CHAPTER

17

Quantum Fields

Relativity Meets the Quantum

The basic ingredients of nature are fields; particles are derivative phenomena.

Steven Weinberg, Physicist, Winner of the Nobel Prize for His Theory of the Electroweak Force Field

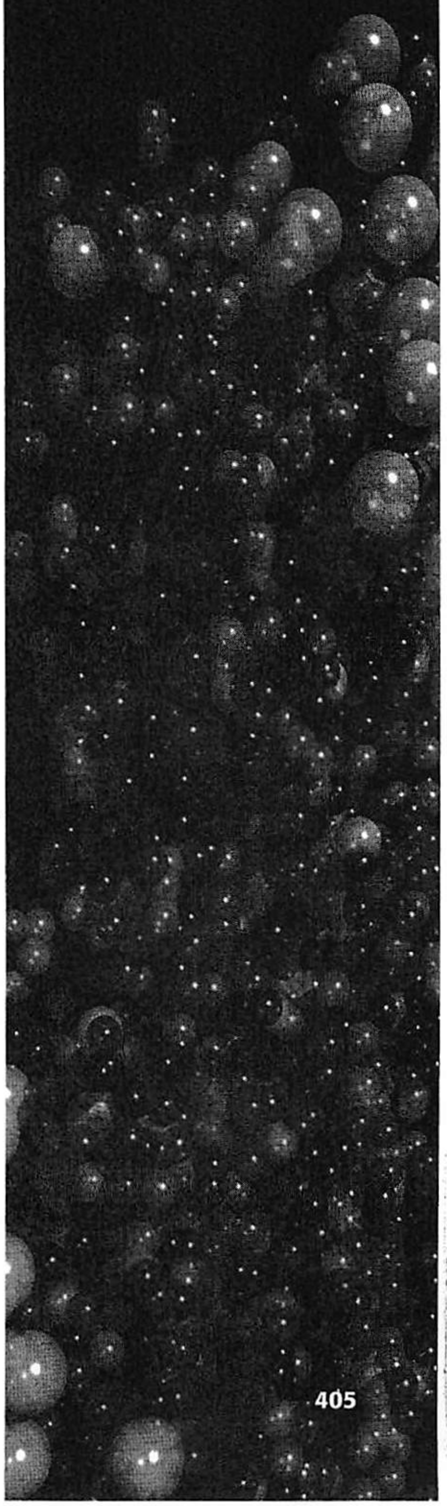
Special relativity and quantum physics extend Newtonian physics in different directions. One extends it up to lightspeed, and the other extends it down to at least the smallest dimensions yet measured, 10^{-19} meters, 10,000 times smaller than an atomic nucleus. But there's a problem with these two theories. Special relativity doesn't contain the quantum principles so it doesn't work at small sizes, and quantum physics doesn't contain the relativity principles so it doesn't work at high speeds. Thus neither theory describes small-scale high-speed phenomena. What's needed is a joining of relativity and quantum physics into a single theory covering all sizes and all speeds.

Such a theory was developed during 1930–1950. It's called **quantum field theory.** One part of this theory, quantum electrodynamics, is the most accurate scientific theory ever invented. Like most of modern physics, quantum field theory is basically simple but takes some getting used to. Its underlying idea, and an enduring theme of modern physics, is the **field view of reality** already discussed in connection with Einstein's mass–energy relation (Chapter 10)—the view that the universe is made entirely of fields. In Section 17.1, we'll further discuss what this means.

Section 17.1 presents the general idea of quantum field theory, and the remaining sections apply this idea to each of the four fundamental forces: electromagnetic (Sections 17.2 and 17.3), weak (Section 17.4), strong (Section 17.5), and gravitational (Section 17.6). Along the way, I'll present several of the most remarkable topics in all of physics: antimatter, creation and annihilation of matter, high-energy particle accelerators (including the Large Hadron Collider), the furious activity occurring in so-called "empty" space, neutrinos, quarks, gluons, the standard model of particle physics, the Higgs field and its quantum particle, quantum gravity, and the string hypothesis.

17.1 QUANTIZED FIELDS: THE REASON THERE ARE PARTICLES

Recall from Chapter 9 that a **field** (examples include gravitational, electromagnetic, and matter fields) is spread out over a region of space. This region needn't contain any matter or "things" at all. A field is a condition of space itself, a kind of stress in space, regardless of any matter that might be in it. For example, a magnetic field is the possibility of a magnetic force, regardless of whether anything feels that possible



The unexpected and the incredible belong in this world. Only then is life whole.
Carl Gustav Jung

force. Recall also that fields, even when no matter is present, contain energy and this implies that they are physically real and not mere mental constructions.

At the core of quantum field theory is the view that the universe is made only of fields. The table on which this book rests is simply a configuration of quivering force fields, similar to the invisible force field surrounding a magnet, and so is this book. The book doesn't fall through the table, however, because the electric force fields in the table repel the electric force fields in the book. And your eye (which is also just fields) sees the book because the book's force fields emit radiation.

It's an odd idea. There is no truly solid or enduring "thing." In this sense, there is "nothing": no thing. Only fields. But this doesn't mean that everything is empty, or nonexistent, or imaginary. Far from it. In fact, the relatively solid table at which you are perhaps sitting right now is made of atoms that are in turn made of fields that exert quite real forces on the atoms (which are also made of fields) in your elbows which are perhaps leaning on the table. That's why you don't fall through the table.

Quantum field theory assumes that each field, such as the electromagnetic (EM) field, obeys the principles of quantum physics and special relativity. You've already studied the basics in Chapter 12, although we called it "quantum physics" instead of "quantum field theory." Here's a quick review of those basics: EM fields fill the universe and are quantized in specific energy increments, as described in Section 12.2. Each time such a **quantized field** interacts with, for example, a viewing screen or your eye, it must gain or lose a whole energy increment, or **quantum.** Even though each quantum is spread out over a region of space, these quanta of the EM field act somewhat like particles and are called photons. The theory also asserts that matter fields fill the universe and that these too are quantized, as described in Section 12.4. The quanta of these matter fields act somewhat like particles and are called electrons, protons, neutrons, atoms, and so forth. In this chapter, we'll learn that there are other kinds of radiation quanta, similar to the photon, and other kinds of material quanta, similar to electrons and protons.

The one part of today's physics that seems to me likely to survive unchanged in a final theory is quantum mechanics.
Steven Weinberg

This view stands Newtonian thinking on its head. Newtonian physics regards the universe as a vast collection of separate, unchanging particles whose motions and interactions determine everything that happens. Quantum physics regards the universe as made of just a few kinds of constantly changing spread-out fields whose motions and interactions are the source of everything that happens. Because these fields are quantized, their interactions must occur in specific energy increments, and these increments appear as photons, electrons, protons, etc. This view also explains why all electrons must be identical, why all photons of a particular frequency must be identical, etc. All electrons, for example, are just quantized bundles of field energy of a *single* type of matter field, so they must be identical, in the same way that 1 joule of energy in your gas tank is identical with any other joule of energy in your gas tank.

So quantum field theory explains why nature exhibits itself as particles of just a few fundamental types. The list of nature's fundamental ingredients no longer needs to include any particles at all—it needs to include only a few fields. This view puts matter and radiation on an equal footing: Both material particles such as electrons and radiation particles such as photons are quantized bundles of field energy. These particles are subject to the usual quantum uncertainties, with the field's intensity at any point determining the probability that the corresponding particle will appear at that point (Chapter 12). The fields (and the associated particles) are also subject to the rules of special relativity, namely, the principle of relativity and the constancy of lightspeed (Chapter 10). To summarize:

The Quantum Theory of Fields

The essential reality is a few fields, such as the EM field, that fill the universe and that obey the principles of quantum physics and special relativity. Everything that happens in nature is a result of changes in these fields. Quantization requires that, whenever an interaction occurs, these fields must exhibit themselves as bundles or quanta of field energy. All of nature's particles of radiation and matter are quanta of this sort.

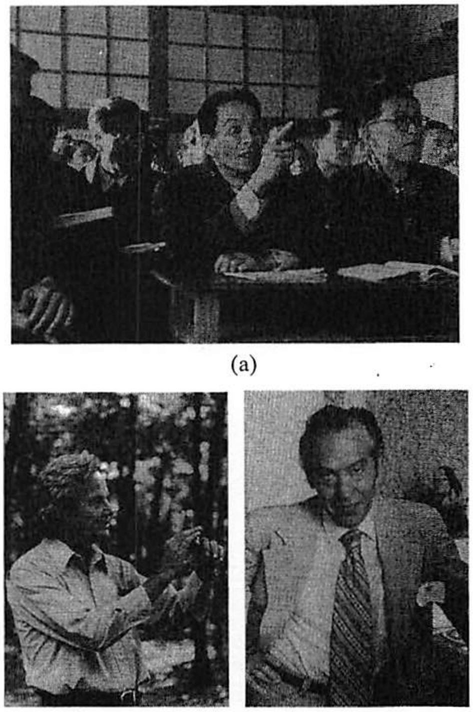
Why does quantum field theory obey the special theory of relativity (Chapter 10) rather than the more general and more correct (because it agrees with a wider range of observations) general theory of relativity (Chapter 11)? It's because nobody has yet figured out how to make quantum physics jibe with general relativity. In other words, within the context of special relativity, quantum field theory incorporates three of the four fundamental forces: electromagnetic, weak, and strong. But nobody has been able to formulate any of these three forces within the context of general relativity; such a theory would have to encompass the fourth force, gravity. For some hypothetical stabs in this direction, see Section 17.6.

The notion that reality is a set of fields that give the probabilities for finding their associated quanta is the most important consequence of relativistic quantum field theory. It is the central concept for the picture of reality. Not only did the idea of matter disappear into the field concept, but the field specified the probability for finding quanta.

Heinz Pagels, Physicist

17.2 QUANTUM ELECTRODYNAMICS: THE STRANGE THEORY OF ELECTRONS AND LIGHT

Quantum field theory emerged during the 1930s as the world was marching toward war. Although nuclear physics flourished in the United States (Chapter 15), quantum physics had to wait. Nevertheless, Shin'ichiro Tomonaga (**Figure 17.1**), working



(a)

(b)

(c)

Figure 17.1
Three who independently invented the theory of quantum electrodynamics, a quantum theory of the EM force. (a) Shin'ichiro Tomonaga (gesturing from his desk) in 1948, five years after publishing his theory. (b) Richard Feynman. He was known to jerk his mind out of a rut by working at a back table in a nightclub, inspired by the blare of the sound system. (c) Julian Schwinger. A solitary worker, he says that he "became the night research staff" at his wartime laboratory.

in wartime isolation in Japan, published a fundamental paper presenting a quantum field theory of the EM force. His paper was not available in English until 1948. After the war, in 1947, two New Yorkers in their 20s, Richard Feynman and Julian Schwinger (Figure 17.1), completed quantum field theories of the EM force. The three theories, known as **quantum electrodynamics,** were invented independently and look strikingly different, but all three say the same thing. I'll present Feynman's more intuitive version.

Quantum electrodynamics is about the interactions between two kinds of quantized fields: quantized EM fields, and quantized **electron fields** (matter fields for electrons). From the particle point of view, the theory is about photons, the quanta of the EM field, and electrons, the quanta of the electron field and the particles that experience the EM force in its purest form. It sounds simple. But the requirement that the EM field and electron field obey both relativity and quantum theory leads to astonishing results.

In Feynman's theory, the old idea of a continual electric force between two electrons is replaced with a quantized transfer of a "bundle" of force in the form of a photon. **Figure 17.2** pictures this. The diagram graphs the positions of two electrons at various times and shows a single quantum interaction between the two electrons. Initially, electron 2 is at rest (its position, shown along the vertical axis, isn't changing as time proceeds along the horizontal axis), and electron 1 is moving downward. Then electron 2 radiates a photon that travels through space and time to electron 1, and then electron 1 absorbs this photon. When electron 2 emits the photon, electron 2 veers downward, and when electron 1 absorbs the photon, electron 1 veers upward. The electrons repel each other by means of **photon exchange,** much as basketball players interact by passing a basketball back and forth. Surprisingly, however, quantum electrodynamics allows two oppositely charged particles, such as a proton and electron, to veer *toward* each other when a photon is exchanged.

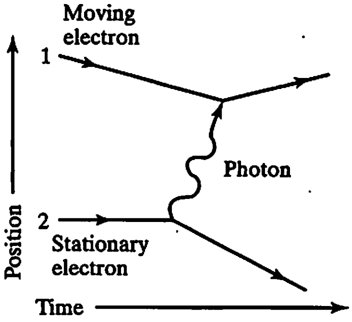


Figure 17.2
A schematic diagram showing a single quantum interaction between two electrons. Diagrams like this are known as "Feynman diagrams."

Every quantum event has quantum uncertainties. In Figure 17.2, the emission and absorption of the photon are uncertain. That is, it's uncertain whether the emission and absorption will occur in the first place, and if they do, it's uncertain where and when they will occur. Quantum field theory replaces the deterministic electric force law with a formula giving the probability of emission and absorption of a photon. In this theory, for a particle to be **electrically charged** means that it has the ability to emit and absorb photons.

This theory replaces the smooth, deterministic, Newtonian paths with jerky, nondeterministic paths. If the force between the two electrons is small, then individual photons have low energy and quantum theory predicts a fairly smooth, nearly Newtonian, path [**Figure 17.3(a)**]. But when the forces are large, the quantum predictions are decidedly non-Newtonian [Figure 17.3(b)].

So far, this is the kind of thing you might have expected from quantizing the electric interaction: quantized force packages and randomness. But something radically new also emerges. In order for the theory to obey the special theory of relativity, a new type of material particle must exist in nature.

The argument that leads to this prediction is an interesting one and is typical of modern physics. It's based on symmetry, a concept that we've encountered several times before. It turns out that, in order to obey special relativity, quantum field theory must be "symmetric under time reversal." In other words, if we imagine a universe precisely like ours, only with time running the other way, the laws of quantum

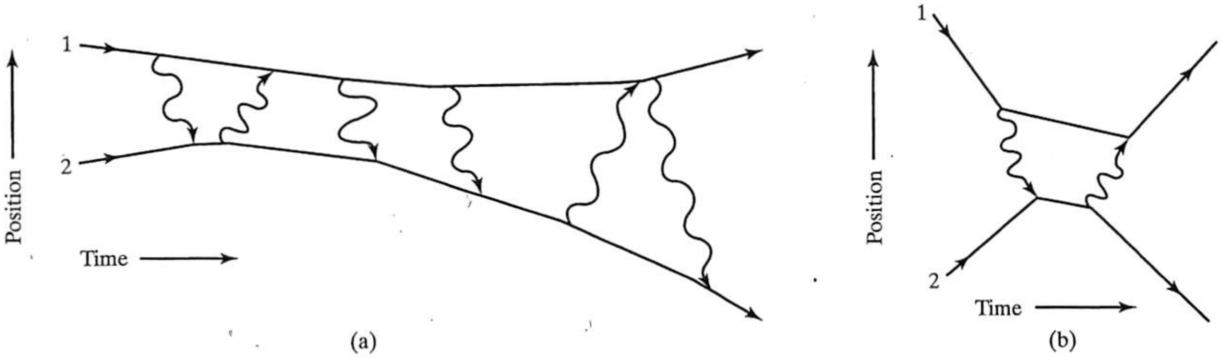


Figure 17.3
(a) A Feynman diagram for a series of interactions between two weakly interacting (i.e. only low-energy photons are exchanged) electrons. The electrons' paths approach smooth Newtonian paths. (b) At stronger interactions (high-energy photons), the paths deviate considerably from smooth paths, and Newtonian physics is no longer a good approximation.

field theory must be valid in that universe.[1] Feynman found that an electron that is imagined to move backward in time would have precisely the same observable effects as would another particle just like the electron, only carrying a positive charge and moving *forward* in time. In order for the laws of physics to be properly symmetric under time reversal, this positive electron, or **positron,** had to exist.

The prediction of the positron illustrates the enormous scope of quantum field theory: Earlier theories, whether Newtonian or relativistic or quantum, had described only how things change in time. Quantum field theory goes well beyond this extrapolation of the present into the future and the past by describing not only how things move but also what kinds of things can exist.

How do we know that positrons and other strange new particles exist? A subatomic particle's path can be revealed by a device known as a cloud chamber. A container or "chamber" is filled with air saturated with water vapor—gaseous H_2O that is just at the point of converting to droplets of liquid water. When a charged subatomic particle such as an electron speeds through the chamber, it nudges some of the air molecules along its path strongly enough to ionize them. Each ion causes a water droplet to form, and the resulting trail of droplets reveals the particle's path. Jet planes form similar vapor trails in the atmosphere, revealing the plane's path.

The cloud chamber was the workhorse of subatomic physics between 1930 and 1960. Its successor is the bubble chamber, based on the formation of tiny bubbles in a liquid. According to scientific lore, its inventor, Donald Glaser, came up with this innovation in a bar in Ann Arbor, Michigan, while watching the bubbles in a glass of beer. It won him a Nobel Prize.

In 1932, Carl Anderson of the California Institute of Technology generated a strong magnetic field in a cloud chamber. Recall that magnetic fields exert sideways forces on moving charged particles. This sideways force makes electrons curve as they move through magnetic fields. A moving particle's speed and mass can be assessed from this curvature because a particle's path is straighter if it's moving faster, and because if two particles move at the same speed, the more massive one will have the straighter path.

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[1] This raises the intriguing question of why, if our most basic physical theory is symmetric in time, the forward direction in time is different from the backward direction. For example, why aren't as many people growing younger as are growing older? The answer is not understood, but it's connected to the second law of thermodynamics (Chapter 7) and the big bang (Chapter 11).

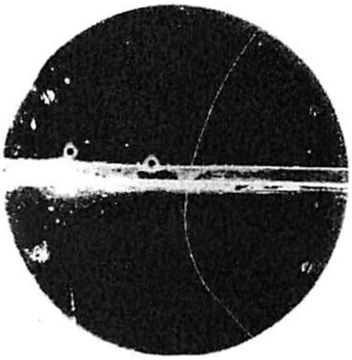


Figure 17.4
The photo that won a Nobel Prize. This photo alone established the existence of a positive electron.

In 1932, the only high-energy particles available for experiments came from space. Allowing these "cosmic rays" to pass through his cloud chamber, Anderson found a surprising number of fairly straight paths. Electrons and protons were the only charged particles known at that time. The paths appeared to be made by fast-moving electrons, but the direction of their curvature was the reverse of what was expected, indicating that the particles carried a positive charge. Anderson's first hypothesis was that these paths were made by electrons that were somehow moving upward through the cloud chamber, despite the expectation that cosmic rays should move downward. He checked this hypothesis by inserting a thin lead plate across the middle of the chamber. Although the fast-moving particles passed easily through the lead, they slowed down in the process, and so the path's curvature increased after passing through. In **Figure 17.4**—the photograph that won Anderson a Nobel Prize—the particle is clearly moving from top to bottom because it curves more in the bottom half of the photo, so its curvature shows that it carries a positive charge. Anderson had discovered the positron.

In order to observe cosmic rays before they interact with much air, Anderson in 1936 built a new magnetic cloud chamber on Pike's Peak in the Colorado Rockies. He found curious tracks that didn't fit protons or electrons, even positive ones. The paths were too curved for protons, yet the particles passed easily through lead plates that should have stopped any particle whose mass was as small as the electron's. This new particle was just like an electron but 200 times more massive. It was a real surprise. As Columbia University physicist I. I. Rabi put it, "Who ordered that?" Today, we still do not know. This particle is called a **muon.**

17.3 ANTIMATTER

The positron was science's first encounter with **antiparticles.** Relativity's requirement that quantum theory be symmetric under time reversal implies that for every existing type of particle, there must be an antiparticle having the same mass but the opposite charge. For example, the electron's antiparticle is the positively charged positron. Similarly, the proton's antiparticle is the negatively charged **antiproton,** and the neutron's antiparticle is the uncharged **antineutron.** Although it carries no overall charge, the antineutron does have magnetic properties that are the opposite of the neutron's.

One of the profound successes of quantum field theory and high-energy experimental physics is the prediction and observation of the **creation and annihilation of matter.** As you know, quantum field theory states that EM fields and electron fields interact with other systems, such as the viewing screen in a double-slit experiment (Chapter 12), by exchanging quanta with the other system. The quanta of the EM field are called photons, and the quanta of the electron field are called electrons and positrons. Quantum field theory predicts what can happen when an EM field and an electron field interact with each other.

> Just as it is possible for a particle to be in a quantum state in which it is neither definitely here nor there. . . so also it is possible to have a particle in a state in which it is neither definitely an electron nor definitely a neutrino until we measure some property that would distinguish the two, like the electric charge.
>
> Steven Weinberg

As one possibility, the EM field could give up one or more quanta (photons) to the electron field, increasing the energy of the electron field. Normally, the observable consequences of this would simply be increased energy for any electrons that might be observed in, say, a cloud chamber. But if the EM field gives up sufficiently high-energy photons to the electron field, something new can happen: Additional electron field quanta can be created. That is, electrons and positrons can be created. However, experiments show that, in any microscopic interaction, the total electric charge is conserved (Section 8.3), so it is always **electron–positron pairs** that are created. Quantum electrodynamics gives the probabilities for this to occur.

The other possibility is that the electron field could give up quanta to the EM field. One way this can happen is for an electron and a positron to vanish from the electron field while one or more high-energy photons appear in the EM field. Thus, electron–positron pairs can annihilate each other as well as pop into existence.

So quantum electrodynamics predicts that a photon has a certain probability of being observed as an electron–positron pair, or as more than one pair, and that such a pair has a certain probability of being observed as one or more photons. **Figure 17.5**, a Feynman diagram for part of a photon's life history, conveys this notion.

This is a very non-Newtonian development. As Heisenberg commented:

> The discovery of particles and antiparticleshas changed our whole outlook on atomic physics. . . As soon as one knows that one can create pairs, then one has to consider an elementary particle as a compound system; because virtually it could be this particle plus a pair of particles plus two pairs and so on, and so all of a sudden the whole idea of elementary particles has changed. Up to that time I think every physicist had thought of the elementary particles along the lines of the philosophy of Democritus [Chapter 2], namely by considering them as unchangeable units which are just given in nature and are always the same thing, they never change, they never can be transmuted into anything else. They are not dynamical systems, they just exist in themselves. After this discovery everything looked different, because one could ask, why should a photon not sometimes be a photon plus an electron–positron pair and so on?. . . Thereby the problem of dividing matter had come into a different light.

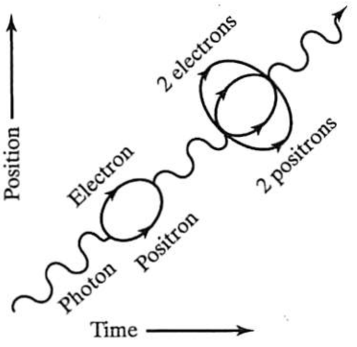


Figure 17.5
A few moments in the life history of a high-energy photon (which is an electron–positron pair during part of this history and two pairs during another part).

Antiparticles imply the possibility of **antimatter,** similar to normal matter but made of antiprotons, antineutrons, and positrons. Indeed, antiprotons were first brought together with positrons in 1996 to form a few atoms of **antihydrogen.** Although they're still a long way from powering the antimatter drive of Captain Kirk's *Enterprise,* researchers today can create and study thousands of antihydrogen atoms at a time at very low temperatures. These cold atoms are moving so slowly that they interact with each other only weakly, enabling scientists to study antihydrogen's spectrum and other properties and compare them with hydrogen's properties. In one experiment, antihydrogen falling in Earth's gravitational field is compared with the fall of hydrogen. Another experiment seeks the antimatter counterpart of the negative H ion (one proton orbited by two electrons), and the antimatter counterpart of the positive H_2 ion (two separate protons orbited by one electron that binds the protons into a single molecule). One goal is to trap large quantities of antimatter at very low temperatures in a single container for long periods of time.

Large naturally occurring collections of antimatter, such as antigalaxies, are possible but are thought not to exist, because if they did we would observe high-energy radiation from annihilation processes when a galaxy collides with an antigalaxy. Because we observe many colliding galaxies but never observe such annihilation processes, the universe is believed to contain very little antimatter.

But symmetry seems to suggest that the universe should be made of equal amounts of both. Why so much matter and so little antimatter? Russian physicist Andrei Sakharov suggested in 1967 that the big bang may have created equal amounts of matter and antimatter and that certain rare symmetry-violating processes during the first second gave rise to a slight excess—less than a part in a billion—of matter, and then the rest of the matter and antimatter annihilated so that the tiny excess formed all the matter that's in the universe today. It's a good thing for life in the universe, including us, that things worked out this way. If it weren't for that slight excess of matter created during the universe's the first second, the universe would be made nearly entirely of radiation, and we wouldn't be here to think about antimatter!

How do we know that antimatter exists? Matter and antimatter are routinely created and annihilated in high-energy physics labs when a high-energy particle enters a bubble chamber and collides with the particles of liquid (**Figure 17.6**). This creates a shower of new particles, including particle–antiparticle pairs. Carl Anderson got his high-energy incoming particles from naturally occurring cosmic rays. Today the incoming particles are first accelerated to high energies by EM forces in particle accelerators such as the Large Hadron Collidor (**Figure 17.7**).

Physicists have always "thrown" tiny things at other tiny things in order to see how they're made. Rutherford's 1911 experiment (Chapter 8) threw alpha particles at the atoms in a piece of metal foil and discovered the atomic nucleus. Today, **particle accelerators** use electromagnetic fields to speed up subatomic charged particles such as protons or electrons to high energies and smash them into other moving particles or into fixed targets. The **Large Hadron Collider** (LHC, Figure 17.7), lying in a circular tunnel 27 km around and buried more than 100 m deep near Geneva, Switzerland, will circulate two oppositely-moving beams of protons (a member of the class of particles known as "hadrons") and allow some protons from each beam to collide with each other at various locations around the ring. Please take a few seconds to compare this "inner space observatory" with the "outer space" observatories of Figure 1.2. Both figures are prime examples of the human thirst for knowledge. These structures are in some ways comparable to the cathedrals of old.

When the LHC runs at maximum energy, each proton will carry seven trillion "electron volts" (eV) of kinetic energy. One eV is the amount of kinetic energy that

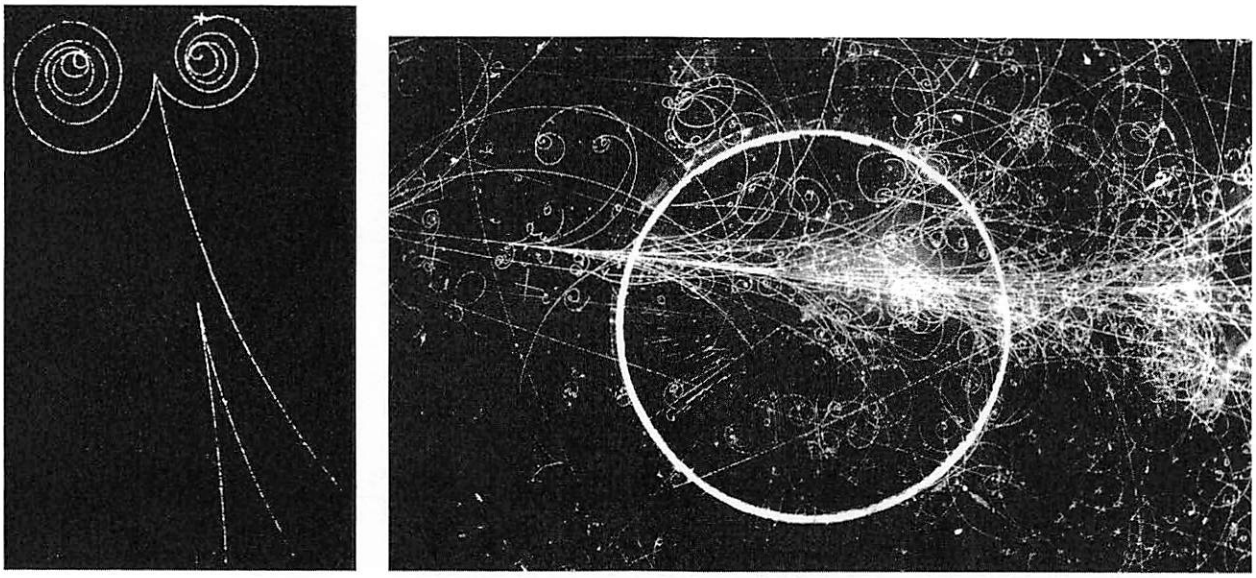
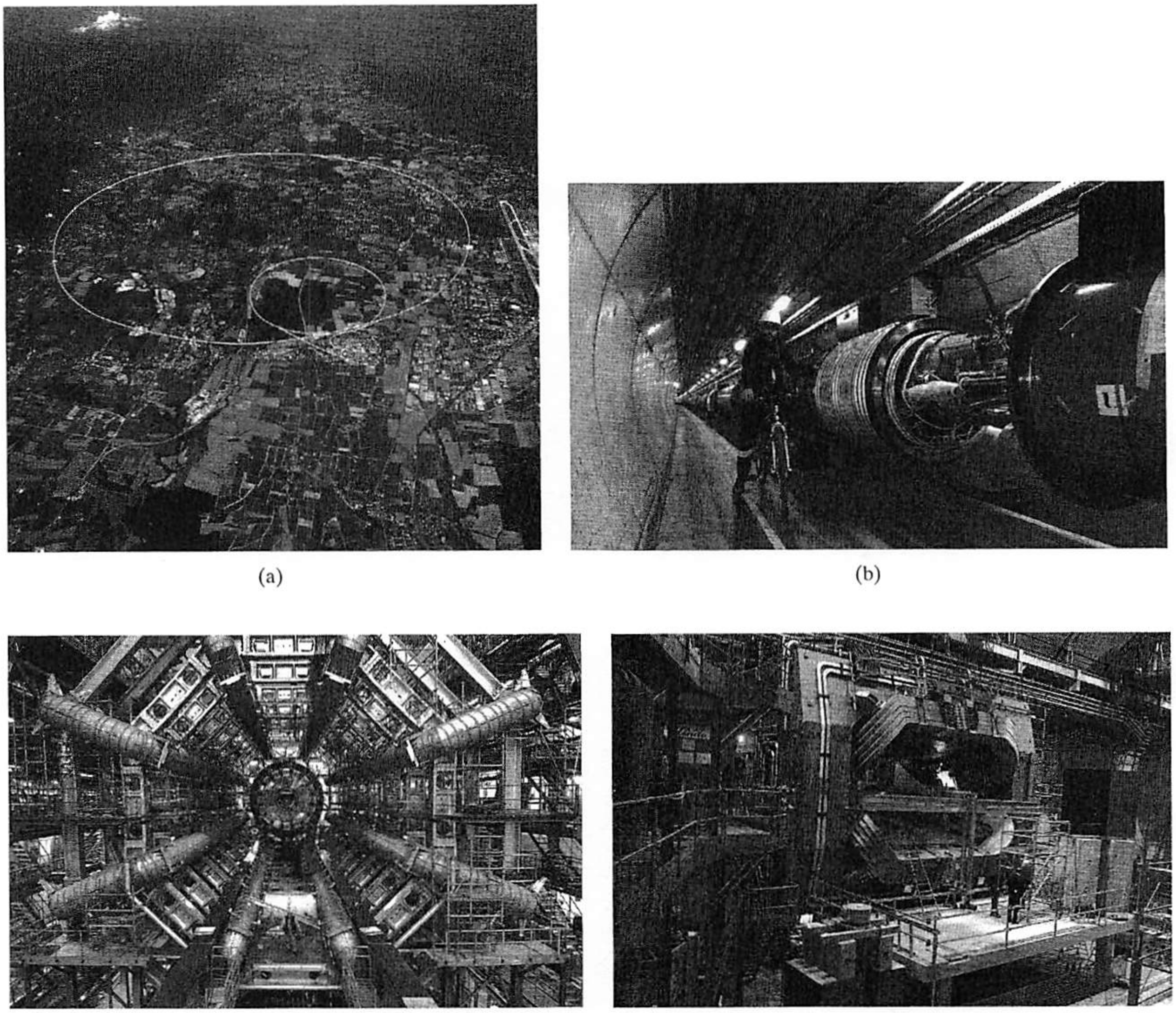

(a) (b)

Figure 17.6
(a) A bubble-chamber photograph of electron–positron pair creations, caused by gamma-ray photons. In the event at the top, a photon has struck an atomic electron and knocked it out of its atom (long curving line), and it simultaneously created an electron–positron pair (tightly curling spirals). Why can't you see the path of the photon? Toward the bottom, a different photon creates an electron–positron pair. How can you tell that each pair has two particles of opposite charge? Of the two pairs, which pair has the highest energy and speed? (b) A high-energy particle striking a particle in a bubble chamber creates a "spray" of particles of various sorts. The bright circle is part of the measuring device.



(a) (b)

(c) (d)

Figure 17.7
The LHC is the world's most powerful particle accelerator. (a) The main two rings are shown drawn on an aerial photograph of the region. The two proton beams, each one thinner than a human hair, circle in opposite directions and cross at four points where they collide within four detectors named Atlas, Alice, CMS, and LHCb. (b) An engineer inside the main ring. He leans on one of the electromagnets, powered by superconducting electric currents, that bends the beam into a circle. (c) Inside the Atlas detector, during construction. For comparison, there's a person standing in front. Atlas is half the size of the Notre Dame cathedral in Paris. It will seek out Higgs bosons, microscopic black holes, extra dimensions of space, and the dark matter particles that constitute most of the matter in the universe. (d) The LHCb detector, under construction. It will look for slight differences, or "asymmetries," between matter and antimatter by studying the bottom (or "b") quark. This will help solve the mystery of why our universe is composed almost entirely of matter with little antimatter.

an electron (or a proton, since it has the same amount of electric charge) gains when it's allowed to "fall" freely through a voltage of one volt—for example, when an electron is allowed to move freely (through empty space) from the negative to the positive terminal of a one-volt battery. At the LHC's maximum energy, each proton will be moving at 0.99999998 (7 nines followed by an eight) times lightspeed and have an inertial mass 7000 times larger than the proton's normal rest mass (due to relativistic mass increase)! When two LHC protons collide, the total collision energy will be 14×10^{12} eV—equivalent to one proton "falling" through fourteen trillion volts. This is about three million times larger than the energy of Rutherford's alpha particles. It's a really large energy to put into two tiny protons, but the total energy isn't as large as you might think. For example, the total chemical energy released (turned into thermal energy) when you strike a match is around 10^{22} eV, about a billion times larger than the LHC's collision energy but spread among about a billion trillion atoms. In other words it's easy to get energies this large; it's just hard to get it all into a couple of protons. The fourteen trillion eV collision energy is seven times larger than the energy of the largest previous accelerator at Fermilab near Chicago.

The energy of each proton–proton collision will be large enough to create the rest-mass energy mc^2 of all sorts of other particles. Physicists think there's a good chance that some of these other particles will be new, never directly observed before. You'll be learning about some of these possible new particles in the remainder of this chapter.

Although the LHC will create conditions resembling the first moments of the big bang, and it's hoped that it will create microscopic black holes, there's no chance of an unforeseen catastrophe such as another big bang. Cosmic rays from outer space, most of them protons, have been striking other protons in Earth's atmosphere for billions of years at far higher energies and much larger numbers than the LHC can produce. And such high-energy proton–proton collisions have been occurring all over the universe throughout time. There have been no catastrophes from any of this.

> No point is more central than this, that empty space is not empty. It is the seat of the most violent physics.
>
> John Wheeler

Quantum field theory paints an odd new view of "empty" space—space that is devoid of matter, commonly called **vacuum.** As you know, EM fields and other fields extend even into regions containing no matter. Quantum uncertainties require that the energies of all these fields at any point in space fluctuate, over short timespans, around its long-time average value. In Section 17.6, I'll further discuss these **energy fluctuations** for the case of the gravitational field. The uncertainty principle implies that the smaller the region of space and the shorter the time interval, the larger these fluctuations must be. This means that at any point in so-called empty space there's a certain likelihood that a photon or a particle–antiparticle pair, including any of the particles discussed in this chapter, will spontaneously pop into and out of existence during short times. So even in empty space there is always some probability of high energy events occurring in small regions. Empty space is not the quiet, uninteresting place we had imagined. Microscopically, it's a seething soup of creation and annihilation. It seems that in nothingness, much is possible.[2]

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[2] Quantum energy fluctuations mean that the law of conservation of energy must be revised. In sub-microscopic regions of space and for short times, energy is not strictly conserved. It is, however, conserved, *on the average* over larger regions of space or longer times.

How do we know that there is energy in "empty" space, and that it fluctuates? One consequence of energy fluctuations in vacuum is a tiny effect on the hydrogen atom's energy levels (Section 13.7). In Schroedinger's nonrelativistic treatment of the hydrogen atom, the energies of the quantum states labeled (b), (c), and (d) in Figure 13.18 are identical. But when relativistic quantum field theory is applied to the hydrogen atom, it is found that vacuum energy fluctuations cause the orbiting electron to jiggle a little and that the energy of this jiggling is slightly different for state (b) than for states (c) and (d). This difference was first noticed experimentally in careful measurements of the hydrogen spectrum by Willis Lamb in 1947. After the experimental discovery of this **Lamb shift,** quantum field theorists calculated it. The theoretically predicted frequency of the radiation absorbed or emitted when a hydrogen atom shifts between these two closely spaced levels is 1057.860 ± 0.009 megahertz. The measured value is 1057.845 ± 0.009 megahertz. This uncanny one part in a million agreement is testimony to both the accuracy of quantum field theory and the precision of spectral measurements.

It is ironic how physics turned out in this [20th] century. The 19th and early 20th century was characterized by a materialistic outlook which maintained a sharp distinction between what actually was in the world and what wasn't. Today that distinction still exists, but its meaning has altered. . . . Nothingness contains all of being.

Heinz Pagels, Physicist

Quantum electrodynamics describes not only electrons and positrons but also the electron-like muons along with antimuons. Furthermore, a third type of electron, along with its antiparticle, was discovered in 1976. Called the **tau,** it's much heavier than the muon, weighing in at 3500 electron masses, or nearly twice the mass of a proton. Again, nobody knows "who ordered that." These three **generations** of electron-like particles appear today to be among the most fundamental constituents of matter. All three, along with their antiparticles, interact by exchanging photons, and all of their interactions are correctly described by quantum electrodynamics.

The muon and tau are "unstable"; in other words, they decay spontaneously into lower-energy entities. Muons and taus play a role today only when fleeting pairs of them are created by vacuum fluctuations or in high-energy interactions. However, these two heavy electrons might have played a crucial role during the big bang. Sakharov's process, mentioned earlier, for creating a slight excess of matter over antimatter requires all three generations. Although they seem esoteric, we might owe our existence to the activities of muons and taus during the first second of the universe.

Are there more generations of still heavier electrons? As you will see, theory combined with astronomical observations predict that the answer is no.

CONCEPT CHECK 1 If you visited an antigalaxy, (a) you would be pulled into its black hole and ripped apart; (b) any planets there would contain many of the same chemical elements as Earth but they would be made of antimatter; (c) you would find gravity to be repulsive rather than attractive; (d) you would be annihilated; (e) it would definitely be a one-way trip.

CONCEPT CHECK 2 A certain gamma-ray source emits photons that have a 20% chance of being found as an electron–positron pair. The source emits 400 photons. How many individual material particles will be found? (a) Approximately 160. (b) Exactly 160. (c) Approximately 80. (d) Exactly 80.

CONCEPT CHECK 3 Which of these feels the electric force? (a) Proton. (b) Electron. (c) Positron. (d) Antiproton.

17.4 ELECTROWEAK UNIFICATION AND NEUTRINOS

Wolfgang Pauli suggested in 1930 that during radioactive beta decay, the nucleus emitted, in addition to a beta particle, another particle of an entirely new type. The hypothesized new particle was dubbed the **neutrino,** or "little neutral one." I discussed the history of this hypothesis, and its connection with energy conservation, in Chapter 6. Although neutrinos would not be discovered experimentally for another 25 years, Enrico Fermi immediately took Pauli's suggestion seriously and argued that neutrinios indicated a new fundamental force, the weak force, was at work. Fermi was aware of the work in progress on the quantum field theory of the electric force, and he quickly adapted these ideas to the weak force. Fermi's theory succeeded in predicting the half-lives of radioactive nuclei and the range of energies with which beta particles emerged from the nucleus during beta decay.

The weak force is the most obscure of nature's four fundamental forces. Gravity and electromagnetism show up all the time in our macroscopic world because they can act over long distances. The strong force is short-ranged but it is, as its name says, strong. It holds the nucleus together, is the major actor in nuclear power and nuclear weapons, and is responsible for radioactive alpha decay. The most noticeable example we have of the weak force is beta decay. The weak force is elusive because it's both weak and short-ranged.

At first glance, all of this sounds like medieval mystics discussing the music of the spheres, angels on the head of a pin, or some similar early approach to cosmology. Is it just a mathematical game we are playing, is it just semantics, or is it reality?

Leon Lederman and David Schramm, in *From Quarks to the Cosmos*

A neutrino barely exists at all. That is, it has almost no properties: no charge, only a tiny rest-mass (far less than an electron's), and it feels neither the electric nor the strong force. Moving at almost lightspeed and feeling only the weak force (and gravity), it's the most elusive known particle and one of the most fantastic.

Because neutrinos have only weak interactions, they hardly "feel" matter as they travel through it. It would take 8 *light-years* of solid lead to stop just half the neutrinos emitted during beta decay! No wonder the physicists studying beta decay had so much trouble trapping this thing (Chapter 6). There are millions of neutrinos from space passing in all directions through your body at any instant, yet it will probably be years before even one of them interacts within your body. The neutrinos now passing downward through you pass easily through our planet, exit Earth's far side in less than a tenth of a second, and are beyond the orbit of the moon in less than 2 seconds.

In 1967, Pakistani physicist Abdus Salam and U.S. physicist Steven Weinberg (**Figure 17.8**), working independently, uncovered a close connection between the weak force and the EM force. They proposed a new quantum field theory that incorporated both force fields into a single **electroweak force field** and that incorporated both the electron matter field and the neutrino matter field into a single **electroweak matter field**—a unification comparable to Maxwell's unification, during the nineteenth century, of electricity and magnetism into a unified EM force.

Recall that quantum electrodynamics describes the electric interactions of electrons and positrons and that this interaction occurs via photon exchanges between the charged particles. The Weinberg-Salam theory is a broader version of this picture. It says that the weak and EM forces both arise from a single force field and so are really different aspects of the same electroweak force. It describes the EM and weak interactions of electrons, positrons, neutrinos, and antineutrinos and states that this interaction occurs via the exchange of various other particles. These **exchange particles** include not only the photon but also three additional kinds of particles. The three new exchange particles differ a little from the photon, the main difference being that all three have mass—in fact, rather large masses for subatomic

Figure 17.8
The co-inventors of the electroweak force. They combined the quantum theories of the electromagnetic field and the weak nuclear field into a single electroweak quantum field theory. (a) Abdus Salam, born in Pakistan, is one of the most prominent scientists of the Islamic faith. He donated his share of the Nobel Prize to the institute with which he is associated in Trieste, Italy, which encourages scientists from developing countries. (b) In addition to his Nobel Prize–winning work in quantum field theory, U.S. physicist Steven Weinberg has written several books for nonscientists. His *Dreams of a Final Theory* is about the fundamental forces and other topics, and *The First Three Minutes* describes and explains the early stages of the big bang.

particles. Each of them is about 100 times more massive than a proton! They are labeled, $\mathbf{W}^+$, $\mathbf{W}^-$, and **Z** and can be thought of as photons that have, for reasons unknown, acquired a mass. Another difference from the photon is that the two Ws are charged, positively and negatively. The Z is, like the photon, not charged. The massive, charge-neutral Z particle was a striking new prediction of the electroweak theory, and its experimental detection six years later in 1973 was a key confirmation of the theory.

Recall that, besides the electron, there are two other generations of heavier electron-like particles, the muon and tau. Since the electroweak force binds the electron and the neutrino together into a single family, we might guess that there is a second-generation neutrino to go along with the muon and a third-generation neutrino to go along with the tau. This would be a good guess. In fact, there is a second-generation matter field whose quanta are the muon and the "muon-neutrino" and a third-generation matter field whose quanta are the tau and the "tau-neutrino." But there are not three generetions of electroweak force particles. Instead, all three generations interact via the same electroweak force field and its four exchange particles: the photon, W^+, W^-, and Z. The electroweak theory correctly predicts all the observed interactions among all these fundamental particles. **Table 17.1** summarizes the theory.

How do we know that neutrinos exist? You saw in Chapter 6 that the neutrino's existence was first suspected around 1930 when beta-decay experiments appeared to conflict with energy conservation. Application of energy conservation and other accepted principles led to the conclusion that, in addition to the observed beta particle, an unseen particle was created in beta decay. Furthermore, the data implied that this particle's (rest) mass was either zero or very small—far smaller than an electron's mass. Most physicists assumed it was zero.

Neutrinos were finally observed in an experiment in 1956. Enormous numbers of neutrinos created by beta decay within a nuclear reactor entered a huge tank of water. Only about three of these neutrinos per hour interacted with protons in the water, creating high-energy gamma photons that scientists could observe, verifying that the interaction had indeed occurred.

Table 17.1

The theory of the electroweak force. Two fundamental electroweak fields pervade the universe: an electroweak force field whose quanta are the four exchange particles listed below, and an electroweak matter field whose quanta are the electron and the electron-neutrino. In addition, there are "second-generation" and "third-generation" matter fields whose quanta are listed below.

Generation	Particle type	Mass (proton = 1)	Charge (proton = +1)
1	electron	0.0005	−1
1	electron-neutrino	[a]	0
2	muon (mu electron)	0.11	−1
2	muon-neutrino	[a]	0
3	tau (tau electron)	1.90	−1
3	tau-neutrino	[a]	0
	Exchange particles:		
	photon	0	0
	W^+	86	+1
	W^-	86	−1
	Z	98	0

[a] The three types of neutrinos have small but nonzero rest-masses, although the values are uncertain. The sum of the three masses of all three types of neutrinos is known to be less than 1 ***millionth*** of an electron's mass.

But physicists were still unable to determine whether the elusive particle's mass was zero, or nonzero but tiny. Today, it's known that the sum of the masses of all three types of neutrinos is less than 1 *millionth* of an electron's mass. Until recently, a mass of zero seemed most plausible; after all, why should this new particle have a mass far smaller than the mass of any other known material particle when a simple "zero" (like the photon) seemed to fit all the data? But nature chose a small number rather than zero. Nobody knows why.

How do we know that neutrinos have mass? The tale of this turnaround from "probably zero" to "definitely nonzero" mass began during the 1960s with observations of neutrinos from the sun. Physicists used widely accepted theories of nuclear reactions occurring in the sun to calculate the number of high-energy neutrinos emitted by the sun. This was a prediction that could be checked using huge neutrino detectors, or "neutrino telescopes" [Figure 1.2(d)], placed deep underground in order to prevent gamma photons and other high-energy particles from space from penetrating the detector. But the results disagreed wildly with predictions: The observed number of neutrinos was only one-third of the predicted number. Such disagreements between theory and observation are creative moments in science, when something really new can be learned.

The experiment was repeated by different groups at different sites using different techniques, but the disagreement persisted. Scientists began to suspect that something was wrong with the theories—either the theory of nuclear reactions in the sun or of fundamental neutrino physics.

Astrophysicists went over the theory of nuclear reactions in the sun with a fine-toothed comb but could find no holes in it. Suspicions turned toward neutrino physics. Several variations on the Weinberg-Salam electroweak theory were proposed. A new and surprising theoretical prediction emerged: If two neutrinos have different masses, then they should be able to spontaneously transform their identity into each other. For example, if electron-neutrinos and tau-neutrinos have different masses, then an electron-neutrino should be able to spontaneously change into a tau-neutrino, and vice versa, in much the same way that a high-energy photon can transform into a particle–antiparticle pair.

Scientists realized that such neutrino transformations could solve the problem of the "missing" solar neutrinos. The neutrinos that were predicted to be emitted from the sun were all electron-neutrinos, and existing neutrino detectors were sensitive only to electron-neutrinos. If some fraction of the neutrinos from the sun changed into one of the other two types of neutrinos during their journey from the sun, then a smaller number of electron-neutrinos would be detected on Earth.

New detectors, able to observe all types of neutrinos, were needed. The Super-Kamiokande detector in Japan, pictured in Figure 1.2d, was built with this in mind. Astrophysicist Masatoshi Koshiba (**Figure 17.9**) used this detector to observe muon-neutrinos created when high-energy particles from space hit Earth's atmosphere. He obtained a surprising result. The number of atmospheric muon-neutrinos coming through our planet and entering the underground detector from *below* was only about half the number entering from *above*. Apparently some of the upward-moving muon-neutrinos were lost during their 0.1-second trip through Earth. This was surprising, because it was known that only a negligible fraction of these particles could be lost due to interactions within Earth. It was suspected that this discrepancy was due to the spontaneous transformation of muon-neutrinos into some other type during that 0.1 second. In 2000, the Super-Kamiokande scientists announced that transmutations from muon-neutrinos to tau-neutrinos actually were occurring.

Convincing icing was put on this result in 2001, when scientists at another new detector in Canada announced a definitive resolution of the solar neutrino problem. In the Canadian experiment, the *total* number of neutrinos of all types coming from the sun agreed precisely with the number of electron-neutrinos predicted to be emitted by the sun, but the number of *electron*-neutrinos from the sun was (as had been observed since the 1960s) only about one-third of the predicted amount. This showed that some two-thirds of the emitted electron-neutrinos from the sun transform into either muon- or tau-neutrinos during their journey to Earth.

The conclusion is that at least some of the three types of neutrinos must have mass, because only neutrinos of different masses can transform into each other and so they cannot all have zero mass.

Figure 17.9
Astrophysicist Masatoshi Koshiba of the University of Tokyo. Using Japan's Super-Kamiokande neutrino detector, he showed that many muon-neutrinos, created in Earth's atmosphere by high-energy cosmic rays, change into tau-neutrinos during their passage through our planet.

Are there more than the three generations of electroweak particles listed in Table 17.1? In a surprising turn of events, astronomical observations indicate that there are only three generations. The argument comes out of a close connection between the large-scale universe and the microscopic world: Outer space and inner space are connected through a microscopic event that quickly became macroscopic. This event was the big bang.

After the first 4 minutes of the big bang, the universe was about 75% hydrogen and 25% helium (Chapter 11). These numbers are predicted by theoretical nuclear physics, and they agree with observations of the oldest material in the universe. The theoretically predicted helium fraction depends on the number of generations of electroweak particles: The predicted helium fraction grows larger if the number of generations grows larger. If there are three generations, this leads to a predicted helium fraction of about 25%; if there are four generations, this leads to a predicted helium fraction that is much higher than the observed 25%. Conclusion: There are only three generations.

Unification is a recurring theme of science (**Figure 17.10**). For example, Copernicus unified Earth with the other planets; Newton unified Earth-based

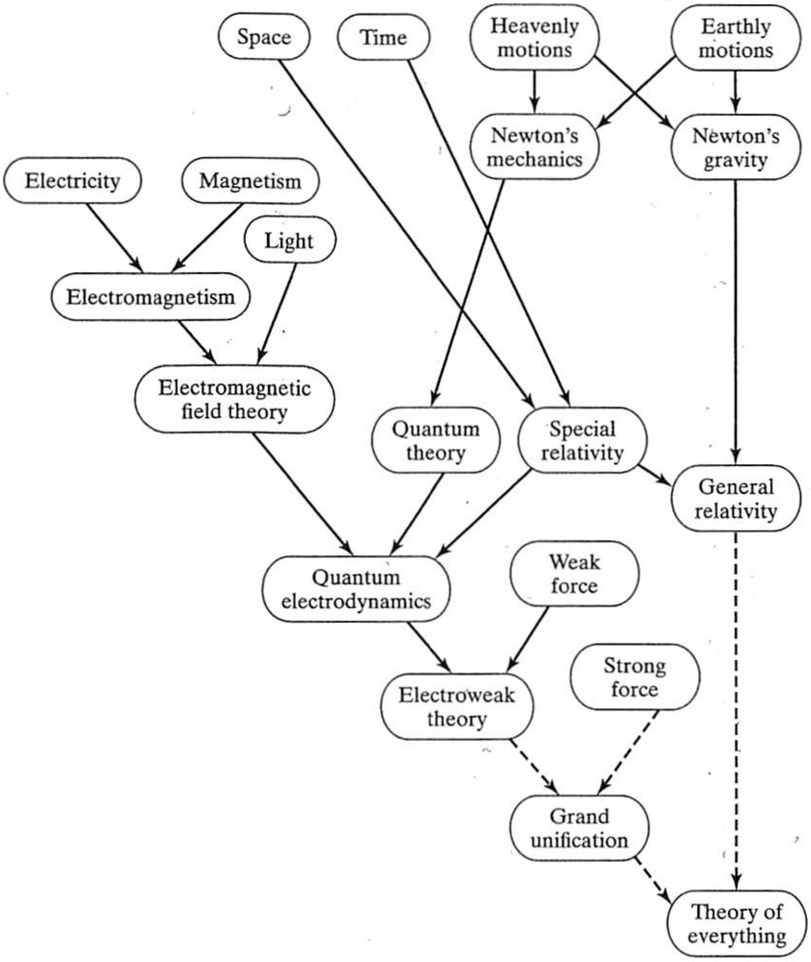


Figure 17.10
Some of the unifications in physics. The dashed lines represent unifications not yet established. Time runs from top to bottom.

physics with physics throughout the heavens; and Maxwell found a field theory that unified electricity, magnetism, and light. By the end of the nineteenth century, scientists believed that there were only two fundamental forces, electromagnetism and gravity. Einstein, after fashioning the new theory that explained gravity as a consequence of the geometry of spacetime, spent much of his scientific career trying to unify electromagnetism with gravity in the hope that a single "unified field theory" would show electricity and gravity to be different aspects of spacetime geometry. He was not successful.

Lately, scientists have sought unification at the microscopic level, based on quantum field theory. As you have seen, these efforts achieved significant success by unifying quantum theory, special relativity, and the EM and weak forces. Physicists today are trying to unify the electroweak with the strong force (Section 17.5) and to unify these with the gravitational force (Section 17.6) to actieve Einstein's dream, a "theory of everything."

CONCEPT CHECK 4 Which of these particles can feel the electric force? (a) Muon. (b) Tau-neutrino. (c) Electron. (d) Photon. (e) W^+. (f) Z.

17.5 THE STRONG FORCE AND QUARKS

As far as the measurements made to date can tell, all the electroweak particles (Table 17.1) are **point particles.** That is, their force fields appear to be centered on a single point that itself takes up no volume. The electric charge of the electron, for example, appears to be concentrated at a single point. But protons and neutrons are different. Experiments done in the 1950s showed that their electric and magnetic force centers are spread over a tiny volume about 10^{-15} meters across. Might they be composites that are made of still smaller particles?

Early in the twentieth century, protons and electrons were thought to be the only subatomic particles. The discovery of the neutron and the positron in 1932 initiated an era of particle discovery that, by 1960, had produced hundreds of new kinds of supposedly fundamental particles. This bewildering list of particles was frequently referred to as the "particle zoo." Surely the universe wasn't made of so many different things.

Murray Gell-Mann (**Figure 17.11**) hoped to bring order to the particle zoo by grouping the known particles into families that corresponded to physical regularities among them. Gell-Mann's work was much like the work of the nineteenth-century chemists who found regularities in the chemical properties of the many known elements in the "atomic zoo" and grouped them accordingly into the pattern known today as the periodic table. It was only later that this periodic table found its natural explanation in a new model of the atom according to which the 100-plus elements are built of just electrons, protons, and neutrons. In a similar way, Gell-Mann's classification scheme led him to speculate on the existence of a few simpler entities, which he called **quarks,** out of which protons, neutrons, and other particles could be built. That set experimentalists on a quark hunt. But despite strenuous searches among bubble-chamber tracks, nobody could come up with direct evidence for quarks.

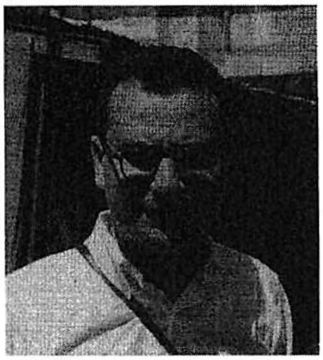


Figure 17.11
Murray Gell-Mann devised a classification scheme for the then-known subatomic particles. In about 1961 this scheme led to the prediction of new particles and suggested the existence of a small number of simpler entities, called quarks, out of which protons, neutrons, and other particles could be built. Quarks were discovered experimentally in 1967.

How do we know that quarks exist? When Richard Taylor, Jerome Friedman, Henry Kendall (**Figure 17.12**), and 12 coworkers set out in 1967 to study the proton and the neutron, they weren't looking for quarks. Using a high-energy electron accelerator at Stanford University, they were following up on earlier experiments showing protons and neutrons to be fuzzy balls 10^{-15} meters across. Hoping to get a clearer picture of these fuzzballs, they hurled high-energy electrons at protons and used huge detectors that they had built specifically to measure the angular deviation of the electrons after they were deflected by the protons (**Figure 17.13**). At lower electron energies, their "scattered" electrons merely gave them a higher-resolution picture of the same old fuzzballs. But at energies so high that the electrons blew the protons and neutrons to bits, they found a surprise. Some of the electrons were deflected through very large angles, as though they were bouncing off hard little granules buried deep within the fuzzball.

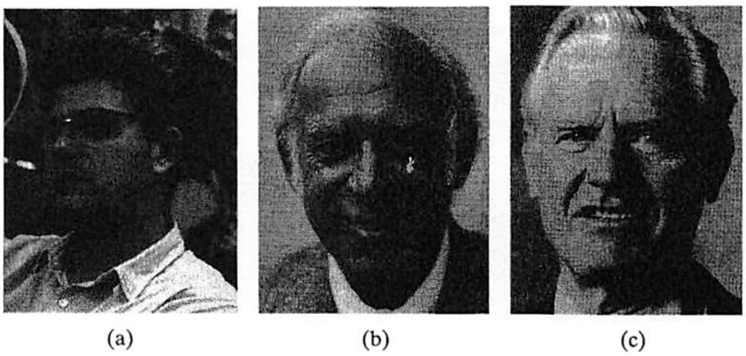

(a) (b) (c)

Figure 17.12
(a) Richard Taylor, (b) Jerome Friedman, and (c) Henry Kendall. In much the same way that Rutherford probed the interiors of atoms by bombarding them with alpha particles, they probed the interior of protons and neutrons by bombarding them with high-energy electrons hurled by an electron accelerator. And just as the scattering of Rutherford's alpha particles revealed a small dense core within each atom—the nucleus—their experiment revealed that within each proton and each neuton lie three tiny force centers: quarks.

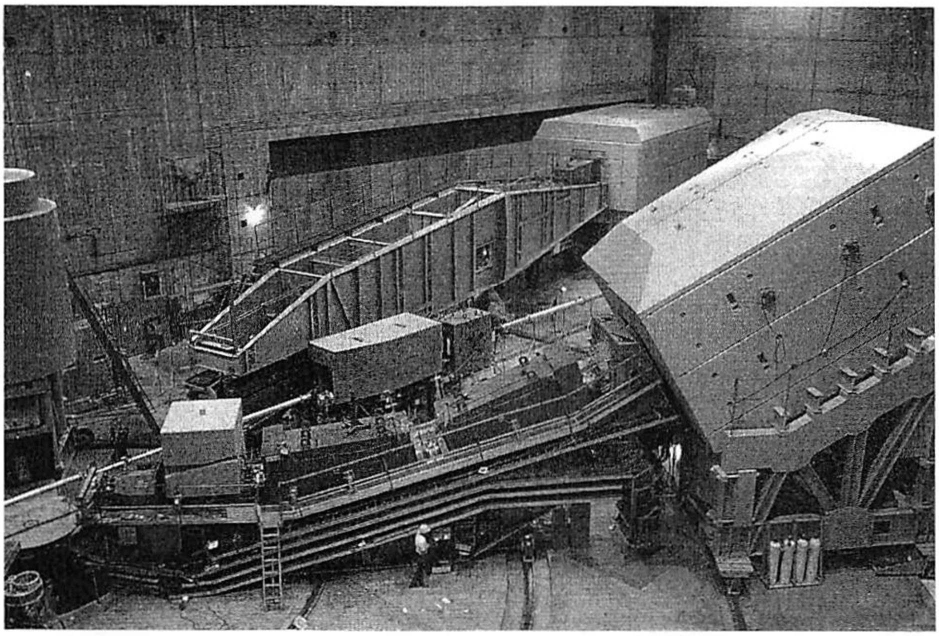


Figure 17.13
The enormous electron detectors at the Stanford electron accelerator. The electron beam enters from the left and collides with protons in a target. The deflected electrons are then analyzed by three detectors: the cylindrical tank at the far left, the large detector in the foreground, and the other large detector in the background.

The experiment and its outcome paralleled Rutherford's discovery of a tiny hard nucleus deep within what had been supposed to be a fuzzball atom (Section 8.2). Only this time there appeared to be not one but three tiny force centers within the proton and within the neutron. Taylor, Friedman, and Kendall had found Gell-Mann's quarks.

Scientists had thought that the proton, neutron, and electron, the three building blocks of all atoms, were "fundamental"—not made of still smaller particles. This might be true of the electron, but quarks imply that the proton and neutron are composite objects, not fundamental particles. Maybe quarks are truly fundamental, or maybe not. The Large Hadron Collider will penetrate to new depths of smallness and could discover that quarks, too, are composite particles. Will we eventually come to the end of nature's successive seeds within seeds (**Figure 17.14**)? Nobody knows.

Physicists have found a version of quantum field theory that describes the interactions between quarks and that has so far agreed with all experiments designed to test it. In this theory, the strong force acts directly between quarks, and the force acting between protons and neutrons is a consequence only of the forces between their quarks. The force field (analogous to the EM field) that is quantized in this new theory is the **strong force field,** and the matter field (analogous to the electron field) that is quantized is the **strong matter field.** The quanta of the strong matter field are quarks of two types, called **u-quarks** and **d-quarks** (and their antiparticles). They are the material particles of this theory, playing a role similar to the electron's role in quantum electrodynamics. The theory predicts that there are two stable configurations of u- and d-quarks, namely, the proton made of two u-quarks and one d-quark, and the neutron made of one u-quark and two d-quarks. This is why there are protons and neutrons! In addition to feeling and exerting the strong force, quarks must also experience the electric force, because protons experience this force and quarks are supposed to explain protons.

CONCEPT CHECK 5 Surprisingly, quarks turn out to be fractionally charged, the u possessing a charge of +2/3 of a proton's charge and the d possessing a charge of −1/3 of a proton's charge. In this case, one u and two d's would have a net charge of (a) 0; (b) 1; (c) 2.

The quanta of the strong force field are called **gluons** because they "glue" quarks together, and on a larger scale they bind the nucleus together. Think of them as the photons of the strong force. Like the photon, they have no mass and no charge. But there's an important difference between the way gluons relate to the strong force and the way photons relate to the electric force. Gluons themselves exert and feel the strong force, unlike photons, which do not directly feel the electric force. In quantum electrodynamics, "electric charge" can be thought of as "the ability to emit and absorb photons." In the same way, the property of feeling the strong force can be thought of as the ability to emit and absorb gluons. But gluons themselves feel the strong force, which means that gluons can emit gluons, unlike photons, which cannot emit photons.

This ability of gluons to make more gluons explains one of the most curious features of quarks (**Figure 17.15**): The force between quarks grows stronger, not weaker, as they are separated, making it impossible to isolate single quarks. When a quark within a proton is pulled a short distance from its neighboring quarks, the gluons must fly farther in order to reach from that quark to its neighbors. This gives these gluons more time to proliferate in flight, which makes more gluons, which makes the force larger as the distance becomes larger. As the quark is pulled farther away, energy quickly builds up in the strong force field, and this energy creates quark–antiquark pairs. After a brief reshuffling, a new quark is created in the proton from which the first quark had been removed! Furthermore, the removed quark and the new antiquark team up to form an unstable pair. This provides a beautifully crazy explanation of why years of looking for isolated quarks in bubble chambers produced no results. Any attempt to pull a quark away from its neighbors just makes more nonisolated quarks.

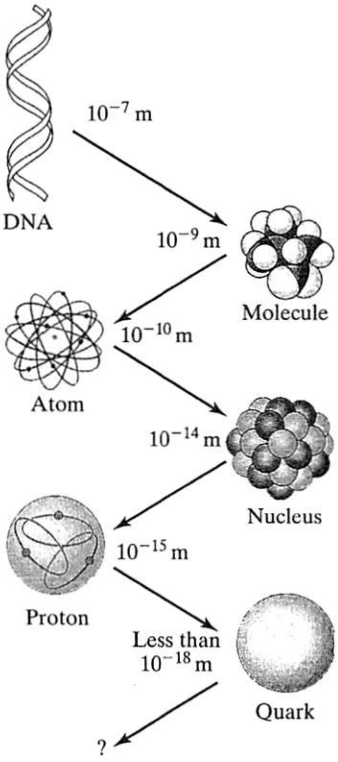
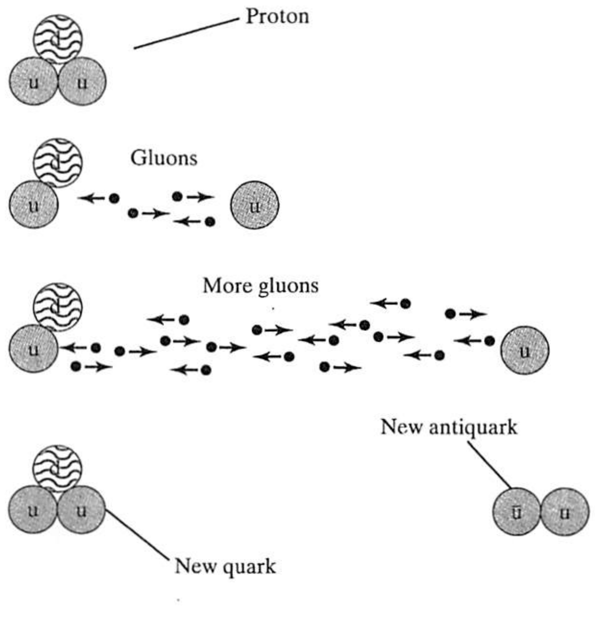


Figure 17.14
Nature's successive seeds within seeds, from DNA to quarks. Note the approximate size of each level.



Suppose you start with the three quarks in a proton—

and begin pulling away one of the quarks. Gluons travel between the quarks.

As the quark is separated further, the gluons make more gluons, which makes the force between the quarks stronger.

Finally, all the gluon energy (strong field energy) creates a quark–antiquark pair, the new quark makes the proton whole again, and the new antiquark combines with the old quark to form an unstable quark–antiquark pair.

Figure 17.15
Here's why you can't separate quarks.

Recall that there are three generations of electroweak particles (Table 17.1). In just the same way, observation reveals three generations of quarks. The second and third generations each consist of two quarks that are heavier and unstable (short-lived) variations on the u- and d-quarks.

Table 17.2 shows the entire setup for the strong force. The last quark to be discovered experimentally, the t-quark, was confirmed in 1994. The t-quark was the most difficult to discover because its mass turned out to be so much larger than the masses of the other five quarks, which (because of $E = mc^2$) meant that much more energy was needed to create it. Weighing in at an estimated 185 proton masses, the t-quark is about as massive as a gold atom! The resemblance between Tables 17.1 and 17.2 is striking and points to a close connection between the electroweak and strong forces. This suggests that there should be a **grand unified theory** that views the electroweak and strong forces as two facets of a single underlying force. So far, such a theory has eluded science's grasp.

Tables 17.1 and 17.2 summarize the current theory of matter at the microscopic level, a theory known as the **standard model**—a boring title for a theory with such fantastic predictions as antimatter, neutrinos, and quarks. To summarize:

The Standard Model

Neglecting gravitational phenomena, only two force fields pervade the universe: the electroweak force field, whose quanta are photons, Ws, and Zs, and the strong force field, whose quanta are gluons. And there are only six matter fields: three generations of electroweak matter fields and three generations of strong matter fields. Ordinary matter arises only from the two first-generation matter fields, whose quanta are electrons and electron-neutrinos interacting via the electroweak force, and u- and d-quarks interacting via the strong force. Second- and third-generation particles are unstable and existed only in the early moments of the big bang and today only briefly following high-energy microscopic events. The electroweak and strong particles, and their properties, are listed in Tables 17.1 and 17.2.

Table 17.2

The theory of the strong force. Throughout the universe there is a strong force field whose quanta are gluons and a strong matter field whose quanta are u-quarks and d-quarks. In addition, there are "second-generation" and "third-generation" matter fields whose quanta are listed below. Only the first-generation particles are stable and play a role in ordinary matter. Protons are made of u-u-d, and neutrons of u-d-d, bound together by the strong force acting between quarks. The unstable second- and third-generation particles decayed during the early moments of the big bang and exist today only during brief high-energy microscopic events.

Generation	Particle type	Mass (proton = 1)	Charge (proton = 1)
1	u-quark	0.003	+2/3
1	d-quark	0.008	−1/3
2	c-quark	1.4	+2/3
2	s-quark	0.1	−1/3
3	t-quark	185	+2/3
3	b-quark	5.0	−1/3
	Exchange particles: gluons	0	0

The standard model represents an enormous unification of knowledge. Neglecting gravity, ordinary matter is a manifestation of only two matter fields and two force fields. Think of the material quanta (u-quarks, d-quarks, electrons, and neutrinos) as the bricks of the universe, and the force quanta (photons, Ws, Zs, gluons) as the cement.

But the standard model cannot be the end of the story. For one thing, it does not incorporate gravity, leaving us with a nonquantum theory of gravity (general relativity—Chapter 11) and a quantum theory of everything else. As you'll see in the next section, this is unsatisfactory. For another thing, which I'll now discuss, the standard model strongly suggests a new field whose quanta have not yet been observed but which might be observed soon.

The God Particle

Title of a Book About the Higgs Particle, by Leon Lederman, Nobel Prize Winner and Former Director of Fermilab Near Chicago

You saw in Chapter 10 that, because of $E = mc^2$, 90% of the proton's or neutron's mass arises from the energy of the strong force fields between the quarks within these particles. So the standard model explains nearly all the mass of ordinary matter. But the standard model doesn't explain why quarks and other particles in Tables 17.1 and 17.2 have mass in the first place. One widely supported hypothesis is that a new kind of fundamental field, called the **Higgs field,**[3] exists throughout the universe. This field, created (like the other fundamental fields) during the big bang, permeates the entire universe in the sense that, except for photons and gluons, every particle interacts at all times with the Higgs field. Even completely isolated particles "feel" the Higgs field!

This interaction acts on accelerated particles in such a way as to resist their acceleration, much as a vat of molasses resists the motion of any object that's submerged in it. The interaction is stronger for quarks, W particles, and Z particles; weaker for electrons and neutrinos; and absent for photons and gluons. So the Higgs field confers a large mass (resistance to acceleration) on quarks, Ws, and Zs; a smaller mass on electrons and neutrinos; and no mass on photons and gluons. However, this molasses analogy is misleading on a couple of counts. First, molasses resists all motion, while the Higgs field resists only accelerated motion. Second, the Higgs field is not the only source of mass; for example, you've seen that the source of at least 90% of the proton's mass arises from the interaction energy among its quarks via Einstein's relation $\mathrm{m} = \mathrm{E}/\mathrm{c}^2$.

Fortunately, this fantasy can be tested against reality. The Higgs field, like other fundamental fields, must obey relativity and quantum theory and so must interact in quantized bundles. High-energy particle accelerators might be able to create these **Higgs particles** within the next several years. The Higgs particle's mass cannot be accurately predicted, but indirect evidence suggests it to be perhaps 200 proton masses—about the mass of a gold atom.[4] Its large mass means, because of $E = mc^2$, that enormous energy is needed to create it in high-energy physics experiments—energies that are beyond the reach of previous particle accelerators. However, the Large Hadron Collider (Figure 17.7) is coming online in 2009–2010, and physicists believe that it will spot the Higgs particle. If so, we will at last have an explanation of the ultimate origin of mass in the universe. It's quite possible that, by the time you read these words, the Higgs particle will have been confirmed or, perhaps, disconfirmed!

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[3] After British physicist Peter Higgs, who invented this idea in 1964.

[4] You might wonder why such a particle, as heavy as a gold atom, cannot simply be discovered moving through space or within ordinary matter. The answer is that, like t-quarks and many other particles, Higgs particles are predicted to be extremely unstable, transmuting into other, less massive particles an instant after they are created. So they are around only briefly, following their creation in high-energy microscopic events such as the collision of two particles in a high-energy particle accelerator.

CONCEPT CHECK 6 According to the standard model, which of the following are fundamental particles? (a) Proton. (b) Electron. (c) Positron. (d) Hydrogen atom. (e) Photon. (f) Water molecule.

CONCEPT CHECK 7 Gluons move (a) slower than lightspeed; (b) at lightspeed; (c) faster than lightspeed.

17.6 QUANTUM GRAVITY: PHYSICS AT THE PLANCK SCALE

Physicists are the Peter Pans of the human race. They never grow up, they keep their curiosity.
I. I. Rabi, Physicist

Physicists have had considerable success in unifying not only all known forces but also all known material particles. Except for gravity, all fundamental forces *and all particles of ordinary matter* have been shown to arise from just a handful of force fields and matter fields. The obvious parallels between the electroweak and strong forces (Tables 17.1 and 17.2) suggest that there should be a single grand unified theory that unites the electroweak and strong forces, although such a theory has not yet been found.

But even an experimentally verified grand unified theory would leave gravity out of the picture. One reason it has been so hard to work gravity into these theories is that so little is known about it at the microscopic level because it is so weak at this level. For example, the gravitational attraction between two protons is a trillion trillion trillion times weaker than their electric repulsion. Only if there are large concentrations of matter, as in a planet or star, are gravitational effects strong enough to be easily observed. In large aggregations of matter, the electric effects of protons and electrons largely cancel each other, while gravity adds up because it's always attractive, so gravity dominates.

Einstein's general theory of relativity has proven correct over an enormous range of phenomena. It is a nonquantum field theory whose field is the spacetime curvature that is caused by masses (Chapter 11). The obvious path toward incorporating this theory with the theories of the other forces would be to subject the gravitational field to the principles of quantum theory. But this turns out to be no simple matter.

General relativity describes gravity as a smooth curvature of space in response to the presence of mass. It works fine over astronomical distances and ordinary macroscopic distances. But over extremely small distances, the smooth curvature described by general relativity conflicts with the most basic quantum principle: the uncertainty principle.

Here's why. Recall (Chapter 13) that the uncertainty principle will not allow the microscopic world to sit still. A highly confined particle must have a highly uncertain speed and therefore a high average speed. In quantum field theory, this principle translates into fields whose motions at the smallest scale are highly agitated and uncertain. That is, if you enormously magnified a small volume of space, you would find the quantum fields in every tiny part of it are violently fluctuating like the surface of a rapidly boiling soup.

The field we want to quantize is the gravitational field—the curvature of space. A quantum theory of the gravitational field would predict a violently fluctuating curvature of space at the smallest scale. As an illustration, **Figure 17.16** shows a small region of space at five successive levels of magnification. Only at the fourth level of magnification do we begin to observe a little of the submicroscopic turbulence of the gravitational field—undulations of space itself. At the highest (fifth) level of magnification, space fluctuates violently, flying in the face of the smooth spatial curvatures described by general relativity. John Wheeler (**Figure 17.17**) describes this fluctuation of space as "quantum foam."

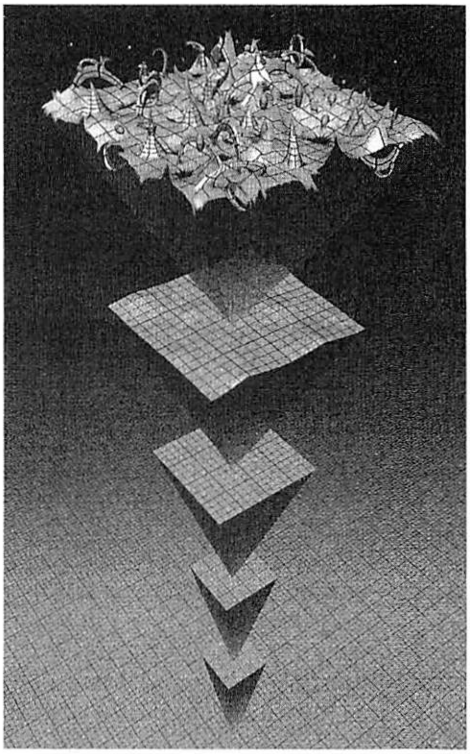

Figure 17.16
A small region of space is taken through a series of five magnifications to reveal its submicroscopic properties. At the highest (fifth) level of magnification, we see the "quantum foam" predicted by quantum field theory. These violent fluctuations fly in the face of the smoother curvatures predicted by general relativity and create great difficulties for any attempt to quantize the general theory of relativity.

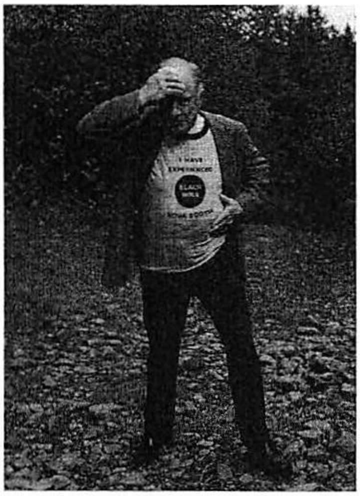

Figure 17.17
John Wheeler, a leading researcher in general relativity and the foundations of quantum theory, has just emerged from Black Hole, Nova Scotia. He appears somewhat dazed. His T-shirt proclaims, "I have experienced Black Hole, Nova Scotia."

Because these violent microscopic fluctions are too much for general relativity to handle, physicists run into absurd answers when they try to quantize the gravitational field. Typically, the probabilities of occurrence of certain microscopic events are predicted to be infinite, and other probabilities are predicted to be negative, even though these predictions are absurd because every probability must lie between 0 and 1. Physicists have made many ingenious attempts to overcome these difficulties. All have failed, except for one. That one is called "the string hypothesis." I'll describe it later.

Taken together, general relativity and quantum theory predict a few fundamentals that are likely to prove valid in the long run regardless of which, if any, theory of quantum gravity is finally verified. One such fundamental is the **graviton,** the quantum of the gravitational field. Like photons (the quantum of the EM field), gravitons have zero mass and zero charge and move at lightspeed. From the quantum point of view, the gravitational forces between two bodies such as Earth and the moon occur via an exchange of gravitons between the two bodies. Gravitons have long been predicted but they have never been observed and perhaps never will be directly observed, because the gravitational force acting at the microscpic level is so weak. For example, if a single proton absorbs a graviton, the proton should recoil, but this recoil is predicted to be so tiny that one cannot hope to observe it.

The basic numerical quantities or "constants" of general relativity and quantum theory would surely show up in any valid theory of quantum gravity. These are the speed of light, Planck's constant, and the "gravitational constant" (6.7×10^{-11} in metric units—see Chapter 5) that fixes the strength of the gravitational force acting between two particular objects. These three constants of nature can be combined in such a way as to yield an estimate of the distance (between particles) at which we would expect quantum-gravitational effects to show up—in other words, the separation between two

As an extreme possibility, it is possible that there is only one theory. . . that is consistent with the existence of intelligent beings capable of wondering about the final theory. If this could be shown, then we would be as close as anyone could hope to a satisfactory explanation of why the world is the way it is.

Steven Weinberg

particles at which we expect their interaction to be significantly influenced by both gravitational and quantum effects. Because quantum effects happen mostly at microscopic distances, and because gravitational forces between two microscopic particles are so much weaker than other forces, it's not surprising that this **Planck length**[5] is tiny, in fact an ultramicroscopic 10^{-35} meters—10 trillionths of a trillionth of a trillionth of a meter! This is also the approximate spatial extent of the disturbances of Figure 17.16.

In a similar way, a fundamental time duration can be worked out, the typical time during which significant changes (in, for instance, the mutual interaction of two particles) would occur when both quantum and gravitational effects are significant. Because the uncertainty principle implies that changes at these small distance scales must be rapid, this **Planck time** is extremely short: 10^{-43} seconds.

Physicists can also work out the predicted energy of typical quantum-gravitational events. The uncertainty principle tells us that events within a region as small as the Planck length must be rapid and hence enormously energetic. This fundamental **Planck energy** turns out to be about a billion joules. This is not so large in our everyday world—it's the amount of chemical energy in 8 gallons (about a gas tank) of gasoline. But this is an enormous amount of energy to pack into a submicroscopic distance. A billion joules has the mass (because of mass–energy equivalence) of some 10^{19} protons, which is surely colossal if packed into a volume measuring only 10^{-35} m across! This **Planck mass** is about 0.01 milligrams, the mass of a typical dust grain.

The Planck length, time, and energy define the **Planck scale,** the approximate size, duration, and energy of typical quantum-gravitational phenomena.

In the 1960s, John Wheeler pointed out a remarkable feature of nature at the Planck scale. He found that in a sphere whose radius is the Planck length and during time intervals whose duration is the Planck time, energy fluctuations as large as the Planck energy are likely to occur and that *this much mass in such a tiny volume causes spacetime to bend back upon itself and form a black hole that is cut off from the rest of the universe.* This phenomenon would break space and time into tiny bundles—quanta of spacetime itself—so that the Planck length and time are the smallest lengths and times that have any physical meaning at all!

It's difficult to observe such phenomena, because the energies of the microscopic events created at today's high-energy accelerators are far smaller than the Planck energy. However, experiment and theory point to a significant trend: The differences among the fundamental forces diminish as the energy rises. The theory of the electroweak force suggests, for example, that at higher energies the weak force increases in strength until it is roughly as strong as the electric force. At still higher energies, the electroweak force becomes as strong as the strong force. And at even higher energies, namely the Planck energy, even the normally tiny gravitational force between microscopic particles becomes as strong as the other fundamental forces.

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[5] Around 1900, before there was a quantum theory of fields or even a completed quantum theory, Max Planck understood that this length, along with the time and energy discussed below, had universal significance.

Here's why. Imagine pushing, say, two protons closer and closer. At "normal" microscopic separations, such as an atom's size (10^{-10} m) or a proton's size (10^{-15} m), the electric force is enormously larger than the gravitational force. But as the outside world does work to make the separation smaller, the forces get stronger and the energy in these force fields increases rapidly. But energy has mass, and mass always pulls gravitationally on other mass. So, as the separation decreases, the mass of the two protons increases, which causes the gravitational force to increase faster than the electric force. Eventually, the mass of the two protons becomes enormous, and in fact when the separation is the Planck length the mass becomes about the Planck mass. At this scale, the microscopic force of gravity about equals the strength of the electric force, and in fact all the forces become roughly equal.

Among those who study quantum gravity, the predicted rough equality of all the fundamental forces at the Planck scale is a strong hint that these forces are aspects of a single underlying force, a unity that becomes obvious at the Planck scale.

The **string hypothesis**[6] is a beautiful and promising attempt to unify general relativity with quantum theory. Although it has had no direct experimental verification during its 25-year history, this hypothesis is good science because it does make specific verifiable predictions that should be tested soon, it does not conflict with any known results, and it could resolve fundamental issues.

The string hypothesis's key idea is that a fundamental particle such as an electron is not concentrated at one infinitely small point, but is instead a tiny loop—think of an infinitely slender rubber band—in a particular state of vibration. These loops are called strings. This spreading out of the point-particle model, so that it resides along a loop rather than at a single point, smoothes its effects on the space around it, smoothing the fluctuations in Figure 17.16 enough for them to be incorporated by general relativity. Strings are small, in fact comparable to—you guessed it—the Planck distance. Viewed from the nuclear or atomic scale, strings are so small that they appear indistinguishable from point particles—which is why we've always thought of them as point particles.

Besides being able to move around in space, strings can vibrate. These vibrations are quantized, and quantum theory allows only particular "modes" (patterns, frequencies, energies) of vibration. According to the string hypothesis, *each such mode of vibration is a different elementary particle:* An electron is a string vibrating one way, a d-quark is a string vibrating another way, a photon is yet another string vibration, and so forth. Underneath all appearances, fundamental particles are really identical: They are all identical strings. Their different properties result merely from their different vibrational modes. The lowest-energy, and hence most stable, of these modes are the particles of ordinary matter—the first-generation particles and exchange particles of Tables 17.1 and 17.2.

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[6] It's commonly called "string theory." Because this book emphasizes the scientific process, I prefer the term *hypothesis* rather than *theory*, indicating the still-tentative, observationally unconfirmed, and incomplete nature of this wonderful idea. As I've emphasized before, the word *theory* is reserved for useful explanatory ideas that have been directly and repeatedly confirmed by observation. For more about the string hypothesis, check out *www.superstringtheory.com*. For nontechnical discussions, click "basics."

This sounds promising, but there is one small fly in the ointment. Strings remove the inconsistencies plaguing quantum theories of gravity *only if the space around us is not 3-dimensional but instead 10-dimensional*, plus one time dimension for an 11-dimensional spacetime. Fewer than 10 spatial dimensions produce logical inconsistencies, as do more than 10. But at exactly 10 spatial dimensions, everything is fine. Of course, this is absurd. Where could the other 7 dimensions be?

Or is it absurd? Remember that the quantum-gravitational effects we want to describe happen only at tiny distances. What if the 7 extra dimensions were, somehow, very *small* (whatever that might mean), so small that we aren't aware of them in our normal activities? In line with this suggestion, the string hypothesis assumes that the other 7 dimensions are tightly "curled up" at every point of our 3-dimensional space. To help you understand this, here's an analogy.[7] Think of a long straight garden hose. When you view it from afar, for instance from a balloon hovering a few thousand feet above your backyard, the hose appears to be a thin straight line, an "uncurved 1-dimensional space." But as your balloon descends and you see the hose up close, you see that the hose's surface is actually 2-dimensional, with the second dimension going around the hose in a circle. From the high-altitude balloon point of view, that second dimension is "curled up" and "small."

Once you accept general relativity's notion that gravity curves space, the string hypothesis's notion of 7 tightly curled spatial dimensions doesn't seem so absurd. The curled-up dimensions exist at every point of our 3-dimensional space—just as the garden hose's curled-up second dimension exists at every point along the hose—but people aren't aware of them because the force of gravity (the only force that can directly detect curvatures in space) cannot probe such small distances in our normal world. In fact, even if an extra dimension were as large as 1 millimeter, it's possible that it would not yet have been detected experimentally, because it's difficult to detect variations in the gravitational force acting over such small distances. The string hypothesis specifies that strings, which do respond to the gravitational force at these small distances, stretch over the full 10 spatial dimensions. The many distinct manners in which these identical strings can wrap around and vibrate within the curled-up dimensions gives strings their distinct properties.

Why on Earth would one entertain such an odd notion, especially when one lacks any real evidence? The reason is that at small distances, quantum field theory and general relativity contradict each other. Yet within their own domains, both theories are as theoretically compelling and as experimentally verified as any scientific theory ever invented. The domain of general relativity is the macroscopic and cosmological level, while the domain of quantum field theory is the microscopic level. There must be a logically consistent way to extend general relativity into the microscopic realm, because, after all, gravity doesn't just vanish at microscopic distances. One observable verification of the need for a theory of gravity that extends into the microscopic realm is the collapse of the centers of galaxies and of some stars into black holes with all their matter concentrated within a microscopic volume that, according to general relativity, is actually a mathematical point. A correct theory of gravity should be able

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[7] This analogy, and Figure 17.16, come from Brian Greene's fine nontechnical book for nonscientists and scientists, *The Elegant Universe: Superstrings, Hidden Dimensions*, and the *Quest for the Ultimate Theory* (New York: Norton & Co., 1999).

to describe such microscopic phenomena without running into logical contradictions, but as you've seen, today's "standard" quantum field theory is unable to do this. The only theory found so far that has some chance of resolving this is string theory.[8]

New theories should predict new things, or at least explain things not yet explained. For example, the existence of three generations of particles (Tables 17.1 and 17.2) might be explainable from general features of the geometry of the seven curled-up dimensions. The string hypothesis also offers a framework for predicting the masses and other properties of every particle, such as why quarks are electrically charged the way they are. Unfortunately, the geometry of the seven curled-up dimensions is so complex that nobody has yet made such predictions.

In the category of as-yet-unobserved phenomena, the graviton turns out to be one of the fundamental patterns of string vibrations. Since gravitons are the most widely expected feature of quantum gravity, this prediction indicates that gravity is woven into the fabric of the string hypothesis.

Finally, the string hypothesis predicts that there is, in addition to the standard-model particles, a new set of particles called "supersymmetric partners," one for each particle of the standard model. They are called "supersymmetric" because, if the grand list of standard-model particles plus the proposed partners actually existed, there would be a certain beautiful symmetry between the material "building-block" particles (electrons, quarks, etc.) and the force-carrying exchange particles (photons, Ws, etc.). This idea, called "supersymmetry," is found in many theories. It is expected to be confirmed (or perhaps disconfirmed), perhaps at the Large Hadron Collider. Supersymmetry emerges quite naturally from the string hypothesis, because patterns of string vibration turn out to come in pairs having just the right supersymmetric properties. The discovery of supersymmetry won't confirm the string hypothesis, but it will put it on a more solid experimental foundation.

This concludes our tour of quantum field theory, and it concludes this book (but do read the epilogue). When we consider general relativity, quantum physics, the string hypothesis, and other contemporary science, it's clear that the natural universe holds possibilities that, to quote philosopher-scientist John Haldane, "are not only queerer than we suppose, but queerer than we can suppose." Perhaps our universe is one among many universes, having their own spacetimes, having different spacetime dimensionalities, and having different physical laws. Perhaps, over many different "times," an infinity of different universes passes into and out of existence, forming collectively a reality that occurs not in space and time at all but that is in some sense beyond space and time.

If we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all . . . be able to take part in the discussion of . . . why it is that we and the universe exist. If we find an answer to that, it would be the ultimate triumph of human reason—for then we would know the mind of God.

Stephen Hawking, Concluding Paragraph of His Book a *Brief History of Time*

In one such universe, in one galaxy called Milky Way, on one planet called Earth, you who read these words and I who write them are privileged beyond measure to be alive and to hold such ideas in our minds. Perhaps our best response to such an immense gift is simply "Thanks."

Answers to Concept Checks and odd-numbered Conceptual Exercises and Problems can be found in the back of the book.

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[8] Another hypothesis called "loop quantum gravity" has been proposed. It seems to be free of contradictions, and it doesn't require extra dimensions. But it "pays" for this simplification by requiring spacetime itself to consist of *movable* loops.

Review Questions

QUANTIZED FIELDS

1. What two theories are combined to form quantum field theory?
2. What is a field? What is a quantized field?
3. Name the quanta of the EM field.
4. Are electrons also "quanta"? Quanta of what?

QUANTUM ELECTRODYNAMICS AND ANTIMATTER

5. What role does the photon play in the electric force between two electrons?
6. Describe the events that are diagrammed in Figure 17.3(a) and (b).
7. What is a muon? A tau?
8. What is an antiparticle? Name two antiparticles.
9. What is antimatter?
10. Describe the creation of a particle–antiparticle pair.
11. Name and describe several devices used to observe the subatomic world.
12. Is empty space really empty? What happens there?

ELECTROWEAK UNIFICATION

13. Why is the neutrino so hard to detect? Which of the four fundamental forces does it experience?
14. Name the six particles that interact via the electroweak force.
15. Name the exchange particle for the electric force. Name the four exchange particles for the electroweak force.
16. The electroweak particles are laid out in "generations." Describe this pattern. How many generations are there?

THE STRONG FORCE

17. Name the fundamental (not composite) particles responsible for the strong force.
18. How were quarks discovered?
19. Are protons fundamental particles? If they are composite particles, of what are they composites? What about electrons?
20. What force or forces do quarks exert on one another?
21. One property of quarks is that they exert and feel the strong force. List at least two other properties.
22. How many kinds of quarks are there? How many of these are found in ordinary matter?
23. Name the exchange particles that carry the strong force.
24. Why do we never observe an isolated quark?

QUANTUM GRAVITY

25. Which of the four fundamental forces can be felt over macroscopic distances?
26. What is a graviton? Has it been discovered experimentally? If so, how? If not, why not?
27. What is the significance of the Planck length and time?
28. What is the string hypothesis?

Conceptual Exercises

QUANTUM ELECTRODYNAMICS AND ANTIMATTER

1. In Figure 17.6(a), what is the evidence that each pair consists of two oppositely charged particles?
2. In Figure 17.6(a), which of the two pairs has the faster-moving particles? How do you know?
3. In Figure 17.6(a), why don't we see the tracks of the two photons that created the two pairs?
4. Each of the two photons created when an electron–positron pair annihilates has a frequency of about 10^{20} Hertz. To what region of the EM spectrum do these photons belong? If the electron and positron were moving instead of at rest, would it make this photon frequency higher or lower?
5. How would the photograph of Figure 17.4 be altered if the particle track had been made by an electron moving upward instead of a positron moving downward?

ELECTROWEAK UNIFICATION

6. Of the 10 electroweak particles (Table 17.1), which ones travel at or near lightspeed?
7. Of the 10 electroweak particles (Table 17.1), which ones can feel the electric force? Which can exchange photons?
8. Into which one of the boxes of Figure 17.10 should the discovery of beta decay be placed?
9. In what ways are the W and Z particles similar to photons? In what ways are they different?

THE STRONG FORCE

10. According to the standard model, which of the following are elementary: neutrino, neutron, quark, muon, photon, antiproton?
11. In what ways are gluons similar to photons? In what ways are they different?
12. In what ways are quarks similar to electrons? In what ways are they different?
13. Give at least one specific reason (other than a general belief in unity) why scientists believe there is probably a single theory that can unite the electroweak and the strong force into a single grand unified force.
14. According to Table 17.2, the total rest-mass of the two u-quarks and one d-quark that make up a proton seems to be only $0.003 + 0.003 + 0.008 = 0.014$ proton mass! Where does the remaining mass of the proton come from?

QUANTUM GRAVITY

15. In the past, it was assumed that the fundamental particles occupied only isolated geometrical points. Why does the string hypothesis assume that they are shaped like tiny loops of string?
16. Explain how a garden hose illustrates the notion of small, curled-up dimensions.

Problems

QUANTUM ELECTRODYNAMICS AND ANTIMATTER

(You'll need to use the formula E = hf from Chapter 12 for some of these.)

1. Each of the two photons created when an electron–positron pair annihilates has a frequency of about 10^{20} Hertz. Find the energy of each photon.
2. A proton–antiproton pair, at rest, annihilates and creates two photons. Using the information in the preceding problem, and the fact that a proton is 1800 times more massive than an electron, find the frequency of each photon.
3. A proton–antiproton pair, at rest, annihilate and create two photons. Find the energy of each photon from the fact that a proton's mass is 1.7×10^{-27} kg. Use this energy to find the frequency of each photon, and compare your answer with the preceding problem.
4. **MAKING ESTIMATES** A large electric power plant generates 1000 MW of electricity. If the energy came from matter-antimatter annihilation, estimate the total mass of matter and of antimatter that would be required each year, assuming that the electricity is generated at an energy efficiency of 50%.
5. **MAKING ESTIMATES** Suppose 1 gram of matter is annihilated with 1 gram of antimatter. Show that the resulting energy could lift the entire U.S. population of about 300 million by about 1 km.