromagnetic radiation?
- **B.** Physicists found equations that could predict the amount of energy radiated at low frequencies or high frequencies but could not find a single equation to cover both. The solution should have been found in a straightforward application of Maxwell's electromagnetic theory.
- **C.** In December 1900, Max Planck presented a paper that solved the blackbody radiation problem, but the solution came at a price. Planck's solution rested on the assumption that electromagnetic energy could be emitted or absorbed only in discrete "packets" that he called *quanta* (later renamed *photons*). Further, quanta were restricted in size to whole multiples of a unit of energy; no intermediate values were permitted.
- **D.** For the next 12 years, Planck attempted to amend his solution to eliminate the assumption of quanta, which contradicted Maxwell's theory. In 1905, Einstein, in his paper on the photoelectric effect, accepted the existence of quanta as a fact of nature. He explained the photoelectric effect by arguing that light and, thus, all electromagnetic radiation, traveled through space as if it were a dilute gas, that is, as discrete, atom-like packets.
- **E.** Between 1905–1909, Einstein applied the quantum hypothesis to solve a series of puzzling problems in physics and chemistry.

III. Einstein's 1905 paper on the photoelectric effect also raised another issue, which has been controversial ever since.

- **A.** Einstein worked into this paper the claim that any serious theory of physics must be capable of giving a picture of reality.

B. The general theory of relativity, for example, is a deterministic theory that gives us a picture of reality. According to Einstein, a physics theory must have a consistent conceptual structure; if a theory is conceptually inconsistent, it cannot be a true picture of reality.

C. This notion would later place Einstein on the outside of further developments in quantum theory.

IV. Quantum theory came to the forefront of physics with the work of a young Danish post-doctoral student named Niels Bohr.

A. In 1911, Bohr won a fellowship to study at the Cavendish Laboratory at Cambridge with J. J. Thompson, the discoverer of the electron. But Bohr soon moved to the University of Manchester lab of Ernest Rutherford, who, in 1919, succeeded Thompson at Cambridge.

B. As background to Bohr's work, we must first take a look at the development of the atomic theory of matter.

1. In 1806, John Dalton had defined the atom as solid and indivisible, but in 1896, J. J. Thompson discovered that atoms had an internal structure.

2. Thompson's discovery of an electrically charged particle inside the atom led to the question: How are these *electrons* organized inside the atom? Thompson proposed a model in which electrons were distributed in a positively-charged substance inside the atom, similar to raisins in pudding.

3. Between 1906 and 1910, a number of alternative models of the atom were suggested, including Rutherford's solar system model. This model was the result of an experiment in which thin sheets of gold were exposed to rays from radioactive material. Rutherford hoped to gain a clearer picture of the arrangement of electrons inside the gold atoms by observing how the positively charged alpha rays were deflected by the negatively charged electrons in the heavier gold atoms.

4. The surprising result of the experiment was that some of the alpha rays nearly bounced back, instead of passing through the gold foil. Rutherford proposed that atoms are not solid but, in fact, are mostly empty space. In Rutherford's understanding, the nucleus is a tiny fraction of the volume of an atom and is surrounded by a cloud of orbiting electrons.

5. This model has one major flaw: According to Maxwell's electromagnetic theory, the electron should instantly spiral into the nucleus. There is no way for the negatively charged electrons to maintain a stable orbit around a positively charged nucleus. Rutherford's model seems correct experimentally but, theoretically, is totally wrong.

C. At this point, fortuitously, Bohr came to Rutherford's lab and suggested applying the quantum hypothesis to the problem. Up to this time, the quantum hypothesis had been applied to electromagnetic energy. Bohr suggested using it to understand the mechanical energy of orbital electrons.

D. Bohr postulated that orbital electrons do not radiate electromagnetic energy, even though they are negatively charged particles moving in the presence of a positively charged particle. They radiate only when they *change* orbits. Further, electrons can occupy only specific orbits around the nucleus of a given atom; in other words, their orbital energy is quantized.

E. Using Bohr's assumptions, the atom becomes stable; further, the physical and chemical properties of atoms in the periodic table can be explained.

F. Bohr's hypothesis also solved another profoundly puzzling problem of physics.

1. Starting in the 1850s, scientists had discovered, using the spectroscope, that pure chemical elements, when heated until glowing, radiated light only at specific frequencies. Every element had its own "light print."

2. Bohr's hypothesis explained why the elements behaved in this way. In every atom, there are specifically permitted and forbidden orbital transitions. When an electron changes its orbit and goes from a higher energy level to a lower energy level, it emits a photon of exactly the frequency corresponding to the loss of mechanical energy that the electron experiences.

G. In our next lecture, we carry this heroic stage in the development of quantum theory into the 1920s, to its culmination in the Copenhagen interpretation of quantum mechanics.

Essential Reading:

George Gamow, *Thirty Years That Shook Physics: The Story of Quantum Theory.*

Barbara Cline, *Men Who Made the New Physics: Physicists and the Quantum Theory.*

Supplementary Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century.*

Questions to Consider:

1. Why was it so difficult for Planck to accept the reality of quanta, and why were Einstein and Bohr so willing to accept it?
2. How should our attitude toward scientific truth claims be affected by the reinterpretation of the established conception of physical reality forced by the relativity and quantum theories early in the 20th century?
3. What significance lies in the fact that the overwhelming majority of those who embraced the relativity and quantum theories were very young scientists, even graduate students, not their professors?

Lecture Four

The Heroic "Old" Age of Quantum Theory

Scope: The "old" quantum theory of 1900–1929, especially Bohr's quantum theory of the atom (which, by 1922, was extended to a theory of the chemical elements), was rescued from problems that had arisen by two new forms of quantum theory: matrix mechanics and wave mechanics. These turned out to be mathematically equivalent and were highly successful experimentally, but as explanations of natural phenomena, they begged for interpretation. Niels Bohr and Werner Heisenberg played the leading roles in creating this interpretation, proposing fundamental changes in the conceptual framework of modern science that were made famous as the *uncertainty relations*, the *principle of complementarity*, and the *Copenhagen interpretation of quantum mechanics*.

Outline

I. As mentioned in the last lecture, Bohr, through his quantization of the electron orbits inside an atom, rescued Rutherford's solar system model of the atom.

- **A.** The explanation of spectroscopic data that had been accumulated since 1850 gave credence to Bohr's theory.
- **B.** The fact that Bohr's theory enabled the building up of the periodic table was also compelling evidence that the theory was accurate.

II. The growth of Bohr's quantum theory from 1912–1925 should not obscure its profound strangeness.

- **A.** First, the theory attributes both particle-like characteristics and wave-like characteristics to electromagnetic energy, but waves and particles are mutually exclusive concepts.
- **B.** The quantum hypothesis also pushes discontinuity deeper and deeper into nature.
- **C.** Further, in 1917–1918, Einstein and Bohr convincingly argued that orbital transitions by electrons are random. Earlier, the disintegration of radioactive atoms had been shown to be random; this process had to be described statistically.
    1. Every radioactive element has its own distinctive disintegration rate (*half-life*), but the individual atoms in a radioactive element display a random pattern of disintegration.

2. The same is true of the orbital transition process. We cannot predict when an individual electron will change its orbit and either emit or absorb a photon.
3. This randomness threatened the deterministic character of 19th-century science.

D. The *correspondence principle* was yet another disconcerting feature of Bohr's quantum hypothesis. According to Bohr, even though the quantum theory fundamentally transforms classical physics, there is still a correspondence between the two.

III. During the period 1920–1925, spectroscopic data, which had originally bolstered Bohr's hypothesis, suddenly became the enemy of quantum theory.

A. Remember that the frequencies of light emitted by specimens were shown to be related to the orbital transitions permitted to electrons around a nucleus.

B. By 1922–1923, new spectroscopic experiments were being performed that called the quantum theory into question.

C. In 1923, Louis de Broglie, a French graduate student, wrote a paper predicting that matter, like electromagnetic energy, also has a dual character and may behave as both a particle and a wave.

1. De Broglie's prediction was based entirely on mathematics, but in 1927, it was confirmed experimentally by two American physicists and, independently, two British physicists.
2. In 1912, Max von Laue had suggested an experiment to demonstrate that X-rays were electromagnetic waves by showing their diffraction by a crystal. This same technique was adapted in 1927 to show that an electron beam was diffracted by a crystal just as X-rays were.

D. Scientists' understanding of matter had already been challenged with the discovery of radioactivity by Henri Becquerel in 1896 and Pierre and Marie Curie's isolation of radium in 1898. Now, physicists had to accept the idea that the wave-particle duality was not a curious fact about only energy, but about matter, as well.

1. By 1910–1911, scientists knew that the products of radioactivity were alpha, beta, and gamma rays.
2. As we mentioned, alpha rays are stripped helium atoms—combinations of two protons and two neutrons. Beta rays are actually electrons released when a radioactive nucleus splits. Gamma rays are extremely high-energy photons.
3. Obviously, these discoveries painted a much more complicated picture of matter than scientists had previously seen.

IV. Between 1923–1925, two physicists, working independently, developed new versions of quantum theory that resolved the spectroscopic crisis.

A. Erwin Schrödinger, an Austrian physicist, based his theory on de Broglie's paper, not waiting for experimental confirmation. Schrödinger adapted some of the mathematical tools of the 19th-century wave theory of light to develop *wave mechanics*, a new quantum theory of electromagnetic energy that addressed spectroscopic questions of the early 1920s.

B. A few months earlier, Werner Heisenberg, a German physicist, also formulated a quantum theory that resolved the crisis but on what seemed to be totally different grounds.

C. Schrödinger's theory has an elegant, deterministic mathematical structure. In contrast, Heisenberg's theory was "ugly."

1. Heisenberg developed his own version of matrix algebra, which operates with arrays rather than individual numbers.
2. Heisenberg showed that by constructing matrices with spectroscopic data and applying the rules of quantum theory, the spectroscopic data can be explained; that is, the frequencies and energy levels of photons emitted by electrons in orbital transition can be predicted.
3. Schrödinger later showed that his theory and Heisenberg's were mathematically equivalent. In 1926, the name *quantum mechanics* was given to this type of theory.

V. By 1926, there was an empirically successful quantum mechanics of matter and energy, but its physical interpretation remained puzzling.

A. Heisenberg's matrices violated an established rule of both physics and ordinary mathematics: that the order in which quantities were multiplied should make no difference in the result. This rule, *commutativity*, does not hold in matrix algebra or in Heisenberg's matrix mechanics. Why not?

1. In 1927, Heisenberg interpreted the non-commutativity of his matrices as revelations of a deep truth about quantum-level reality: There is an inevitable uncertainty in our ability to collect information from the subatomic world.
2. Heisenberg used the term *uncertainty relations* to assert the idea that there are limits to the precision with which we can know certain kinds of coupled facts about nature. For example, we cannot know both the exact position of a particle and its velocity. Interestingly, the uncertainty relations prevents our knowing just those facts that are required for a deterministic theory of nature!
3. At first, Heisenberg's uncertainty relations seemed to illustrate the limits in humans' ability to gain information from nature.

Ultimately, however, the uncertainty relations were seen as facts about nature itself.

B. Bohr responded to Heisenberg's uncertainty relations with two philosophical insights, the first of which was the *principle of complementarity*.

  1. Bohr argued that our ability to explain natural phenomena was constrained by our ability to form concepts. Our concepts come from experience, but we cannot directly experience photons. Inevitably, we must use complementary concepts, such as *wave* and *particle*, to explain the full spectrum of behaviors that nature reveals at a lower level than we can experience.

  2. This principle carries with it a blurring of the line between subjective and objective, between mind and world.

C. In 1929, Bohr and Heisenberg collaborated on the second insight, the *Copenhagen interpretation of quantum mechanics*. This states that nature, at the most fundamental level, is probabilistic, not deterministic.

Essential Reading:

Abraham Pais, *Niels Bohr's Times: In Physics, Philosophy, and Polity*.

———, *The Genius of Science: A portrait gallery of twentieth-century physicists*.

Sam Treiman, *The Odd Quantum*.

Supplementary Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Questions to Consider:

1. Can scientists settle for the Bohr-Heisenberg view that theories describe human experience, not what's really out there and causing our experience?
2. The world we experience is highly orderly, continuous, and predictable, so how can the fundamental processes underlying experience be random and discontinuous?
3. Why do scientists "stick with" new theories that require deep conceptual change and pose serious problems they cannot initially solve, such as Rutherford's solar system model of the atom and Bohr's quantum theory of orbital electrons?

Lecture Five

A Newer Theory—QED

Scope: From 1929 on, quantum mechanics met the challenge of explaining a growing range of atomic phenomena, some of them its own predictions; some, the result of experiments with "atom-smashing" particle accelerators; and some, new discoveries, including the neutron, antimatter, cosmic rays, nuclear structure, and nuclear fission. The "old" quantum theory (1900–1925) was replaced in 1929 by quantum electrodynamics (QED), a quantum version of Maxwell's electromagnetic theory consistent with the special theory of relativity. From 1929 through the 1950s, QED developed increasingly more comprehensive explanations of the interaction of matter and electromagnetic energy, but it remained an extension of wave/matrix mechanics and of the atomic theory of matter on which it rested. New instruments for probing the structure of the atom, however, began to force new theories of matter.

Outline

I. In the past few lectures, we have discussed the "heroic" phase of quantum theory, starting about 1900 and climaxing around 1929 with the Copenhagen interpretation. As we move into the "working" phase of quantum electrodynamics (QED), we take a brief look at the progress of the theory.

  A. Quantum theory had addressed a series of problems for physicists, such as blackbody radiation, the photoelectric effect, and the meaning of spectroscopic data.

  B. The price that had to be paid for explaining these problems, however, was high. A number of longstanding scientific concepts were undermined or displaced by quantum theory.

    1. The first of these was the concept of causality. At the quantum level, events occurred that had no assignable cause. Quantum theory introduced randomness into fundamental natural processes.

    2. As we discussed, the concept of continuity was also undermined. Quantum theory insists that natural phenomena are discrete, not continuous.

  C. In 1929, the British physicist P.A.M. Dirac incorporated the special theory of relativity into Schrödinger's wave mechanics to arrive at a relativistic theory of the electron.

    1. In 1930, Dirac published a textbook that became a bible for physicists working in electromagnetics and electrodynamics. Thus, quantum electrodynamics (QED) became a framework for solving problems that involved the interaction of electromagnetic forces and material particles.

2. The time was ripe, then, for the integration of the earlier quantum theory into standard physics.

II. Dirac's new equations had a number of consequences that were startling, even by the standards of quantum theory.

A. The equations described the energy states of electrons but had negative solutions. Because Dirac believed that mathematics was capable of capturing the structure of reality, he did not discard these negative solutions. Instead, he posited the existence of antimatter; specifically, he predicted the existence of an electron with a positive charge, an anti-electron.

1. In 1932, the American physicist Carl Anderson discovered the anti-electron through his research into cosmic rays. He named this particle, which had roughly the same mass as the electron but the opposite charge, the *positron*. Anderson's discovery confirmed Dirac's bizarre prediction, which was derived only from mathematics, not from experimental research.
2. In fact, P.M.S. Blackett and Guiseppe Occhialini, in Rutherford's laboratory at Cambridge, found the positron before Anderson, but they were not ready to announce the existence of such an extraordinary particle. Instead, they announced an equally amazing finding, seen in their cosmic ray emulsions: confirmation of Einstein's $E = mc^2$ in the conversion of photons into particles. Matter could be created out of energy.

B. Dirac's theory yielded a still more striking prediction: the zero energy state of an electron is, in fact, rich in virtual energy, which can manifest itself as photons.

1. Imagine an electron in an atom absorbing a passing photon, in the process jumping to a higher energy orbit. Later, the electron spontaneously returns to its previous orbit, emitting a photon of the same energy that it had earlier absorbed. Where did the photon come from?
2. Dirac concluded that the absorbed photon continues to exist in a zero energy state, which has "room" mathematically for an infinite number of photons, and it emerges out of this state to a positive energy state when it is emitted. The vacuum, thus, is latently rich in mass-energy!
3. Together with the uncertainty principle, Dirac's theory implied a new, dynamic conception of the vacuum, predicting the existence of negative vacuum energy states that would become central to cosmology in the 1980s in Alan Guth's inflation theory.

III. QED had a number of problems that were substantially resolved only after World War II.

A. One of these was that QED did not fully account for the special theory of relativity. The equations of quantum mechanics make predictions, involving changes in probability distributions, that seem to violate the special theory of relativity rule that no signal can travel faster than the speed of light in a vacuum.

B. Further, some tension existed between the energy side of quantum mechanics and the matter side. The particle descriptions and the energy field descriptions did not completely mesh.

C. Finally, the mathematics of Dirac's theory is replete with infinities, which physicists had to negate using an ad hoc process.

D. Empirically, however, QED worked, and it became the framework for the theories that physicists used to identify and calculate the interaction of electromagnetic energy and matter.

IV. In 1932–1933, the attention of physicists began to focus on a problem *within* the atom.

A. QED had been primarily concerned with the interaction of orbital electrons and electromagnetic energy. The new focus on matter shifted the attention of physicists to gaining a better understanding of the nucleus.

B. The first act in this rise of nuclear physics was the discovery of the neutron.

1. In the decade before the 1920s, scientists had realized that the combined mass of electrons and protons in an atom was lower than the mass of the atom. It was assumed that the nucleus must contain some electrically neutral substance that accounts for the missing mass.
2. In 1920, Rutherford postulated that the nucleus must be an electron-proton hybrid. This idea also explained the existence of beta "rays," which are actually electrons, given off by radioactive atoms when they decay.
3. James Chadwick had been working in Rutherford's lab, trying to understand the range of energies given off by the electrons in beta decay. Chadwick insisted that the spectrum of energies was continuous, contrary to quantum theory, and over the course of the 1920s, experimental evidence seemed to support this conclusion.
4. In the late 1920s, Bohr, to maintain discreteness and rescue quantum theory, saw the need to give up the long-standing principle of the conservation of energy. Oddly enough, many of the leading physicists of the day were prepared to go along with Bohr.

        5. Wolfgang Pauli, however, one of the architects of quantum mechanics in the 1920s and of QED in the 1930s, proposed an alternative: that there was an electrically neutral particle of about the same mass as the electron in the nucleus that was expelled, along with the electron, in beta decay; its energy, together with that of the electron, satisfied the requirements of conservation. Subsequently, Enrico Fermi called this particle a *neutrino*.

    C. At the same time, in the early 1930s, Chadwick repeated some experiments reported in Germany and France in which particles were fired at samples of beryllium. Chadwick showed conclusively that the beryllium was converted to carbon with the release of a particle called a *neutron*.

    D. A new theory of beta decay was proposed by Enrico Fermi in 1934: A neutron in a radioactive nucleus spontaneously turns into a proton and an electron, along with a neutrino.

        1. Neutrinos remained undetected until 1955. Although they are the most numerous particle in the universe, they are extremely elusive.
        2. Neutrinos were originally thought to be without mass and electrically neutral, but they are now known to have an extremely small mass and to exist in three forms.

    E. At this point in history, QED has set the stage for the emergence of nuclear physics, which we will discuss in the next lecture.

Essential Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Silvan Schweber, *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*.

Sam Treiman, *The Odd Quantum*.

Questions to Consider:

1. Mathematical equations can summarize experimental data, but how can they predict new aspects of reality, as with Dirac's anti-electron?
2. With respect to the threat to quantum theory posed by Chadwick's explanation of beta decay in 1930 and Bohr's and Pauli's responses, how do scientists know when to give up a principle believed to be fundamental, like conservation of energy; when to modify a theory to protect the principle; or when to give up a theory as wrong because it conflicts with the principle?
3. What does it tell us about scientists' commitment to their theories that QED, a theory based on an intimate connection between mathematics and reality, was rescued from a serious mathematics-based problem by the "trick" called renormalization?

Lecture Six

QED Meets Fission and Fusion

Scope: The history of nuclear fission is dominated, and distorted, by the understandable fascination with the atom bomb, as the story of fusion is by the hydrogen bomb. The broader story of fission, however, is even more fascinating. Recognition of the reality of fission and, with it, the possibility of the transmutation of elements, had to overcome deep resistance to what seemed to many physicists and chemists a revival of alchemy. What was at stake was the very concept of an element, a truly fundamental building block of the world. The history of fission is a chapter in the story of the discovery of the complex internal structure of the atom, revealing a dizzying world of subatomic particles. Another chapter in that story is the development of "atom-smashing" machines that provided the theorists with startling new data.

Outline

I. We ended the last lecture with the discovery of the neutron and the development of a satisfying theory of beta decay.

    A. The discovery of the neutron focused the attention of physicists on the nucleus and resulted in a three-particle theory of matter. How, then, were the protons and neutrons arranged in the nucleus, and what forces hold the nucleus together?

    B. These questions defined the field of nuclear physics in the mid-1930s. At the same time, a number of lines of inquiry, such as radioactivity, fission, and QED, began to converge.

II. One important theory, developed in the mid-1930s, was that protons and neutrons were arranged in concentric shells in the nucleus, just as electrons were arranged in concentric orbits around the nucleus.

    A. In 1937, Hideki Yukawa, a Japanese physicist, proposed that the nuclear particles were bound by *weak* and *strong* interactions, or *forces*. In quantum theory, every force must have a carrier. For example, the carrier of the electromagnetic force is the photon. Thus, Yukawa also predicted the existence of a short-lived nuclear particle, a *mesotron* or *meson*, that was soon "found" in cosmic ray experiments.

    B. Yukawa's work was an expression of the attempts to work out a theory of the nucleus that would be consistent with the growing body of experimental evidence about radioactivity and the ability of atoms to undergo fission.

III. From 1930 on, physicists used QED for a specific task, that is, to calculate the probability that an atom will absorb or scatter a particle that approaches it.

- **A.** In scattering experiments, charged particles are "fired" at a target and the angles through which they are deflected are carefully measured. From the mass and energy of the beam particles, inferences can be made about the internal structure of the target atoms.
- **B.** In absorption experiments, the objective is to observe what happens when a nucleus absorbs, rather than deflects, a beam particle. The result must be some fundamental change in the nature of that atom. If the atom absorbs a neutron, it could simply become an isotope of itself, or it could become unstable and split.
- **C.** This context, of applying QED to the understanding of fission, occupied scientists in the period 1934–1939. At the time, physicists focused their research on uranium.
  - **1.** Uranium-235 was sensitive to slow neutrons. QED allowed scientists to calculate the probability that uranium-235 atoms would absorb a neutron, undergo fission, and release neutrons, as well as energy.
  - **2.** The released neutrons would then trigger a chain reaction of fission in other uranium atoms, resulting in a tremendous amount of energy in a short period of time*.
- **D.** This process was beginning to be understood by the end of the 1930s, and hundreds of scientists around the world were involved in a surge of nuclear physics research.
  - **1.** Key roles were played by Enrico Fermi in Italy and by Lisa Meitner and her long-term partner, Otto Hahn, in Germany. By 1939, all the "pieces" for releasing atomic energy were in place, and with the outbreak of World War II, the development of an atom bomb became inevitable.
  - **2.** Niels Bohr played a small but essential role in the calculation of the absorption coefficient, which told scientists whether it would be possible for a small amount of the isotope uranium-235 to create the fission reaction required for a bomb.
  - **3.** Heisenberg was the head of the German atomic bomb project in World War II. He seems to have mistakenly concluded that too much uranium would be needed to construct a weapon that could be carried in an airplane.
  - **4.** In 1940, President Roosevelt created the National Defense Research Council (NDRC) to organize the nation's academic scientists as a resource in the event of war. Later, the NDRC became the Office of Scientific Research and Development. One of its first projects was to authorize Enrico Fermi to build a small nuclear reactor to test Bohr's QED calculation of neutron absorption by uranium nuclei.
  - **5.** The Manhattan Project, led by the United States and directed by physicist J. Robert Oppenheimer, was created in late 1942. By 1944, most of the physics was done, and building the bombs was primarily an engineering challenge.

IV. Fission was only one track that nuclear research followed in the 1930s. Concurrently, a group of physicists began to explore fusion: the possibility of fusing protons together to build elements from the bottom up, rather than breaking them apart via fission.

- **A.** Hydrogen atoms are the "easiest" atoms to fuse because they are the simplest atoms.
  - **1.** Fusing four hydrogen atoms results in one helium atom, but the energy required to achieve fusion is enormous.
  - **2.** The hydrogen, for example, would have to be heated to approximately the same temperature as the core of the Sun, over 15 million degrees, and compressed. The difference in mass between the resulting helium atom and the four hydrogen atoms would manifest itself as energy.
- **B.** In 1938, Hans Bethe formulated a fusion-based theory of how stars produce their energy that finally gave us an understanding of how the universe is structured.
  - **1.** As a star collapses gravitationally, if it has enough mass, it will eventually become hot enough at the center to ignite a fusion reaction. That reaction will convert hydrogen to helium for as long as hydrogen is present.
  - **2.** When the hydrogen runs out, the star begins to collapse again, and its temperature increases again. Eventually, the helium begins to fuse into more complicated atoms.
  - **3.** At some point, the star can no longer resist gravitational collapse and explodes, spewing a complex combination of atoms created through the fusion process into interstellar space.
- **C.** In 1939, George Gamow speculated that Bethe's theory of how stars generate their energy explained the origin of the universe in his *Big Bang theory*.
- **D.** In the course of the atomic bomb project, Edward Teller, a Hungarian physicist working in Los Alamos, argued that an atomic bomb could be used as a trigger to explode a hydrogen bomb.
  - **1.** Immediately after the war, Oppenheimer and many of the physicists who had worked on the atomic bomb project were quite frightened by what they had created.

2. Teller, however, received Truman's approval to design a hydrogen bomb and did so with crucial assistance from Stanislaw Ulam, a Polish mathematician.
3. Teller also denounced Oppenheimer as a security risk, leading to a scandal that rocked the American physics community.

Essential Reading:

Daniel Kevles, *The Physicists: The History of a Scientific Community in Modern America.*

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century.*

Supplementary Reading:

Mary Jo Nye, *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940.*

Questions to Consider:

1. With the broad publication of research in nuclear physics from 1935–1939, was the atomic bomb inevitable? Was the hydrogen bomb? Is any application of a scientific theory?
2. Why has access to fission and fusion energy proven so problematic for us, given our long experience with the controlled release of chemical energy?
3. What insights into conceptual creativity can we derive from George Gamow's radical ideas of quantum "tunneling" in 1930 (see the next lecture) and the origin of the universe in 1939?

* *Clarification*: Slow neutrons do have an unexpectedly large probability of being captured by U-235 and U-238 nuclei, and this is key to the controlled fission of U-235 atoms in a nuclear power reactor, for example, and to transforming U-238 atoms into Plutonium-239. But only fast neutrons, with a lower capture probability, can generate the rapid chain reaction required by an atomic bomb.

Lecture Seven

Learning by Smashing

Scope: We return to QED in the 1930s and a survey of the experimental world that drove theory by building new kinds of machines that revealed aspects of matter and energy utterly unanticipated before the 20th century. The "atom-smashing" machines themselves are the "stars" of this part of the story.

Outline

I. A problem common to all atomic physicists in 1930 was the lack of a source of high-energy particles with which to bombard atoms of target materials, "smashing" them in order to see what they were made of.

   A. As early as 1919–1920, Ernest Rutherford had been calling for the invention of a machine that would provide a focusable beam of charged particles with which to "smash" target atoms. Radioactivity is not the optimal tool to use for this form of experimentation.

   B. The unit that physicists use to discuss the energy of particles is the *electron volt* (*ev*). The energy equivalent of the mass of an electron is about 500,000 ev; that of a proton is about 1000 Mev.

   C. Around 1930, John Cockcroft and Ernest Walton, in Rutherford's lab, designed an electrostatic proton accelerator, which resembled something out of an early science fiction film.

      1. This device built up significant charges of electrical energy and generated a spark, then accelerated those particles to achieve modest energies, initially less than 400,000 ev.
      2. In 1930, George Gamow published a textbook in which he identified a peculiar consequence of quantum mechanics. According to quantum theory, there is a small but nontrivial probability that a weak particle can get past an energy barrier in a phenomenon called *tunneling*. Thus, a proton accelerating at only 400,000 ev could tunnel into a nucleus.

   D. Several years earlier, Merle Tuve and Gregory Breit at the Carnegie Institution of Washington, D.C., built a particle accelerator that achieved 1 Mev, but the beam was too weak to be useful for research.

   E. In the early 1930s, Ernest O. Lawrence of the University of California at Berkeley emerged as the atom smasher *par excellence*.

      1. Lawrence adapted a design for a particle accelerator, called a *cyclotron*, from an idea proposed by a European electrical engineer, Rolf Wideröe. This device worked by periodically boosting a charged particle to accelerate it to higher and higher speeds.

2. The design took advantage of a principle called *resonance*, which is one of the most fundamental insights into nature achieved by modern science. *Resonance* is the selective transfer of energy between objects by exploiting periodicity.
3. The principle is similar to pushing a child on a swing. If you push gently but repeatedly at just the right moment, the heavy swing goes higher and higher.
4. It is because of resonance that all the C strings on the sounding board of a properly tuned piano vibrate when any one of them is struck, while the D string immediately adjacent to the struck C string does not vibrate at all.
5. Similarly, a radio or a TV receiver selectively absorbs and amplifies only the electromagnetic waves to which it is tuned, ignoring the myriad others that wash over the receiver's antenna.
6. The concept of resonance is central to any wave-like or periodic phenomenon.

II. In 1930, as a new Berkeley assistant professor, Lawrence directed two graduate students, David Sloan and M. Stanley Livingston, in building two different types of cyclotrons.

A. Lawrence's first machine was only 5 inches in diameter. Charged particles were injected at the center of this 5-inch disk and spiraled out to its circumference. The particles were periodically boosted with an electrical signal to accelerate them to higher velocities. The output was only 80 Kev.

B. In 1932, the team of Lawrence, Livingston, and Sloan scaled up the cyclotron to 11 inches and achieved 1 Mev.

C. By 1939, Lawrence's lab had a 60-inch-diameter cyclotron and had achieved a 10-Mev beam. The team also had a Rockefeller Foundation promise of $1.4 million to build a 184-inch machine that would reach 100 Mev. This accelerator was ultimately co-opted by the war effort.

1. Using the cyclotron at Lawrence's lab, Glenn Seaborg discovered the element plutonium, which was found to be, like uranium, ideally suited for the release of nuclear energy.
2. The cyclotron principle could also be used to separate weapons-grade uranium-235 from naturally occurring uranium-238.

D. At the end of the war, Lawrence's design was found to be flawed, because it did not take into account the special theory of relativity: As particles begin to approach a significant fraction of the speed of light, they behave as if they have enormous masses. More and more energy is required, then, to accelerate the particles further. The design of the cyclotron would have to be modified.

III. In 1946, a significant design advance led to retrofitting the 184-inch Berkeley cyclotron as a 195-Mev synchro-cyclotron, a machine that generated pulses of protons rather than a continuous beam.

A. Synchrotrons were able to create mesons in the lab. Suddenly, scientists were free from their dependence on cosmic rays to reveal the presence of mesons.

B. But cosmic rays were soon discovered to produce heavier particles than mesons, and more powerful machines were needed if the lab were to serve as a substitute for nature.

1. In 1952, at Brookhaven National Laboratory, a further design advance resulted in a 3-Gev (3 billion ev) machine called a Cosmotron. This device eliminated the spiral path of the cyclotron and kept the beam of charged particles traveling in a circle using powerful magnets. At two intervals in the circular path, the particles are given a pulse of energy to accelerate them further.
2. The Cosmotron was followed by a 6.2-Gev machine at Berkeley in 1954, called the Bevatron. This accelerator enabled discovery of the anti-proton, which had been predicted by Dirac in 1930.
3. The design of the Bevatron also opened the way to much higher energies by colliding contra-rotating beams: A prototype colliding-beam machine was built in 1965 as a Princeton-Stanford collaboration. This design became the standard in constructing particle accelerators.

IV. Before we close, we must note that particle accelerators are useless without detectors and information processing.

A. Luis Alvarez built a 72-inch bubble chamber as a detector for the Bevatron. It required a 3-million-watt power supply of its own. For the linear accelerator at Stanford, David Nygren worked for 10 years to build the time projection chamber, which is now standard equipment for all large particle accelerators.

B. Further, a typical particle accelerator "run" generates millions of events and vast quantities of data that must be analyzed by powerful computers.

C. A global particle accelerator race took place in the 1960s–1970s that pushed accelerator sizes and energies higher and higher. In the 1980s, FermiLab in the United States and the European Center for Nuclear Research (CERN) each had particle accelerators in the Tev (1 trillion ev) range. In late 1993, the United States essentially bowed out of the race when Congress cancelled funding for the Superconducting SuperCollider.

D. In 2002, CERN began an upgrade of its 1-Tev accelerator to a 7-Tev machine with a circumference of 27 km. This device will be just capable of "seeing" the Higgs boson, which we will discuss in a later lecture.

Supplementary Reading:

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

Frank Close, et al., *The Particle Odyssey: A Journey to the Heart of the Matter.*

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century.*

Questions to Consider:

1. Is there a kind of logical circularity implicit in using complex instruments designed in accordance with a theory to discover new realities independent of that theory?
2. Do powerful particle accelerators reveal reality or create artificial realities that reflect their own operation?
3. Why has the public in the United States and Western Europe, for more than 50 years, supported the very high costs of building and operating increasingly expensive particle accelerator–based research?

Lecture Eight

What Good Is QED?

Scope: Between 1929, when Dirac laid the foundation for QED, and 1964, when Gell-Mann and Zweig laid the foundation for its successor, quantum chromodynamics, quantum mechanics was intensively "used" as a theory in chemistry, as well as in physics. It guided the development of nuclear and subatomic physics and anchored a new theory of matter and the complex structure of nuclei. It played a central role in the theory and the application of fission and fusion. But it also played a central role in areas of physics and chemistry that, after World War II, drove technological innovations that transformed societies worldwide, among them, computers and lasers. In addition, QED became the basis for a new theory of chemical bonding that, by 2000, was fundamentally changing how chemists thought and worked and what they could do with matter and energy.

Outline

I. As we close our study of the "working" period of QED, we will take a look at its practical applications, as well as some philosophical issues that surrounded it. What was the quantum theory of the 1930s–1950s good for?

- **A.** Science has become a big-budget, heavily politicized institution, but its ultimate goal is still to understand natural phenomena. The goal of QED, at the deepest level, is to help us understand the ultimate constitution of matter and the relationship between matter and energy. The more specific goal is to identify a single comprehensive theory of matter and energy.
- **B.** QED does not yield this comprehensive theory. It gives us insight into the electromagnetic force but does not encompass the strong and weak forces or the force of gravity. A *theory of everything* (*TOE*) will unify these forces in one overall explanation.
- **C.** In the 1960s–1970s, as the Big Bang theory started to receive support among scientists, the atom smashers that had been built in the preceding years were recognized as time machines. These devices re-created conditions that existed in the universe in the first few moments after its violent birth.
  1. At that time, the total energy level of the universe was greater than the energies that we can replicate in any existing particle accelerator.
  2. The CERN accelerator that we discussed in the last lecture may be able to replicate conditions at about 10^{-12} seconds after the birth of the universe, when the Higgs boson existed.

   3. Particle accelerators are not used merely to destroy atoms and examine the resulting bits and pieces. They allow us to infer important information about the universe in which we live.

II. QED provoked a decades-long philosophical debate between Albert Einstein and Niels Bohr.

- **A.** From 1929–1953, Einstein and Bohr, along with many other scientists, engaged in a dialogue about the nature of the relationship between science and reality. What is the object of scientific theories?
  - **1.** According to Bohr, scientific theories tell us about our experience. According to Einstein, they tell us about an independently existing, external reality.
  - **2.** Einstein believed that our scientific theories "lift a corner of the veil" that separates us from seeing reality. Bohr believed that we can never lift the veil; we can interpret reality using only the concepts that come to our minds based on our experience.
- **B.** Einstein and Bohr also debated the principle of causality. Bohr believed that there is no causal theory of nature below the quantum level. Einstein recognized that quantum theory was accurate, but he believed that a causal and deterministic level lay underneath the predictions of quantum theory. Most physicists sided with Bohr.
- **C.** Finally, a third issue between Bohr and Einstein was whether the special theory of relativity was of universal applicability.
  - **1.** Remember that the special theory of relativity states that no signal can travel faster than the speed of light in a vacuum, but quantum theory seems to allow some kind of physical influence to propagate instantaneously.
  - **2.** Imagine that we measure the position of an electron at time 0. Then, we use quantum theory to calculate the probabilities for the position of the electron a short period of time later.
  - **3.** According to our results, there is a non-zero probability that the electron is near Jupiter, but according to the special theory of relativity, the electron cannot be near Jupiter because it cannot travel faster than the speed of light.
  - **4.** Whether these probability functions can be physically interpreted has been controversial since the mid-1920s.
- **D.** In 1935, Einstein co-authored a paper asserting that, according to quantum theory, a situation could exist in which one particle could influence another particle instantaneously. Einstein believed that this situation was absurd and, therefore, quantum theory was incomplete.
  - **1.** In the early 1950s, the Irish physicist John Bell reduced Einstein's thought experiment to an inequality equation. Thirty years later, a French physicist, Alain Aspect, translated Bell's inequality into a lab experiment and proved that quantum theory is correct: An influence on one of two particles created at the same time can have an instantaneous impact on the second particle.

  - **2.** In the year 2002, a team of physicists at the University of Vienna demonstrated a device based on this experiment that transmitted a quantum-encrypted signal across the River Danube.

III. We now turn from the philosophical to important practical applications of QED.

- **A.** As early as 1927, a number of the physicists who created quantum mechanics began applying it to the behavior of electrons in metals. In 1929, Felix Bloch, a student of Heisenberg's, discovered that in a material with a lattice structure, the energy states of the electrons were not the discrete states associated with orbital electrons, but a discrete set of continuous "bands" of energies.
  - **1.** In 1931, Alan Wilson, a British physicist studying with Bloch and Heisenberg, applied Bloch's band theory to semiconductors, characterizing them as insulators with a band gap that suitably excited electrons could cross. Others found that semiconductors came in two types—called *p-type* and *n-type*—and that odd things happened to currents at their junctions with one another.
  - **2.** In December of 1947, William Shockley, Walter Brattain, and John Bardeen, extending Wilson's semiconductor theory, created the first primitive transistor using a germanium crystal. In 1948, the improved device, using silicon, would revolutionize electronics and enable the computer age.
- **B.** In 1917 and 1918, Einstein and Bohr established the randomness of the emission and absorption of light quanta by individual orbital electrons.
  - **1.** In 1950, experiments showed that it was possible to "pump" electrons in certain substances "up" to an unstable, high-energy orbit around their nuclei, after which they spontaneously "fell" all at once to the same lower level, in the process emitting photons of exactly the same frequency because each had the same energy. Such a single-frequency beam of photons is called *coherent*.
  - **2.** In 1951, Columbia University professor Charles Townes put all these ideas together with his own idea of enclosing the substance he used, ammonia gas, in a resonant cavity. His invention successfully generated coherent beams of high-frequency microwave radiation, but it also, thanks to the resonant cavity, amplified them. Townes called the device a *maser*, short for "microwave amplification by the stimulated emission of radiation."
  - **3.** In 1958, Townes and Bell Labs physicist Arthur Schawlow published a detailed analysis of "optical masers," shortly after dubbed *lasers*, but it was a Hughes Research Labs physicist, Theodore Maiman, who built the first laser, using ruby crystals, in 1960.

C. Another application of QED is superconductivity, the complete disappearance of electrical resistance in a conductor at extremely low temperatures, typically between 4 and 8 degrees Kelvin.

  1. Explaining superconductivity turned out to be more difficult than expected, but in 1957, building on earlier ideas, John Bardeen, John Schrieffer, and Leon Cooper developed a quantum theory of ultra-low-temperature (below 30 degrees K) superconductivity that matched the experimental data and made predictions that were confirmed.
  2. Medical, military, and research applications followed, among them the superconducting magnets at FermiLab and CERN that dramatically increased accelerator beam energies.

D. We will look at the applications of QED in chemistry in another lecture, but here we should note the quantum mechanics–based theory of chemical bonds worked out by Linus Pauling, which in principle, allows scientists to calculate chemical reactions in advance of their occurrence.

Essential Reading:

Amir Aczel, *Entanglement: The Greatest Mystery in Physics.*

John Gribbin, *Schrödinger's Kittens and the Search for Reality.*

Abraham Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein.*

Questions to Consider:

1. Does the value of a scientific theory that improves our understanding increase because it has practical applications?
2. Was Einstein simply stubborn in refusing to accept the probability interpretation of quantum mechanics, or was he justified by the importance of the world view he was defending?
3. What must reality be like if the universe is internally connected in the ways suggested by Alain Aspect's photon entanglement experiments?

Lecture Nine

The Newest Theory—Quantum Chromodynamics

Scope: By the 1960s, the number of "elementary" subatomic particles created by ever-more powerful particle accelerators was in the hundreds and the need for a unifying theory was pressing. Concurrently, new experiments suggested the need to extend QED to explain new phenomena. The result was a quantum theory of matter and energy, named *quantum chromodynamics* (*QCD*), which reduced all material particles to one of two elementary types and dropped protons and neutrons from the ranks of elementary particles. Electrons survive as elementary particles, now as members of a family of six particles called *leptons*, three carrying whole negative electric charges, each with its own type of neutrino. Protons, neutrons, and the host of once "elementary" particles are members of a family called *hadrons* and are composed of various combinations of six truly elementary particles called *quarks* and *anti-quarks*, bound by mass-less particles called *gluons*. The story of QCD is fascinating even by the standards of quantum theory!

Outline

I. In the late 1940s, Schwinger, Feynman, and Tomonaga, working independently, had put QED on a much firmer mathematical foundation, accounting for the infinities found in mathematical calculations of the theory through *renormalization.*

  A. In 1953, Abraham Pais and Murray Gell-Mann reviewed the state of quantum theory and reached the conclusion that four forces seemed to be responsible for all physical phenomena at the most fundamental level of nature: the gravitational force; the electromagnetic force; the *weak* force associated with nuclear processes, such as the decay of the neutron into a proton, electron, and neutrino; and the *strong* force that held the nucleus together. Unifying these forces with one theory became a goal for physics in the late 1950s.

  B. At this point, physics had a theory of the electromagnetic force, namely, QED, as well as a patched-together theory of the weak force, covered by Fermi's theory of beta decay. The gravitational force was not considered at the atomic level, but still, physics did not have a theory to explain the strong force.

II. In the late 1950s and early 1960s, because of the explosive growth in the power of particle accelerators, the number of "elementary" particles had reached more than 200, which seemed ridiculous to physicists.

  A. Murray Gell-Mann and, independently, Israeli physicist Yuval Ne'eman devised an elegant system for organizing these particles into eight families. Gell-Mann called this system the *Eightfold Way*, after the Buddhist doctrine of virtue.

B. Gell-Mann and Ne'eman predicted the existence and properties of a particle that had not yet been detected; this particle would be the last member of one of their 10-member particle families.

C. A short time later, the particle was found in the Cosmotron accelerator at Brookhaven National Laboratory. Gell-Mann named the particle *omega*, after the biblical reference to God as first and last, in Greek, as *alpha* and *omega*.

III. Between 1962 and 1964, Gell-Mann at Caltech and, independently, George Zweig at CERN, proposed a new theory of the strong force, in which protons and neutrons are not elementary particles.

A. From the 1930s, physicists already knew that the neutron is, at best, an unstable particle, because it disintegrates outside the nucleus. In the 1960s, particle accelerators, especially the linear accelerator at Stanford University (SLAC), were "smashing" electrons into protons, and the protons were also disintegrating!

1. The Gell-Mann/Zweig proposal was that matter is composed of two types of particles: *leptons*, the family of particles to which electrons and neutrinos belong (which respond only to the electromagnetic and weak forces), and *hadrons*, which is the family that includes everything else. All hadrons are made of combinations of *quarks*. Quarks are held together by *gluons*, of which there are eight.

2. In 1964, the mathematician Oscar Greenberg realized that gluons had to be categorized into one of three different *color charges*.

B. Initially, Gell-Mann proposed three quarks, named *up*, *down*, and *strange*.

1. The up and down quarks, together with electrons, fully account for the behavior of ordinary matter in ordinary physical and chemical interactions.

2. When the energy levels get high enough, however, such as in stars, black holes, cosmic ray collisions, and at the birth of the universe, then strange quarks come into play.

C. The apparent whimsicality of the names in this new theory, *quantum chromodynamics* (QCD), is a deliberate attempt to avoid a problem that plagued "old" quantum theory and QED. Applying classical-physics names to quantum-level descriptions unconsciously led to thinking classically and inappropriately about quantum-level phenomena classically. Whimsical names force a recognition that the quantum level of reality is beyond our experience.

IV. Quarks are peculiar particles.

A. Quarks have mass, *spin*, and fractional charge. Quarks and anti-quarks, unlike matter and antimatter, combine constructively, not destructively. Quarks are also *much* smaller and *much* lighter than protons and neutrons. Where, then, does their mass come from?

1. Quarks move so rapidly that relativity comes into play, and particles made of quarks—protons, for example—seem to have more mass than they actually do.

2. We must uncouple, in our minds, the concepts of mass and solidity.

B. In 1973, Burton Richter at SLAC and Samuel Ting at Brookhaven independently discovered a fourth quark, named *charm*. In 1977, Leon Lederman at FermiLab discovered a fifth, named *bottom*. QCD required that if there were five quarks, then there must be a sixth, which would be called *top*.

C. It took 18 years and major upgrades to the particle accelerators at FermiLab and CERN to discover the top quark. By 1995, the accelerator at FermiLab had reached 1.8 Tev.

1. The team at FermiLab had to examine 16 million collision events to identify a handful of top resonances. Although the results were announced in 1995, the data had been collected two years earlier.

2. It is worth noting that the FermiLab team involved in this discovery consisted of 440 physicists, mathematicians, computer scientists, and engineers from 35 institutions in a dozen countries.

D. The announcement of the top quark in 1995 completed QCD. From 1964, when this theory of the strong force was first proposed, to the end of the 20th century, the theory has resisted all challenges that have been mounted against it.

1. This is not to say that QCD is without problems. For example, the question of whether or not the neutrino has mass has provoked some controversy, and QCD has been unable to explain the fact that this particle does, indeed, have some mass.

2. Nevertheless, by the end of the 20th century, QCD could be used as a platform on which to attempt unification. As we will see in our next lecture, this attempt had actually begun in the 1960s, in parallel with the development of QCD.

Essential Reading:

Murray Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and the Complex*.

Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics*.

Martin Rees, *Just Six Numbers: The Deep Forces That Shape the Universe*.

Supplementary Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Questions to Consider:

1. Who decides how many particles can be "elementary" and on what grounds?
2. What lessons are there in the whimsical names used in QCD for how our thinking can mislead us when reasoning about new situations?
3. We've seen how mathematics can reveal new aspects of physical reality, but how can simple classification schemes, like the Gell-Mann/Ne'eman Eightfold Way (or Mendeleev's periodic table), have predictive power?

Lecture Ten

Unifying Nature

Scope: Between 1964 and 2000, three of the four fundamental natural forces identified by Pais and Gell-Mann as implicit in QED were successfully united in what is called the *standard model* of quantum theory, which links physics today to the physics of the early universe. The fourth force, gravity, has resisted integration into a single theoretical framework with the other three. Physicists are pursuing the unification of the general theory of relativity and the Standard Model into a quantum theory of gravity. In the process, models of nature have been generated that seem too fanciful even for science fiction but are highly provocative intellectually: for example, suggesting that our conception of the universe today may be as narrow as Copernicus's was in his time or that the entire vast universe derives from a "pocketful" of negative vacuum energy and is an information structure!

Outline

I. This lecture explores the attempts in the last decades of the 20th century to unify the theories explaining the four fundamental forces of nature.
   A. The goal of these attempts is to unify the forces in a way that is physically real. Physicists are trying to trace these four forces back to a single "mother force" in the universe that underwent a series of collapses, resulting in the strong, weak, electromagnetic, and gravitational forces.
   B. An analogy can be made with steam, which as a gas, operates under a certain set of laws. As the steam cools, it becomes water, which operates under a different set of laws. If the water cools further, it may freeze and become ice, operating under a third set of laws.
   C. Unification theorists are looking for a single original force in the universe that has undergone similar *phase transitions* to become the four forces that we know today.
      1. At some point, it is postulated that the universe had a certain high energy level operating under the laws of a single force. Then, as the universe cooled, it went through a series of phase transitions and the forces that we know today "froze out."
      2. For example, gravity separated at approximately 10^{-43} seconds after the Big Bang, but the other forces were still subsumed under the single force.

II. In the 1950s, Schwinger, Pakistani physicist Abdus Salam, and British physicist John Ward tried to unify the weak and electromagnetic forces.

A. QED—the theory of the electromagnetic force—and the weak force are natural allies because they are both associated with electrons. This first attempt at unification, however, was premature and did not succeed.

B. In 1961, Harvard physicist Sheldon Glashow revisited the work of Schwinger, Salam, and Ward and creatively reformulated it to predict the existence of a carrier of the weak force.

  1. As we've discussed, in quantum theory, every force must have a carrier. The photon, for example, is the carrier of the electromagnetic force. The gluon is the carrier of the force that holds hadrons together. The *graviton* is the projected carrier of the gravitational force.

  2. As the carrier of the weak force, Glashow proposed a family of three particles called *intermediate vector bosons* (*IVBs*). One would have a positive charge, one would have a negative charge, and one would be electrically neutral; all three would have mass.

C. Over the next 10 years, this unification approach was developed further by Glashow and the American Steven Weinberg, by Salam, by the British physicist Peter Higgs, and by the Dutch physicist Gerardus t'Hooft. Glashow, Salam, and Weinberg used three concepts in particular for their formulation of the *electro-weak theory*, for which they shared a Nobel Prize.

  1. The first of these is a mathematical requirement of scale, or as it is called *gauge*, invariance, introduced in 1918 by Herman Weyl in an unsuccessful attempt to unify the general theory of relativity and classical electrodynamics. As a rule, when the scale changes in an equation, the laws of physics do not change. Unification theories are required by physicists to be scale invariant.

  2. The second technique used by Glashow, Salam, and Weinberg was a 19th-century abstract mathematical invention called *group theory*. Unification theorists invent groups with mathematical properties that parallel the physical relationships that would solve their problems, then look at the empirical data to see if they fit!

  3. The third concept used by unification theorists is *spontaneous symmetry breaking*.

    a. At its most fundamental level, nature is assumed to be simple and symmetrical. Asymmetries arise because something has disturbed the underlying symmetry.

    b. In 1961, the Japanese physicist Yoichiro Nambu postulated spontaneous symmetry breaking in an attempt to develop a new theory of superconductivity. Weinberg and Salam incorporated this idea into electro-weak unification. In this view, photons and IVBs become the asymmetric "debris" of the collapse of an earlier force.

D. What is this earlier force, out of which photons and IVBs are thought to have come into a separate existence? This earlier energy state is called the *Higgs field* and its carrier is the *Higgs boson.*

  1. The Higgs field and its carrier, if real, are pivotal to the unification of the fundamental forces of nature.

  2. The interaction of hadrons with the Higgs field may explain why hadrons have mass. This same line of thinking may also be applied to lepton mass. Mass itself may be an energy interaction with the Higgs field.

  3. When the CERN particle accelerator returns to operation in 2006, it should have enough energy (7 Tev) to find the Higgs boson.

III. The unification of the electro-weak theory and QCD in the 1980s came to be called the *standard model* of matter-energy.

A. This framework is the realization of Max Planck's tentative hypothesis, formulated in December 1900, that the absorption and emission of electromagnetic radiation is discrete, not continuous.

B. By the end of the century, the idea that natural processes are discrete has flowered into a comprehensive theory of matter and energy that allows us to give satisfying theoretical accounts of the universe, beginning minute fractions of a second after the Big Bang.

IV. The most exciting prospect for many physicists is the possibility of extending the standard model, which unites QCD and electro-weak theory, to a quantum theory of gravity.

A. This would be a theory that unites all four known forces of nature, either by assimilating the general theory of relativity into the standard model or by replacing the general theory of relativity with a better theory of gravity. These attempts at unification are called *supersymmetry theories*.

B. Such a unification would identify the original symmetric state of the universe that spontaneously "broke," perhaps only 10^{-43} seconds after the Big Bang, into the gravitational force field and the unified force field underlying the standard model, then broke again and again to form the weak, strong, and electromagnetic forces that determine all "ordinary" phenomena in the universe today.

C. In the 1980s–1990s, two supersymmetry theories arose: *string theory* and *loop theory*.

  1. It is tempting to wonder if these two "rival" approaches will turn out to be mathematically equivalent, as with wave and matrix mechanics.

  2. In both of these theories, the ultimate physical reality is a structure, built of either minute multidimensional loops or multidimensional strings. In both theories, in the instant after the Big Bang, the universe had 10 dimensions, but these collapsed to 3 dimensions as the universe cooled.

D. Another group of theorists has defined a third supersymmetry approach. The distinctive contribution of this approach is the identification of the reality behind gravity and the standard model with process and relationships, not as a "thing" with properties.

   1. These theorists draw inspiration from the work of Stephen Hawking and Jakob Bekenstein on the nature of black holes.

   2. Bekenstein, especially, forced a recognition that black holes had complex properties that were properly identified with the concept of *entropy*, defined as a measure of information. Thus, this third group of theorists interprets the universe as an information structure.

   3. Earlier, we acknowledged that energy is "real" and that the universe may "be" energy. Could information be "real" in the same sense? Could the universe "be" information? Is it possible that our universe is a cosmic Burma Shave sign in some far greater scheme of things?

Essential Reading:

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

Stephen Hawking, *A Brief History of Time.*

Lee Smolin, *Three Roads to Quantum Gravity.*

Supplementary Reading:

Lee Smolin, *The Life of the Cosmos.*

Questions to Consider:

1. How will our thinking about physical reality have to change if, as expected, the Higgs boson is detected at CERN and mass, the most fundamental feature of ordinary experience, is explained away as an effect of the Higgs field?
2. What's left for physicists to explain if they succeed in formulating a quantum theory of gravity, thus unifying the four forces of nature?
3. Are physicists going too far in postulating that the ultimate structure of the universe, hence all physical reality, is *information*, that is, no *thing* at all?

Lecture Eleven

Chemists Become Designers

Scope: In the course of the 20th century, chemistry has evolved into a more theory-based science, especially mathematics and quantum theory–based, and a science exemplary of cross-disciplinary fertilization. The evolution of chemical bonding theories from 1900 to 2000 includes the triumph of the atomic theory of matter early in the century, the assimilation of quantum theory by chemists in the mid-century, and with access to late-20th-century supercomputers, a growing ability to predict the properties of molecules before they are produced and to produce to order a range of new kinds of "artificial" molecules with properties specified in advance. The implications of this capability are profound for genetic engineering, pharmaceuticals, and the nascent nanotechnology industry, as well as for the manipulation of matter generally in all forms of manufacturing, including the continued miniaturization of sensors and computer components.

Outline

I. In this lecture, we take a short step away from quantum physics to explore the science of chemistry.

A. The essence of chemistry is the study of the way that atoms form molecules and the way that molecules interact with one another. In turn, chemical reactions are determined by the behavior of orbital electrons at the outermost level of the atom.

B. Quantum theory is naturally applied to chemistry, then, because it originated in attempts to understand the behavior of orbital electrons.

C. Indeed, in the 1930s, Linus Pauling developed a quantum mechanics–based theory of the chemical bond, which became dominant after his 1940 text.

   1. In this theory, Pauling described two kinds of bonds: "weak," or *ionic* bonds, in which an electron is transferred from one atom to another, and "strong," or *covalent* bonds, in which an electron is shared between two atoms.

   2. Using quantum theory, Pauling described the conditions in which electrons form ionic and covalent bonds, depending on the energies of the outermost orbital electrons.

II. Let's begin by looking at some highlights of chemistry over the course of the 20th century.

A. Unlike physics, chemistry in 1900 had very little mathematical theory associated with it.

1. Chemists used thermodynamics to account for energy transfer in chemical reactions. Chemists had also discovered that chemical reactions have a precise quantitative character. These applications of mathematics, however, were relatively modest.
2. Explanations of molecular structure and chemical reactions were empirical and descriptive.
3. But chemists could do a great deal with their knowledge that was of practical commercial value, as evidenced by the spin-off in 1900 of chemical engineering from chemistry and strong industry support of chemical research.

B. Chemistry made a real difference in life.

1. By 1900, chemistry had created the artificial dye, pharmaceutical, explosives, and cellulose-based synthetics industries.
2. Soon after 1900, Fritz Haber's synthesis of ammonia from atmospheric nitrogen created the artificial fertilizer industry and eliminated the need for natural saltpeter in the manufacture of explosives.
3. Bakelite was synthesized in 1907 by Columbia University chemical engineering professor Leo Baekeland, and the plastics industry was born around resin-based materials.
4. The commercial production of synthetic rubber began in 1910. In 1935, nylon was developed by a DuPont research chemist, and at the same time, the first synthetic drugs, called *sulfa drugs*, were invented by the German chemist Gerhard Domagk. This development played a significant role in shifting Western medicine away from a homeopathic model to allopathic therapies.

C. A laundry list of the impact of chemistry on 20th-century life can be fascinating, but our focus is on the organizing ideas of the sciences and how they changed from 1900 to 2000. In chemistry, we particularly see the impact of developments and ideas from physics.

1. One major development in physics that was applied to chemistry was the technique of X-ray crystallography. First proposed in 1912 by Max von Laue, X-ray crystallography, in the 1920s, became a tool for identifying the molecular structure of any substance that could be crystallized. In 1953, X-ray crystallography data revealed the molecular structure of DNA.
2. A second important tool developed in physics but used in chemistry was the mass spectrometer, which has some similarities to the cyclotron. This device enables chemists to measure molecular weights. Interestingly, the mass spectrometer was invented to prove the existence of isotopes.
3. Perhaps the most familiar tool for chemists, introduced in the 1940s, was chromatography. This technique allows chemists to identify the constituent molecular groups in complex molecules.

4. The most exciting development may be spectroscopic instruments that allow chemists to "see" chemical reactions at the atomic level in real time. Until the 1960s, chemists could observe reactions on time scales of seconds to, in a few cases, milliseconds. In the 1960s, using lasers, it became possible to observe reactions on the nanosecond level. In the 1980s, *femtosecond* spectroscopy was introduced, which allows chemists to watch reactions on a time scale of 10^{-15} seconds.

D. Chemists carried many of these techniques into biology, and in the course of the 20th century, biology became increasingly centered on biochemistry. At the same time, biology also assimilated the tools and ideas of physics that had come to be part of chemistry.

1. In 1900, one of the theories that dominated biological thinking was *colloid theory*, which asserted that organic molecules were relatively short but could be linked into weak chains. In 1920, Hermann Staudinger proposed a rival theory of very long, rigid *macromolecules*; Hermann Mark later determined that Staudinger was correct about the existence of macromolecules but mistaken about their rigidity.
2. The controversy that Staudinger sparked was resolved by the ultracentrifuge, an instrument invented by Theo Svedbrg in the late 1920s. The instrument showed that hemoglobin, the first molecule examined, contained 66,000 atoms.
3. This discovery was pivotal to the growth of polymer chemistry and our understanding of proteins.

III. All these changes were supported by another family of instruments, beginning in 1931 with the invention of the electron microscope.

A. The electron microscope was improved between 1931 and 1960 and eventually achieved high resolutions but only in two dimensions. Further, the electron microscope could not image biological materials.

B. In 1981, the scanning tunneling microscope (STM) was invented, which took advantage of quantum theory. In 1986 and 1987, further development of the STM led to the atomic force microscope, which is capable of imaging a single atom in three dimensions and can image biological materials.

C. As we close, we return to quantum theory. Computers have now become powerful enough that they can solve the complex quantum mechanical equations associated with multiple atoms sharing electron bonds in complex three-dimensional configurations.

1. By the end of the 20th century, supercomputers were able to model meaningful chemical reactions; thus, quantum chemistry became a subdiscipline that allows calculation of properties of molecules before the molecules are actually created.

2. The implications of this ability to create *designer molecules* for pharmaceuticals and other areas of science and industry are tremendous.

Essential Reading:

Philip Ball, *Designing the Molecular World.*

Trevor Levere, *Transforming Matter: A History of Chemistry from Alchemy to the Buckyball.*

Supplementary Reading:

Mary Jo Nye, *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940.*

Questions to Consider:

1. Why was chemistry, unlike physics, able to develop into a mature science with very little use of abstract mathematics?
2. Considering that chemists first called attention to the precise spatial organization of atoms as a cause of molecular properties, why was there so much opposition by chemists to precise structure when applied to macromolecules, such as proteins and polymers?
3. Was it scientific for chemists to believe in the reality of the atom for 150 years before the scanning tunneling and atomic force microscopes made atoms visible? Do we actually "see" atoms in these instruments?

Lecture Twelve

Mathematics and Truth

Scope: The general theory of relativity and quantum theory played central roles in the evolution of our conception of the universe between the early 1920s and 2000. But before describing that evolution, it is worth taking some time to appreciate a characteristic of 20th-century science that has been an obstacle to public appreciation of it: the forbidding mathematical language of its theories. The publicity surrounding the "confirmation" of the general theory of relativity made much of the incomprehensibility, even to non-specialist scientists, of this new theory because of its highly abstract mathematics. This was certainly true of the rapidly developing quantum theory, and soon, complex forms of mathematics were essential to the practice of chemistry, biology, psychology, sociology, economics, and even linguistics. Why? What gives mathematics this power? How can mathematical abstractions tell us anything about concrete experience? As we have seen, scientists repeatedly deduce new experiences from mathematical models, which suggests that reality is, in some sense, mathematical.

Outline

I. This is the first of two lectures on the role of mathematics in the sciences.

    A. One of the characteristics of science in the 20th century is that it became increasingly mathematical.

    B. Mathematics is, in a sense, responsible for a disturbing development in the sciences. The practice of science was traditionally open and democratic, but by the late 1800s, physical science had taken on the characteristics of an esoteric cult, because of mathematics.

    C. This lecture is structured around two ideas: mathematics as the language of science and mathematics as the language of right reasoning.

II. We begin with mathematics as the language of science.

    A. Galileo said that nature is, fundamentally, mathematical, so that when you use mathematics in science, you are speaking the language of nature. For this reason, mathematical theories in science are true; they are, in some sense, an image of the underlying structure of reality.

    B. Even in the 17th century, there was considerable controversy over what role mathematics should play in the sciences. Descartes argued strongly for the use of mathematics as the core of natural science. Francis Bacon, in contrast, was suspicious of mathematics.

    C. This controversy was resolved in favor of mathematics with the work of Newton and Leibniz. In the 19th century, this issue was revived in the question: What is the connection between mathematical models and reality? Some physicists argued that the fact that mathematics makes accurate predictions about nature means that the two are connected. We have seen several examples of this in the history of quantum theory.

III. Mathematics also has a long history of association with the notion of right reasoning. The discovery of non-Euclidean geometries in the mid-19th century severed the necessary connection between deductive reasoning and reality. Again, scientists were faced with the question: What is the connection between mathematical truth and physical reality?

IV. This question became real for scientists at the end of the 19th century, but it also became an issue for mathematicians. What is the basis of mathematical truth?

A. In the wake of non-Euclidean geometry, set theory, symbolic logic, and other 19th-century developments, mathematicians experienced a crisis of confidence. Three schools of thought emerged to address the questioning of mathematics: *logicism*, *formalism*, and *intuitionism*.

B. At the end of the 19th century, Gottlob Frege embarked on a project to reduce arithmetic to logic.

1. Frege argued that arithmetic and geometry were the "elementary" branches of mathematics from which all others derived, and he attempted to reduce arithmetic to a system of purely logical laws and definitions.
2. Frege's reduction of arithmetic to logic was revealed by Bertrand Russell to contain a flaw that undermined Frege's entire project, and Frege abandoned it.
3. Russell, together with Alfred North Whitehead, then attempted an even bolder reduction of *all* of mathematics to logic. This effort, in spite of improvements made by others in the 1920s, is not convincing.
4. Thus, the attempt to reduce mathematics to logic fails. Mathematics is its own branch of knowledge.

C. David Hilbert's formalist interpretation of mathematics made mathematics into a kind of logic game, one in which mathematicians freely invented such terms as *number*, *point*, *line*, *triangle*, *function*, and so on, then explored the logical consequences of these terms in various combinations according to specified rules, for example, addition and multiplication, with these rules also freely invented.

1. For Hilbert, mathematics has no necessary connection at all to anything outside itself and no meaning outside of itself. It is an empirical fact that some mathematical expressions in their logical structure emulate natural processes and that scientists choose to associate these expressions with "laws" of nature.

2. At a mathematics conference in Paris in 1900, Hilbert challenged the world's mathematicians to solve a collection of 23 problems that he considered of critical importance. Two of these are of particular interest to us: (a) to show that mathematics is consistent and complete and (b) to show that mathematics includes an effective decision procedure for solving any problem.
3. In the 1930s, proofs that neither of these can be shown to be true were of profound intellectual and scientific significance.

D. Finally, an "intuitionist" interpretation of mathematics was championed by Dutch mathematician Luitzen Brouwer. This interpretation is of interest here, because it illustrates that what was at issue early in the 20th century was not mathematics *per se*, but reasoning itself.

1. Brouwer's view challenged 2400 years of Western intellectual history. He believed that mathematics is an example of the mind imposing order on experience. There is no necessary connection between mathematics and reality.
2. For Brouwer, mathematical reasoning is fundamentally intuitive. We intuit the kinds of mathematical relationships that will be useful and interesting, then we explore them logically.
3. The main difference between Brouwer and Hilbert is that Brouwer argued that the *law of contradiction* is not a valid logical law; it is merely an empirical law. A double negative does not necessarily imply a positive. This assertion changes the character of mathematics.

Essential Reading:

John Casti, *Five Golden Rules: Great Theories of 20th-Century Mathematics—and Why They Matter.*

Stuart Shapiro, *Thinking about Mathematics: The Philosophy of Mathematics.*

Benjamin Yandell, *The Honors Class: Hilbert's Problems and Their Solvers.*

Questions to Consider:

1. Why do we attribute such high value to deductive reasoning when inductive reasoning is the only kind we can apply to ordinary experience?
2. If the basis of truth claims is unclear in mathematics, what should we think of truth claims in science, which is so dependent on the use of mathematics?
3. Which is primary, logic or mathematics? Is truth a matter of logic or of correlation with experience or correspondence with reality?

Timeline

1900	Max Planck's quantum hypothesis. Recovery of Mendel's research on discrete inheritance. David Hilbert's first challenge to the world's mathematicians. Freud's *Interpretation of Dreams* published.
1903	William Bateson coins term *genetics*. Marie Curie calculates magnitude of energy released by radium. Fritz Haber announces process for making ammonia from atmospheric nitrogen.
1905	Special theory of relativity. Einstein's photoelectric effect paper founds quantum physics; Brownian motion paper convinces many physicists that atoms are real. Russo-Japanese War: Japan a world power.
1907	Bateson coins term *gene*. Pareto publishes his theory of society/economy. Creation of Bakelite, launching plastics industry. Emil Fischer shows that proteins are combinations of amino acids.
1908	First nearly complete Neandertal skeleton unearthed.
1909	Gene recombination identified as source of variability for evolution.
1910	T. H. Morgan converted to gene theory by fruit fly research. Rutherford's "solar system" model of atom. Synthetic rubber and rayon.
1912	Bohr's quantum theory of atom. von Laue predicts X-ray crystallography.
1913	Charles Beard's *Economic Interpretation of the U.S. Constitution.* Henrietta Leavitt announces cosmic "yardstick." First absolute geological time scale. John Watson founds behavioral psychology.
1914	World War I; German intellectuals publish "Declaration to the Civilized World."
1915	General theory of relativity. Wegener's continental drift theory.
1916	Ferdinand de Saussure's "Course in General Linguistics" published posthumously by his students. Harlow Shapley announces first cosmic distance: 400,000 light years to Large Magellanic Cloud.
1918	World War I ends.
1919	Confirmation of general theory of relativity's prediction of bending of light rays. Mt. Wilson Observatory 100-inch telescope becomes operational observatory.
1920	Harlow Shapley defends Milky Way as only galaxy in public debate.
1923	Louis de Broglie predicts matter waves if the special theory of relativity and quantum theory are correct. *Scopes* trial in Tennessee ends in conviction.
1924	Edwin Hubble announces Andromeda "nebula" is a galaxy, and thousands more galaxies are out there.
1925	Erwin Schrödinger and Werner Heisenberg create quantum mechanics.
1927	Heisenberg's uncertainty principle. First artificial mutations induced by radiation.

1929	Hubble announces expanding universe. Copenhagen interpretation of quantum mechanics. Dirac combines the special theory of relativity and quantum mechanics, leading to the creation of quantum electrodynamics. New York Stock Exchange crash; global depression begins.
1930	Dirac predicts existence of anti-electron/positron. Pauli predicts existence of neutrino to explain beta decay. Population genetics theory formalized, reviving Darwinism.
1931	Cockcroft and Walton achieve first artificial transmutation of one element into another. Lawrence team builds first cyclotron. Gödel's proof published. Electron microscope invented.
1932	Carl Anderson discovers Dirac's positron. James Chadwick discovers neutron. Blackett and Occhialini confirm energy can become matter.
1935	Sulfonamide drugs invented. Nylon invented. Radiotelescopy invented by Karl Jansky.
1936	J. M. Keynes publishes his *General Theory*. Quantum theory of nucleus founds nuclear physics. Nuclear fission research frenzy. Turing's proof; conceptual design of computer.
1938	Bethe's fusion theory of stellar energy. B. F. Skinner revives behaviorism against Gestalt psychology, psychoanalysis.
1939	Fission of uranium with great energy release announced. Gamow's initial Big Bang hypothesis. World War II begins.
1940	Vannevar Bush convinces Roosevelt to create the National Defense Research Council, which becomes the Organization for Scientific Research and Development when the United States declares war. Linus Pauling's chemical bond theory published.
1942	Manhattan Project created. Enrico Fermi-led team builds first nuclear reactor. First of 10 annual Josiah Macy Foundation conferences. McCulloch and Pitts propose electrical model of neurons.
1943	Game theory introduced.
1944	Oswald Avery shows DNA basis of heredity. Turing publishes *Machine Intelligence*.
1945	Germany surrenders (May). "Trinity" A-bomb test, Alamogordo, New Mexico (July). Hiroshima and Nagasaki A-bombs (Aug.). Japan surrenders (Aug.). ENIAC becomes operational.
1946	QED problems resolved by Schwinger, Feyman, Tomonaga.
1947	Radiocarbon 14 dating method invented by Willard Libby. Complete molecular structure of insulin determined.
1948	Invention of transistor. Norbert Wiener's *Cybernetics* published. Shannon/Weaver information/communication theory. Hoyle-Bondi-Gold propose the Steady State theory of the universe.
1949	EDVAC, first stored-program electronic computer. Wiener predicts microwave background radiation. Palomar 200-inch telescope becomes operational.
1950	National Science Foundation created.

1951	Invention of maser. Pauling determines helical structure of protein molecules.
1952	Twenty European nations form joint Center for European Nuclear Research.
1953	Watson and Crick announce double-helix structure of DNA.
1954	Berkeley Bevatron reaches 6.2-GeV energy, discovers anti-proton.
1956	First artificial intelligence conference.
1957	Sputniks 1 and 2 orbit Earth. Mechanism of DNA replication revealed. Noam Chomsky's *Syntactic Structures* published.
1958	First U.S. satellites; discovery of Van Allen radiation belts. Quasars detected.
1959	First neural net computer, Perceptron.
1960	Invention of laser. Transit, Tiros, Echostar orbital satellites. President Eisenhower warns of military-industrial complex.
1962	Gell-Mann and Ne'eman's Eightfold Way classification of elementary particles. Penzias and Wilson detect microwave background radiation. Rachel Carson's *Silent Spring* published. Thomas Kuhn's *The Structure of Scientific Revolutions*.
1963	MIT AI lab founded.
1964	Gell-Mann and Zweig announce three-quark theory of matter, founding QCD.
1966	Tanzania's Olduvai Gorge excavations reveal antiquity of human lineage and culture.
1967	The United States creates FermiLab national particle accelerator research center. First chess-playing program.
1968	Plate tectonics theory becomes mainstream geology.
1969	First Apollo moon landing. Environmental Protection Agency created. Clean Air and Water Acts passed.
1970	First black hole candidate detected, Cygnus X-1.
1971	Electro-weak theory proposed.
1972	First Landsat satellite orbited. First recombinant DNA experiment First commercial CAT-scanning machine.
1973	Fourth quark discovered by B. Richter and by S. Ting. Mariner space probe to Mercury.
1974	"Lucy" skeleton unearthed in east Africa, crystallizing the out-of-Africa hypothesis of human origins.
1976	Viking probes land on Mars.
1977	Fifth quark discovered by Leon Lederman. Voyager 1 and 2 space probes launched to outer planets. Mid-ocean thermal vents discovered.
1978	Pioneer space probe to Venus.
1979	Luis Alvarez proposes collision theory of dinosaur extinction.
1980	Alan Guth proposes cosmological inflation theory.
1981	Scanning tunneling microscope invented, atoms imaged. First commercial MRI machine.
1982	FDA approves recombinant DNA insulin from bacteria.
1983	Electro-weak theory confirmed by discovery of predicted intermediate vector bosons. First monoclonal antibody approved by FDA.

1985	PCR method for mass replication of DNA invented. Recombinant Human Growth Hormone approved.
1988	Atomic force microscope invented: three-dimensional atomic images.
1989	Human Genome Project announced.
1990	Hubble Space Telescope orbited.
1991	*Homo erectus* bones found in Republic of Georgia.
1994	U.S. Congress cancels Superconducting SuperCollider.
1995	Sixth quark discovered.
1997	Deep Blue chess computer defeats Gary Kasparov.
1998	Acceleration of universe's expansion announced.
2000	Keck telescope observes transit of planet 153 light years away. Human Genome Project successfully completed.
2002	NASA LIGO gravity wave telescope operational.
2003	NASA Space Infra-Red Telescope Facility orbited.

Glossary

Aether: The name given by 19th-century physicists to a cosmic space-filling substance that served as the medium in which light waves traveled. The special theory of relativity and the quantum theory made the aether unnecessary.

Amino acids: The building blocks of proteins, amino acids are organic molecules that can form short or long chains, called *peptides* and *polypeptides*, respectively.

Angiogram: X-ray photographs of blood vessels, whose soft tissue is ordinarily transparent to X-rays, made by injecting a substance opaque to radiation.

Atomic number: The number of protons in the nucleus of an atom, unique to each element.

Atomic weight: The total number of protons plus neutrons in the nucleus of an atom.

ATP: Adenosine triphosphate, a protein that is the key source of chemical energy in all organisms.

Aurignacean: The name given by archaeologists to the forms of culture exhibited by early humans, predominantly Neandertals, from about 400,000 B.C.E. to 50,000 B.C.E.

Autocatalytic: In chemistry, a reaction caused by the products of a catalytic reaction but also applied to self-organizing and complex systems in which nonequilibrium is sustained by the products of the systems' own activity.

Baryon: Particles that respond to the strong force, contained in the nuclei of atoms; thus, in the standard model, all of the particles composed of combinations of three quarks held together by gluons, especially protons and neutrons.

Biologicals: Biologically based products that provide immunity to disease.

Blackbody: A term used by physicists to describe an object that absorbs all of the electromagnetic radiation, of whatever frequency, that is incident upon it.

Brownian motion: The erratic, random motion displayed by minute particles suspended in a fluid, the cause being the random motions of the atoms or molecules in the fluid.

Bubble chamber: An instrument invented by Donald Glaser in 1952 for revealing visual evidence of high-energy "elementary" particles created in particle accelerator collisions.

Buckyballs: Colloquial for buckminsterfullerene, a roughly soccer ball–shaped molecule of 60 carbon atoms first created in 1985 and useful for storing/transporting molecules that can be trapped and released in a controlled fashion.

Carbon nanotubes: The process that produces buckyballs can also produce cylindrical carbon atom tubes, each of nanometer length (10^{-9} meters) that can be concatenated into much longer cylinders of enormous strength.

Carrier (of force): In quantum theory, every force is "carried" by a particle whose exchange is the exertion of the force. For example, the electromagnetic force is carried by photons and acts when a photon is absorbed or emitted.

Chaos theory: The colorful but somewhat misleading name given to complex but deterministic physical systems, such as the atmosphere, that are nonlinear, that is, in which minute changes in input lead to large changes in behavior.

Chromatography: A now-universal technique developed in the 1940s and after for separating the molecules in a compound by their molecular weight. The technique exploits the selective adsorption (surface adhesion) of molecules in either gas or liquid form onto a solid material, for example, specially treated paper.

Cloud chamber: An instrument that uses supersaturated water vapor to visualize charged particles that cause ionization trails to form when they pass through the chamber.

Commutativity: The rule in mathematics that the sequence of an operation is irrelevant. Thus, addition and multiplication are commutative, because $n + m = m + n$ and $n \text{ x } m = m \text{ x } n$, but subtraction and division are non-commutative because the order of operation makes a difference.

Completeness: In logic and mathematics, the property that an axiomatic system will generate all of the theorems that are true in that system.

Complexity theory: See **chaos theory**.

Conservation of energy: The principle, fundamental to classical thermodynamics, that energy can neither be created nor destroyed, only transformed from one form into another, for example, from motion into heat.

Conservation of matter: The principle that matter can neither be created nor destroyed and, thus, that the total amount of matter in the universe is constant. After the special theory of relativity and quantum theory, matter can be created out of energy and converted into energy, so it is the total of matter-energy that is conserved, not each separately.

Consistency: In logic and mathematics, the property of an axiomatic system that is free of contradiction.

Correspondence principle: Formulated by Niels Bohr in 1919, it states that there are fertile correspondences between classical and quantum physics in spite of their exclusivity, because as quantum systems increase in complexity, they become classical systems.

Creationism: The view, opposing Darwinism, that the universe, and especially the Earth and man, were created by a Providential Deity.

Cybernetics: The name given by Norbert Wiener to the theory of machines, organisms, and information systems that display apparently purposive behavior by exploiting feedback and self-regulatory control circuits.

Deconstruction: The theory, initially applied in the 1960s and 1970s to literary works but then more widely, that meaning was, in principle, indeterminate, because it is a function of open-ended relationships involving the entire cultural network in which interpretation takes place.

Deduction: A form of logical argument in which the conclusion must be true if the premises are.

Diachronic: Historical; change over time.

Differential geometry: A form of geometry in which spatial relationships, for example, the properties of curves, are described in general terms and studied using the differential calculus.

Diffraction: When examined closely, the shadow cast by a light beam is not sharp and, in fact, displays interference patterns, as if the beam were a wave wrapping around the opaque edge casting the shadow.

Dynamics: A system in which unbalanced forces are acting, thus, not in equilibrium.

Dynamo effect: Moving a magnet around a conductor, or moving a conductor around a magnet, causes a current to flow in the conductor. This remains the principle underlying virtually all electricity generation today (except for photovoltaic and thermoelectric generation).

Electromagnetic theory: Maxwell's theory of the 1860s according to which electricity and magnetism or moving charged particles can interact to generate waves of energy that, in a vacuum, travel at the speed of light, visible light being those waves to whose frequencies our eyes are sensitive.

Electron beam diffraction: The diffraction of a beam of electrons (or even of atoms) analogous to the diffraction of beams of light. Predicted by Louis de Broglie in 1923, it revealed that particles behaved like waves by displaying interference effects.

Emergence: Colloquially, what people mean by the whole being greater than the sum of its parts, that is, systems/wholes can display properties that are not displayed by any of the parts of which the system/whole is composed.

Encephalography: Studying the structure and activity of the brain, by X-ray photography, displacing the cerebrospinal fluid by air to serve as a contrast medium; electrically, using electroencephalography, or EEG; or acoustically, using ultrasound.

Entropy: In thermodynamics, a measure of the *un*availability of energy in a closed system, reflecting the irreversibility of real-world processes and, in 19th-century physics, implying the ultimate running down, or "heat death," of the universe. The study of self-organizing systems in the second half of the 20th century led to a reinterpretation of entropy.

Enzymes: Proteins that serve as catalysts in reactions; that is, they are not themselves changed by the reaction.

Equilibrium: A system in which no unbalanced forces are operating and with no cumulative, directed changes taking place is in equilibrium.

Ethical drugs: Synthesized pharmaceuticals, a late-19th-century spin-off of the invention of synthetic dyes beginning in 1856.

Eukaryote: Cells with a nucleus separated from the rest of the cell by a membrane.

Field theory: The mid-19th-century theory, championed especially by Michael Faraday and James Clerk Maxwell, that certain forces, among them, electrical and magnetic repulsion and attraction, acted not by direct mechanical contact between sources, but at a distance, by filling the space surrounding the source of the field in accordance with precise mathematical laws.

Fractal geometry: The name given by Benoit Mandelbrot to the fractional dimensionality of self-similar shapes.

Functionalism: Any theory whose objective is determining how the elements of a system function and what their mutual interrelationships are; rather than determining what they "are" ultimately or what they mean, just what they do.

Game theory: In von Neumann and Morgenstern's 1943 classic text, the theory of choices made by participants in a conflict situation, assuming that each attempts to maximize his or her self-interest, hence, the basis of rational choice theory. Later, game theory was extended to cooperative game situations. Very widely applied in economics and social science.

Geisteswissenschaft: A German word invented in the late 19th century to denote knowledge of human social and cultural phenomena, acquired through objective, critical, methodological study; thus, what we now call the humanities and social sciences.

Geodetics: Mapping the Earth's surface with special attention to elevation and deviation from sphericity, hence, requiring measurement of variation in the gravitational force.

Group theory: A branch of mathematics that studies the properties of sets under some rules for operating on them (addition, multiplication, and so on).

Hadron: A generic name for the families of strong force–interacting (hence, nuclear) particles that, according to quantum chromodynamics, make up all ordinary matter. Hadrons are either baryons or mesons, composed of quark-anti-quark pairs. Leptons are the other family of elementary particles, responding to the weak force. Leptons and hadrons are connected by the beta decay process that neutrons and mesons exhibit. *Hadron* is sometimes used to refer to both weak and strong force–responsive particles.

Hydrothermal vents: Fault lines in the ocean floor, typically near the mid-ocean ridges, from which hot, mineral-rich water pours, the water heated by contact with molten rock beneath the ocean floor, and surrounded by flourishing dense ecologies of plants and animals, even at temperatures above the boiling point of water.

Induction: A form of inference in which the conclusion reached may be false even if the premises are all true, hence, probabilistic inference, as opposed to deductive inference, in which the conclusion must be true if the premises are true.

Information theory: Especially after Claude Shannon's 1948 formulation, the mathematical study of the character, storage, and transfer of information using probability theory and interpreting information as the opposite of the thermodynamic concept of entropy (hence, *negentropy*, a term coined by Norbert Wiener).

Interference: A name for interactions among overlapping waves which, depending on the timing and form of their overlap, can cancel each other out, reinforce one another to form a single stronger wave, or form some more complex hybrid wave.

Interferometry: A technique in which a beam of light is divided in two and, after traveling separate, carefully controlled paths, the two beams are caused to overlap, for example, by reflecting mirrors. The resulting interference patterns allow extremely accurate measurement of the wavelength of the waves and/or of the distances the beams have traveled. Interferometry is fundamental to late-20th-century radio, visible light, and gravity wave telescopy.

Interferon: A protein produced by cells in response to viral infection.

Interstellar wind: The flow of atoms and molecules across interstellar space, typically produced by nova and supernova.

Isostasy: A turn-of-the-20th-century American geological theory that explained the equilibrium of the Earth's surface, deformed by mountains and valleys, by postulating a constant net density and uniform net gravitational force. Thus, the "excess" of matter associated with mountains is compensated for by assuming that the matter beneath the mountains was less dense than average.

Kuiper Belt: A vast region of the solar system beginning just beyond Neptune and extending far beyond the orbit of Pluto. It is believed to contain hundreds of thousands of comet nuclei and *planetesimals* ("micro-planets") and to be the source of those comets that return periodically. Pluto may be a Kuiper Belt object rather than a "true" planet.

Lepton: In quantum chromodynamics, the family of elementary particles made up of electrons, pions, and tau particles and their respective neutrinos. Leptons respond to the so-called weak force and to the electromagnetic force but not to the strong force.

Magnetic moment: A measure of the strength of a magnet. In quantum theory, charged particles, such as the electron, and nuclei as wholes have magnetic moments and, thus, magnet-like properties that can be exploited to manipulate matter in subtle ways.

Metabolomics: The study of the correlation between proteins and metabolic processes, without first understanding how the structure of a protein determines its action.

Mitochondria: A cellular structure with its own membranes and its own short ring of DNA, outside the nucleus, in which ATP is produced. Except for random mutations, it is believed that mitochondrial DNA rings are transmitted from mother to daughter identically and, thus, can serve as an absolute genealogical marker.

Modernity: A name for the commitment to reason, especially as exemplified in natural science, mathematics, and logic, as the only means by which truth, knowledge, and progressive improvement of the human condition can be achieved.

Monoclonal antibody: An antibody produced by a cell culture created by cloning a single parent cell, so that the antibody produced by all the cells in the culture is identical.

Mousterian: A name for the more sophisticated culture—tools, artifacts, art, and lifestyle—of *Homo sapiens* and, possibly, Neandertals in the period 50,000–30,000 B.C.E.

Mutation: In genetics, a random change in the base sequences in the DNA molecule, thereby affecting the gene coding for protein synthesis and, ultimately, the cellular process(es) the protein participated in. Sometimes, chromosomes undergo random structural changes that are also called mutations.

Nanotechnology: Technologies based on the manipulation of matter at the level of 10^{-9} meters, typically, on the order of tens to a few hundreds of atoms in size.

Naturwissenschaft: Scientific knowledge of natural phenomena.

Network theory: A branch of mathematics that studies the properties of networks that emerge as a result of their structure, that is, of the form of the connections among the network's nodes.

Neural nets (or networks): A type of computer inspired by the neuronal structure of the brain. The computing in a neural net computer does not follow a rigorously controlled sequence of program instructions. Instead, the input nodes of the net are linked to output nodes by one or more layers of intermediate nodes, all interconnected and with the intermediate nodes free to set their own responses to inputs and feedback from outputs. Neural nets are not programmed in the traditional sense; they are "trained" to adjust themselves internally to reliably generate a desired output for a given input.

Neutron star: A collapsed star too small to form a black hole.

Newtonian science: The search for experimentally validated mathematical laws for the motion of matter under the action of specified forces. More specifically, physics keyed to Newton's definitions of space, time, and matter and Newton's laws of motion. Broadly, modern science from Newton to Einstein.

NMR: Nuclear magnetic resonance, the basis of magnetic resonance imaging (MRI) technology. A nucleus with a magnetic moment behaves like a magnet and, in a strong magnetic field, if stimulated by radio waves of appropriate frequency, will radiate a signal that can be used to create an image of the sample nuclei.

Nonequilibrium state: A condition of directed change, produced by the action of forces in a system.

Non-Euclidean geometry: Any logically valid, deductive system of geometry that uses definitions, axioms, or postulates different from the ones used by Euclid.

Nonlinear system: One in which small changes in input or initial conditions result in large changes in output over time.

Oncogene: A gene linked to cancer because it causes uncontrolled cell growth.

Organic: In chemistry, carbon molecule–based reactions and, by extension, reactions associated with biological molecules.

Particle theory of light: Any theory that light is composed of particles, not waves. This explains the linear transmission and reflection of light beams, the apparent sharpness of shadows, and in the 20th century, many quantum-level phenomena, such as the photoelectric effect, but not refraction, diffraction, or interference.

Perceptron: The first neural net computer, a primitive single-layer device built by Frank Rosenblatt around 1960.

Periodic table: Dmitri Mendeleev's late-1860s innovative organization of the chemical elements based on their chemical weights and "family" chemical properties.

Photoelectric effect: The emission of electrons by certain materials, typically metals and semiconductors.

Piltdown Man: An elaborate and extraordinarily successful fraud that mislead paleoanthropologists for decades. A fossil human-like skull unearthed in 1912 near Piltdown in the county of Sussex in England was hailed as the missing link between apes and man because it had an ape-like jaw and a human cranium. Radiocarbon dating techniques in 1953 revealed the skull to be a fraud.

Plate tectonics: The theory that the Earth's surface/crust is in constant motion as a result of the continual upwelling of molten material from the mantle at mid-ocean ridges. This upwelling, driven by convection currents in the mantle carrying away the great heat of the Earth's iron core, forces the ocean floor to spread and, where the floor collides with the continental "plates," to descend into the mantle to melt again. The pressure of the spreading floor keeps the plates in continual motion as well, and when they collide, mountains form.

Positron: An anti-electron, that is, a particle with exactly the same physical properties as an electron but with a positive charge.

Prokaryotes: Cells without a nucleus.

Proteins: The complex molecules, composed of combinations of amino acids, that control cell metabolism. There are some 10,000 different proteins in the human body, out of the millions of possible combinations of amino acids.

Proteomics: The study of the complex, folded shapes and functions of individual proteins, especially the relationship between shape and function.

Pulsars: Rapidly rotating magnetized neutron stars that, like cosmic lighthouses, emit beams of electromagnetic radiation as they spin.

Quantum mechanics: A name applied by Max Born to the successful quantized theories of matter and energy presented by Schrödinger and Heisenberg in 1925. Subsequently, used generically for quantum physical theories, such as quantum electrodynamics and quantum chromodynamics.

Radiogenic heat: Heat whose source is the decay of radioactive elements. The discovery of radioactivity in 1896 quickly led geologists to realize that changes in the Earth's surface could be driven by a continuing source of energy.

Rational choice theory: See **game theory**.

Recombinant DNA technology: Using special enzymes to cut and paste segments of DNA from different individuals of the same type or different types of organisms.

Resonance: When a system of any kind is stimulated, even at very low power at its natural frequency of vibration, very large increases in the energy of the system can be achieved.

Science Wars: A name for the "battle" in the 1980s and after between those who argued that objective knowledge is not possible because all knowledge is necessarily interpretive and, thus, value-laden and those who defended science, at least, as providing objective knowledge of an independently existing reality.

Self-organization: Many kinds of physical, chemical, and biological systems exhibit and sustain spontaneous order under specifiable conditions. Such systems must be thermodynamically open, that is, capable of drawing energy from their environment, and thus, the classical limitations of entropy do not apply to them, but they exist as subsystems within a wider closed system.

Set theory: The study of the properties of collections of objects depending on the axioms imposed on membership in the set and relationships among sets. Set theory became central to attempts to understand the foundations of mathematical truth in the late 19th and early 20th centuries.

Solar wind: The charged particles—electrons, protons, nuclei—blown outward by the dynamic processes at work in the Sun: flares, coronal storms, prominences. There are high-speed and low-speed winds, and during particularly violent storms, perhaps associated with the 11-year sunspot cycle, they pose serious threats to electronics on the Earth and in orbit.

Spectroscopy: The study of the distinct frequencies, wavelengths, and energies of which emitted and absorbed light (and electromagnetic energy generally) is composed.

Spin: A quantum property assigned to charged particles (photons have zero spin) as if they were little tops and could spin clockwise or counterclockwise, thus having one of two possible values characteristic of that type of particle. It is the spin that generates the magnetic moment associated with a particle and, thus, its magnet-like behavior.

Symbolic logic: One name for modern logic, which uses symbolic notation to study much more complex forms of reasoning/inference than in traditional Aristotelian logic. The use of symbols, pioneered by George Boole and extended by Gottlob Frege to a mathematization of logic, stimulated the identification of new logical concepts and the exploration of the properties belonging to relationships other than the classical subject-predicate relationship.

Synchronic: Contemporary; at the same time.

Systems theory: The study of the nature of part-whole relationships and the emergent properties of specific systems; a central concern of researchers studying complexity theory and self-organization.

Tectonics: The surface deformations of the Earth.

Thermodynamics: The study of the laws governing the behavior of heat.

Tomography: A mathematical technique for reconstructing a three-dimensional image of an object (the Earth's interior, the brain, and so on) from sequential two-dimensional sections of that object.

Topology: That branch of mathematics that studies spatial relationships under various imposed restrictions in the most general terms. Also applied to the properties of network relationships and, metaphorically, to relationships in general.

Transgenic: Using recombinant DNA technology to transfer genetic material across species.

Transistor: Exploiting the junction properties of semiconductor materials to accomplish the same electrical circuit functions as vacuum tubes—rectification of current, amplification, detection, switching—at much smaller sizes and with much lower energy requirements.

Wave theory of light: In the 19th century, the theory that light was a wave, not a particle, and furthermore, a transverse wave, that is, one whose wave pattern was at right angles to the direction of travel. In the 1860s, Maxwell argued that light was a product of conjoined electrical and magnetic waves and Einstein, in 1905, postulated that the speed of light in a vacuum was a constant for all observers in uniform motion.

Wissenschaft: Knowledge acquired through the application of an objective, critical methodology, thus, scholarly or scientific knowledge.

X-ray crystallography: Using diffraction to determine the structure of a specimen crystal. A beam of X-rays is focused on the crystal and the diffraction pattern (see **diffraction**) created by the edges of the crystal reveals the angles at which the atoms composing the crystal are arranged. The structure of any substance that can be crystallized can be determined in this way.

Notes