Elementary Particles and Forces

A coherent view of the fundamental constituents of matter and the forces governing them has emerged. It embraces disparate theories, but they may soon be united in one comprehensive description of natural events

by Chris Quigg

The notion that a fundamental simplicity lies below the observed diversity of the universe has carried physics far. Historically the list of particles and forces considered to be elementary has changed continually as closer scrutiny of matter and its interactions revealed microcosms within microcosms: atoms within molecules, nuclei and electrons within atoms, and successively deeper levels of structure within the nucleus. Over the past decade, however, experimental results and the convergence of theoretical ideas have brought new coherence to the subject of particle physics, raising hopes that an enduring understanding of the laws of nature is within reach.

Higher accelerator energies have made it possible to collide particles with greater violence, revealing the subatomic realm in correspondingly finer detail; the limit of experimental resolution now stands at about 10^{-16} centimeter, about a thousandth the diameter of a proton. A decade ago physics recognized hundreds of apparently elementary particles; at today's resolution that diversity has been shown to represent combinations of a much smaller number of fundamental entities. Meanwhile the forces through which these constituents interact have begun to display underlying similarities. A deep connection between two of the forces, electromagnetism and the weak force that is familiar in nuclear decay, has been established, and prospects are good for a description of fundamental forces that also encompasses the strong force that binds atomic nuclei.

Of the particles that now appear to be structureless and indivisible, and therefore fundamental, those that are not affected by the strong force are known as leptons. Six distinct types, fancifully called flavors, of lepton have been identified. Three of the leptons, the electron, the muon and the tau, carry an identical electric charge of -1; they differ, however, in mass. The electron is the lightest and the tau the heaviest of the three. The other three, the neutrinos, are, as their name suggests, electrically neutral. Two of them, the electron neutrino and the muon neutrino, have been shown to be nearly massless. In spite of their varied masses all six leptons carry precisely the same amount of spin angular momentum. They are designated spin-1/2 because each particle can spin in one of two directions. A lepton is said to be right-handed if the curled fingers of a right hand indicate its rotation when the thumb points in its direction of travel and left-handed when the fingers and thumb of the left hand indicate its spin and direction.

For each lepton there is a corresponding antilepton, a variety of antiparticle. Antiparticles have the same mass and spin as their respective particles but carry opposite values for other properties, such as electric charge. The antileptons, for example, include the antielectron, or positron, the antimuon and the antitau, all of which are positively charged, and three electrically neutral antineutrinos.

In their interactions the leptons seem to observe boundaries that define three families, each composed of a charged lepton and its neutrino. The families are distinguished mathematically by lepton numbers; for example, the electron and the electron neutrino are assigned electron number 1, muon number 0 and tau number 0. Antileptons are assigned lepton numbers of the opposite sign. Although some of the leptons decay into other leptons, the total lepton number of the decay products is equal to that of the original particle; consequently the family lines are preserved.

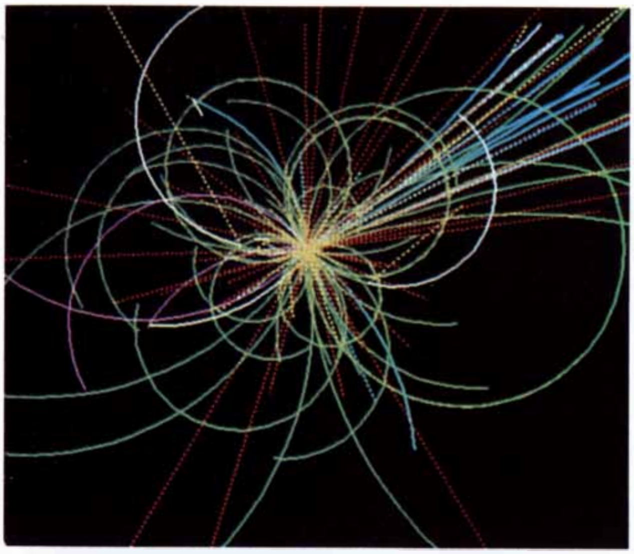
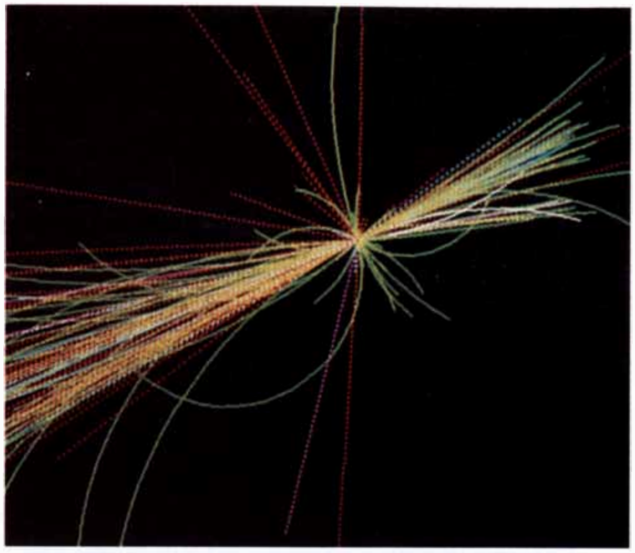
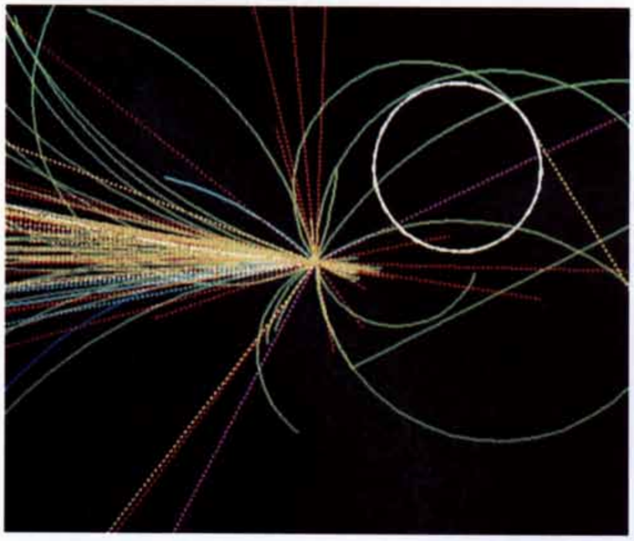
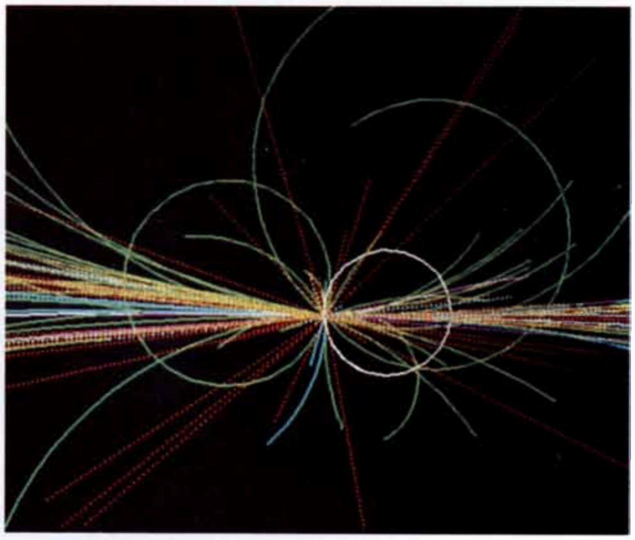
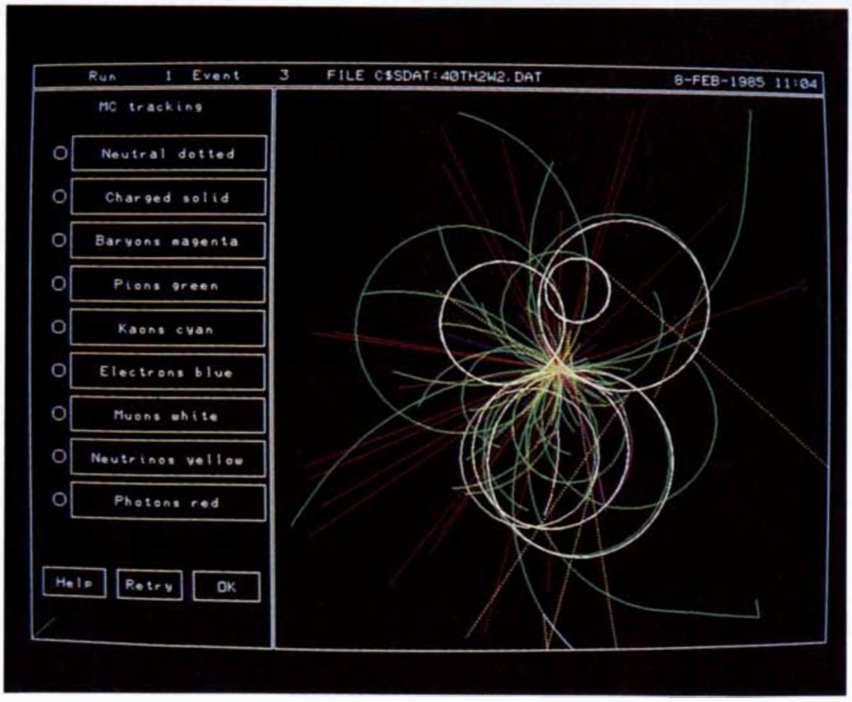
The muon, for example, is unstable. It decays after a mean lifetime of 2.2 microseconds into an electron, an electron antineutrino and a muon neutrino through a process mediated by the weak force. Total lepton number is unaltered in the transformation. The muon number of the muon neutrino is 1, the electron number of the electron is 1 and that of the electron antineutrino is -1. The electron numbers cancel, leaving the initial muon number of 1 unchanged. Lepton number is also conserved in the decay of the tau, which endures for a mean lifetime of 3×10^{-13} second.

The electron, however, is absolutely stable. Electric charge must be conserved in all interactions, and there is no less massive charged particle into which an electron could decay. The decay of neutrinos has not been observed. Because neutrinos are the less massive members of their respective families, their decay would necessarily cross family lines.

Where are leptons observed? The electron is familiar as the carrier of electric charge in metals and semiconductors. Electron antineutrinos are emitted in the beta decay of neutrons into protons. Nuclear reactors, which produce large numbers of unstable free neutrons, are abundant sources of antineutrinos. The remaining species of lepton are produced mainly in high-energy collisions of subnuclear particles, which occur naturally as cosmic rays interact with the atmosphere and under controlled conditions in particle accelerators. Only the tau neutrino has not been observed directly, but the indirect evidence for its existence is convincing.

Quarks

Subnuclear particles that experience the strong force make up the second great class of particles studied in the laboratory. These are the hadrons; among them are the protons, the neutrons and the mesons. A host of other less familiar hadrons exist only ephemerally as the products of high-

DEBRIS of a hypothetical high-energy collision between two protons is depicted in computer simulations made in accordance with the known and conjectured behavior of elementary particles. James Freeman of the Collider Detector Group at the Fermi National Accelerator Laboratory (Fermilab) devised the simulation program using the ISAJET model devised by Frank E. Paige, Jr., of the Brookhaven National Laboratory. The collision, possible outcomes of which are shown, takes place at an energy of 40 TeV (trillion electron volts), far greater than can be reached in today's accelerators. The enormous energy is assumed to give rise to a Higgs boson, a massive particle that plays a crucial role in theory but has not been observed. The Higgs boson promptly decays into two *W* bosons, also short-lived and massive, which then decay by several routes. Some of the particles whose tracks are plotted are the products of the *W* bosons' decay; others emerged from the breakup of the incident protons. The electrons, muons and neutrinos are elementary particles; the baryons, pions and kaons are composites of fundamental constituents, and the photons are quanta of energy. A magnetic field is simulated, causing paths of charged particles to curve, whereas neutral ones are not affected.

energy collisions, from which extremely massive and very unstable particles can materialize. Hundreds of species of hadron have been catalogued, varying in mass, spin, charge and other properties.

Hadrons are not elementary particles, however, since they have internal structure. In 1964 Murray Gell-Mann of the California Institute of Technology and George Zweig, then working at CERN, the European laboratory for particle physics in Geneva, independently attempted to account for the bewildering variety of hadrons by suggesting they are composite particles, each a different combination of a small number of fundamental constituents. Gell-Mann called them quarks. Studies at the Stanford Linear Accelerator Center (SLAC) in the late 1960's in which high-energy electrons were fired at protons and neutrons bolstered the hypothesis. The distribution in energy and angle of the scattered electrons indicated that some were colliding with pointlike, electrically charged objects within the protons and neutrons.

Particle physics now attributes all known hadron species to combinations of these fundamental entities. Five kinds, also termed flavors, of quark have been identified—the up (u), down (d), charm (c), strange (s) and bottom (b) quarks—and a sixth flavor, the top (t) quark, is believed to exist. Like the leptons, quarks have half a unit of spin and can therefore exist in left- and right-handed states. They also carry electric charge equal to a precise fraction of an electron's charge: the d, s and b quarks have a charge of $-1/3$, and the u, c and the conjectured t quark have a charge of $+2/3$. The corresponding antiquarks have electric charges of the same magnitude but opposite sign.

Such fractional charges are never observed in hadrons, because quarks form combinations in which the sum of their charges is integral. Mesons, for example, consist of a quark and an antiquark, whose charges add up to -1, 0 or $+1$. Protons and neutrons consist respectively of two u quarks and a d quark, for a total charge of $+1$, and of a u quark and two d quarks, for a total charge of 0.

Like leptons, the quarks experience weak interactions that change one species, or flavor, into another. For example, in the beta decay of a neutron into a proton one of the neutron's d quarks metamorphoses into a u quark, emitting an electron and an antineutrino in the process. Similar transformations of c quarks into s quarks have been observed. The pattern of decays suggests two family groupings, one of them thought to contain the u and the d quarks and the second the c and the s quarks. In apparent contrast to the behavior of leptons, some quark decays do cross family lines, however; transformations of u quarks into s quarks and of c quarks into d quarks have been observed. It is the similarity of the two known quark families to the families of leptons that first suggested the existence of a t quark, to serve as the partner of the b quark in a third family.

In contrast to the leptons, free quarks have never been observed. Yet

LEPTONS			
PARTICLE NAME	SYMBOL	MASS AT REST (MeV/c²)	ELECTRIC CHARGE
ELECTRON NEUTRINO	ν_e	ABOUT 0	0
ELECTRON	e or e^-	0.511	−1
MUON NEUTRINO	ν_μ	ABOUT 0	0
MUON	μ or μ^-	106.6	−1
TAU NEUTRINO	ν_τ	LESS THAN 164	0
TAU	τ or τ^-	1,784	−1

QUARKS			
PARTICLE NAME	SYMBOL	MASS AT REST (MeV/c²)	ELECTRIC CHARGE
UP	u	310	2/3
DOWN	d	310	−1/3
CHARM	c	1,500	2/3
STRANGE	s	505	−1/3
TOP TRUTH	t	> 22,500; HYPOTHETICAL PARTICLE	2/3
BOTTOM BEAUTY	b	ABOUT 5,000	−1/3

FORCE	RANGE	STRENGTH AT 10^{-13} CENTIMETER IN COMPARISON WITH STRONG FORCE	CARRIER	MASS AT REST (GeV/c²)	SPIN	ELECTRIC CHARGE	REMARKS
GRAVITY	INFINITE	10^{-38}	GRAVITON	0	2	0	CONJECTURED
ELECTROMAGNETISM	INFINITE	10^{-2}	PHOTON	0	1	0	OBSERVED DIRECTLY
WEAK	LESS THAN 10^{-16} CENTIMETER	10^{-13}	INTERMEDIATE BOSONS: W^+	81	1	+1	OBSERVED DIRECTLY
			W^-	81	1	−1	OBSERVED DIRECTLY
			Z^0	93	1	0	OBSERVED DIRECTLY
STRONG	LESS THAN 10^{-13} CENTIMETER	1	GLUONS	0	1	0	PERMANENTLY CONFINED

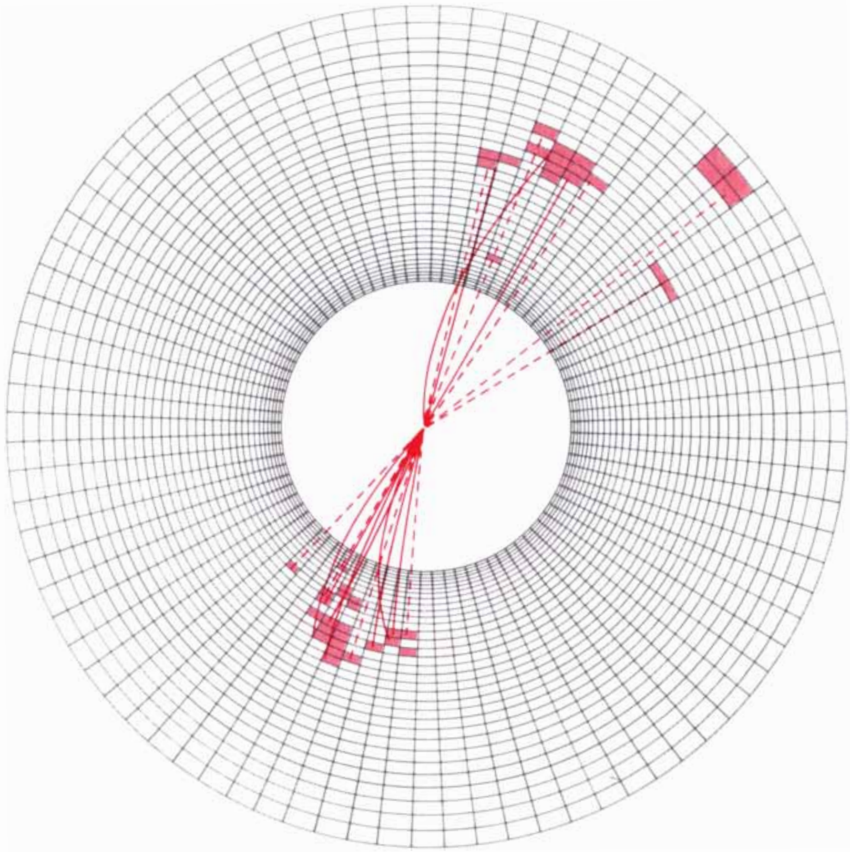
FUNDAMENTAL SCHEME OF NATURE, according to current theory, embraces 12 elementary particles (*top*) and four forces (*bottom*). All the particles listed are thought to be structureless and indivisible; among their properties are an identical amount of spin, given by convention as 1/2, and differing values of electric charge, color charge and mass, given as energy in millions of electron volts (MeV) divided by the square of the speed of light (c). Only the pairs of leptons and quarks at the top of each column are found in ordinary matter; the other particles are observed briefly in the aftermath of high-energy collisions. The four forces thought to govern matter vary in range and strength; although the strong force is the most powerful, it acts only over a distance of less than 10^{-13} centimeter, the diameter of a proton. All the forces are conveyed by force particles, whose masses are given in billions of electron volts (GeV) divided by the square of the speed of light. Because of its weakness, gravity has not been studied experimentally by particle physicists.

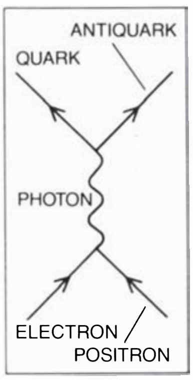
circumstantial evidence for their existence has mounted steadily. One indication of the soundness of the quark model is its success in predicting the outcome of high-energy collisions of an electron and a positron. Because they represent matter and antimatter, the two particles annihilate each other, releasing energy in the form of a photon. The quark model predicts that the energy of the photon can materialize into a quark and an antiquark. Because the colliding electron-positron pair had a net momentum of 0, the quark-antiquark pair must diverge in opposite directions at equal velocities so that their net momentum is also 0. The quarks themselves go unobserved because their energy is converted into additional quarks and antiquarks, which materialize and combine with the original pair, giving rise to two jets of hadrons (most of them pions, a species of meson). Such jets are indeed observed, and their focused nature confirms that the hadrons did not arise directly from the collision but from single, indivisible particles whose trajectories the jets preserve.

The case for the reality of quarks is also supported by the variety of energy levels, or masses, at which certain species of hadron, notably the psi and the upsilon particles, can be observed in accelerator experiments. Such energy spectra appear analogous to atomic spectra: they seem to represent the quantum states of a bound system of two smaller components. Each of its quantum states would represent a different degree of excitation and a different combination of the components' spins and orbital motion. To most physicists the conclusion that such particles are made up of quarks is irresistible. The psi particle is held to consist of a *c* quark and its antiquark, and the upsilon particle is believed to comprise a *b* quark and its antiquark.

What rules govern the combinations of quarks that form hadrons? Mesons are composed of a quark and an antiquark. Because each quark has a spin of 1/2, the net spin of a meson is 0 if its constituents spin in opposite directions and 1 if they spin in the same direction, although in their excited states mesons may have larger values of spin owing to the quarks' orbital motion. The other class of hadrons, the baryons, consist of three quarks each. Summing the constituent quarks' possible spins and directions yields two possible values for the spin of the least energetic baryons: 1/2 and 3/2. No other combinations of quarks have been observed; hadrons that consist of two or four quarks seem to be ruled out.

The reason is linked with the answer to another puzzle. According to the exclusion principle of Wolfgang Pauli, no two particles occupying a minute region of space and possessing half-integral spins can have the same quantum number—the same values of momentum, charge and spin. The Pauli exclusion principle accounts elegantly for the configurations of electrons that determine an element's place in the periodic table. We should expect it to be a reliable guide to the panoply of hadrons as well. The principle would seem to suggest, however, that exotic hadrons such as the delta plus plus and the omega minus particles, which materialize briefly following high-energy collisions, cannot exist. They consist respectively of three *u* and three *s* quarks and possess a spin of 3/2; all three quarks in each of the hadrons must be identical in spin as well as in other properties and hence must occupy the same quantum state.





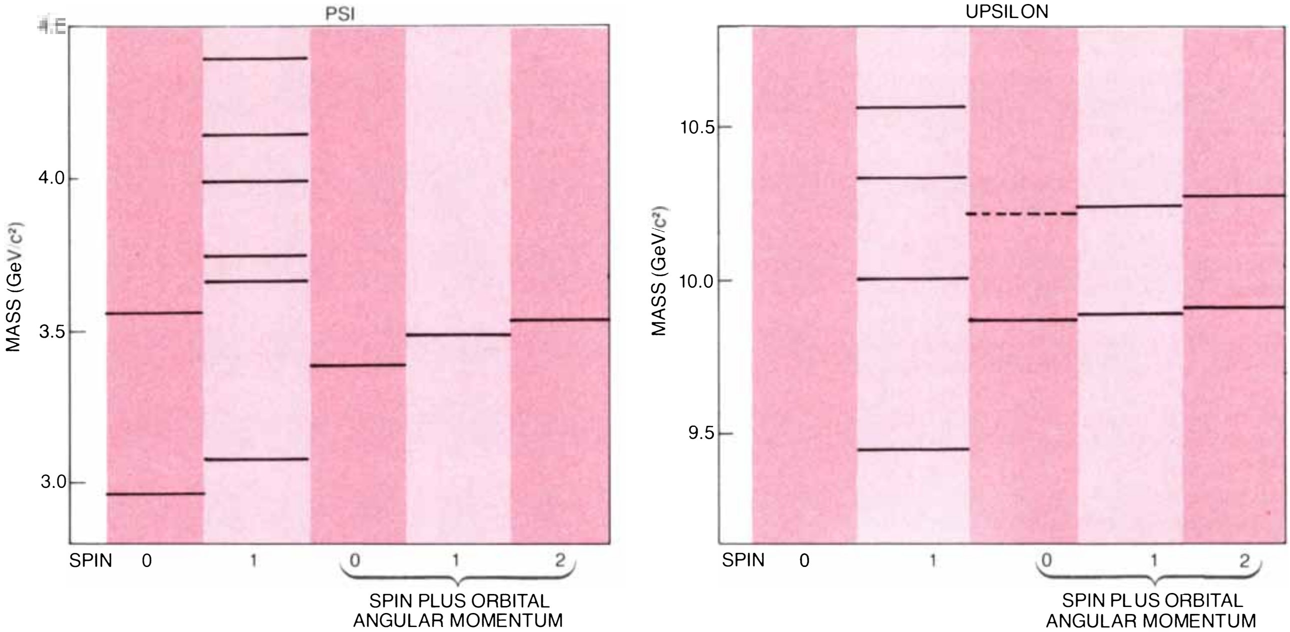
EVIDENCE OF QUARKS, two narrow jets of particles emerge from the collision and mutual annihilation of an electron and an antielectron, or positron. The annihilation releases energy, which gives rise to matter. The detected particles have a variety of masses and spins; some are neutral (*broken lines*) and some electrically charged (*solid lines*). If the particles arose directly from the annihilation, they would be expected to follow widely divergent paths. The focused character of the jets suggests instead that each jet developed from a single precursor: a quark or an antiquark. They are the immediate products of the photon of electromagnetic energy released in the collision, which is diagrammed at the left using arrows to represent the relative motion of the particles. The event shown was recorded in the JADE detector of the PETRA accelerator at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg. The paths of the particles were reconstructed by computer from ionization tracks and from the pattern of energy (*color*) deposited as the particles struck the inner layer of the 2.4-meter-long cylindrical detector.

Colors

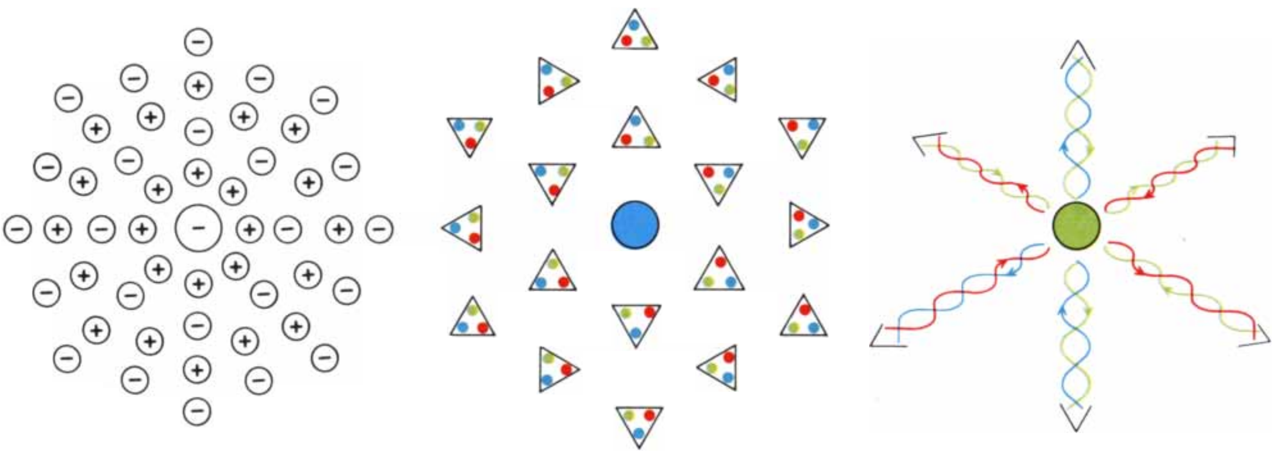
To explain such observed combinations it is necessary to suppose the three otherwise identical quarks are distinguished by another trait: a new kind of charge, whimsically termed color, on which the strong force acts. Each flavor of quark can carry one of three kinds of color charge: red, green or blue. To a red quark there corresponds an antiquark with a color charge of antired (which may be thought of as cyan); other antiquarks bear charges of antigreen (magenta) and antiblue (yellow).

The analogy between this new kind of charge and color makes it possible to specify the rules under which quarks combine. Hadrons do not exhibit a color charge; the sum of the component quarks' colors must be white, or color-neutral. Therefore the only allowable combinations are those of a quark and its antiquark, giving rise to mesons, and of a red, a green and a blue quark, yielding the baryons.

Colored states are never seen in isolation. This concealment is consistent with the fact that free quarks, bearing a single color charge, have never been observed. The activity of the strong



VARIETY OF MASSES at which two-quark systems known as the psi (*left*) and the upsilon (*right*) particles are observed reveal the energy states each can adopt. The psi particle consists of a *c* quark and its antiquark, bound by the color force; the upsilon particle is a similar combination of a *b* quark and its antiquark. Each column within a spectrum of masses corresponds to a different combination of the quarks' spins and orbital angular momentum. Different masses or, equivalently, energy levels within a column represent quantum levels of excitation. The resemblance of the spectra to the spectra of atoms indicates that particles such as the psi and the upsilon are also bound systems of smaller constituents. Such spectra offer insight into the behavior of the color force at short distances.



SCREENING AND CAMOUFLAGE EFFECTS modify the behavior of fundamental forces over distance. The left panel shows an electron in a vacuum; it is surrounded by short-lived pairs of virtual electrons and positrons, which in quantum theory populate the vacuum. The electron attracts the virtual positrons and repels the virtual electrons, thereby screening itself in positive charge. The farther from the electron a real charge is, the thicker the intervening screen of virtual positive charges is and the smaller the electron's effective charge will be. The color force is subject to the same screening effect (*center*). Virtual color charges (mostly quark-antiquark pairs) fill the vacuum; a colored quark attracts contrasting colors, thereby surrounding itself with a screen that acts to reduce its effective charge at increasing distances. An effect called camouflage counteracts screening, however. A quark continuously radiates and reabsorbs gluons that carry its color charge to considerable distances and change its color, in this case from blue to green (*right*). A charge's full magnitude can be felt only outside the space it occupies. Therefore camouflage acts to increase the force felt by an actual quark as it moves away from the first quark, toward the edge of the color-charged region. The net result of screening and camouflage is that at close range the strong interaction, which is based on the color charge, is weaker, whereas at longer ranges it is stronger.

force between colored quarks must be extraordinarily powerful, perhaps powerful enough to confine quarks permanently within colorless, or color-neutral, hadrons. The description of violent electron-positron collisions according to the quark model, however, assumes the quarks that give rise to the observed jets of hadrons diverge freely during the first instant following the collision. The apparent independence of quarks at very short distances is known as asymptotic freedom; it was described in 1973 by David J. Gross and Frank Wilczek of Princeton University and by H. David Politzer, then at Harvard University.

Analogy yields an operational understanding of this paradoxical state of affairs, in which quarks interact only weakly when they are close together and yet cannot be separated. We may think of a hadron as a bubble within which quarks are imprisoned. Within the bubble the quarks move freely, but they cannot escape from it. The bubbles, of course, are only a metaphor for the dynamical behavior of the force between quarks, and a fuller explanation for what is known as quark confinement can come only from an examination of the forces through which particles interact.

The Fundamental Interactions

Nature contrives enormous complexity of structure and dynamics from the six leptons and six quarks now thought to be the fundamental constituents of matter. Four forces govern their relations: electromagnetism, gravity and the strong and weak forces. In the larger world we experience directly, a force can be defined as an agent that alters the velocity of a body by changing its speed or direction. In the realm of elementary particles, where quantum mechanics and relativity replace the Newtonian mechanics of the larger world, a more comprehensive notion of force is in order, and with it a more general term, interaction. An interaction can cause changes of energy, momentum or kind to occur among several colliding particles; an interaction can also affect a particle in isolation, in a spontaneous decay process.

Only gravity has not been studied at the scale on which elementary particles exist; its effects on such minute masses are so small that they can safely be ignored. Physicists have attempted with considerable success to predict the behavior of the other three interactions through mathematical descriptions known as gauge theories.

The notion of symmetry is central to gauge theories. A symmetry, in the mathematical sense, arises when the solutions to a set of equations remain the same even though a characteristic of the system they describe is altered. If a mathematical theory remains valid when a characteristic of the system is changed by an identical amount at every point in space, it can be said that the equations display a global symmetry with respect to that characteristic. If the characteristic can be altered independently at every point in space and the theory is still valid, its equations display local symmetry with respect to the characteristic.

Each of the four fundamental forces is now thought to arise from the invariance of a law of nature, such as the conservation of charge or energy, under a local symmetry operation, in which a certain parameter is altered independently at every point in space. An analogy with an ideal rubber disk may help to visualize the effect of the mathematics. If the shape of the rubber disk is likened to a natural principle and the displacement of a point within the disk is regarded as a local symmetry operation, the disk must keep its shape even as each point within it is displaced independently. The displacements stretch the disk and introduce forces between points. Similarly, in gauge theories the fundamental forces are the inevitable consequences of local symmetry operations; they are required in order to preserve symmetry.

Of the three interactions studied in the realm of elementary particles, only electromagnetism is the stuff of everyday experience, familiar in the form of sunlight, the spark of a static discharge and the gentle swing of a compass needle. On the subatomic level it takes on an unfamiliar aspect. According to relativistic quantum theory, which links matter and energy, electromagnetic interactions are mediated by photons: massless "force particles" that embody precise quantities of energy. The quantum theory of electromagnetism, which describes the photon-mediated interactions of electrically charged particles, is known as quantum electrodynamics (QED).

In common with other theories of the fundamental interactions, QED is a gauge theory. In QED the electromagnetic force can be derived by requiring that the equations describing the motion of a charged particle remain unchanged in the course of local symmetry operations. Specifically, if the phase of the wave function by which a charged particle is described in quantum theory is altered independently at every point in space, QED requires that the electromagnetic interaction and its mediating particle, the photon, exist in order to maintain symmetry.

QED is the most successful of physical theories. Using calculation methods developed in the 1940's by Richard P. Feynman and others, it has achieved predictions of enormous accuracy, such as the infinitesimal effect of the photons radiated and absorbed by an electron on the magnetic moment generated by the electron's innate spin. Moreover, QED's descriptions of the electromagnetic interaction have been verified over an extraordinary range of distances, varying from less than 10^{-18} meter to more than 10^8 meters.

Screening

In particular QED has explained the effective weakening of the electromagnetic charge with distance. The electric charge carried by an object is a fixed and definite quantity. When a charge is surrounded by other freely moving charges, however, its effects may be modified. If an electron enters a medium composed of molecules that have positively and negatively charged ends, for example, it will polarize the molecules. The electron will repel their negative ends and attract their positive ends, in effect screening itself in positive charge. The result of the polarization is to reduce the electron's effective charge by an amount that increases with distance. Only when the electron is inspected at very close range—on a submolecular scale, within the screen of positive charges—is its full charge apparent.

Such a screening effect seemingly should not arise in a vacuum, in which there are no molecules to become polarized. The uncertainty principle of Werner Heisenberg suggests, however, that the vacuum is not empty. According to the principle, uncertainty about the energy of a system increases as it is examined on progressively shorter time scales. Particles may violate the law of the conservation of energy for unobservably brief instants; in effect, they may materialize from nothingness. In QED the vacuum is seen as a complicated and seething medium in which pairs of charged "virtual" particles, particularly electrons and positrons, have a fleeting existence. These ephemeral vacuum fluctuations are polarizable just as are the molecules of a gas or a liquid. Accordingly QED predicts that in a vacuum too electric charge will be screened and effectively reduced at large distances.

The strong interaction affecting quarks that is based on the color charge also varies with distance, although in a contrary manner: instead of weakening with distance the color charge appears to grow stronger. Only at distances of less than about 10^{-13} centimeter, the diameter of a proton, does it diminish enough to allow mutually bound quarks a degree of independence. Yet the explanation for this peculiar behavior is found in a theory that is closely modeled on QED. It is a theory called quantum chromodynamics (QCD), the gauge theory of the strong interactions.

Like QED, QCD postulates force particles, which mediate interactions. Colored quarks interact through the exchange of entities called gluons, just as charged particles trade photons. Whereas QED recognizes only one kind of photon, however, QCD admits eight kinds of gluon. In contrast to the photons of QED, which do not alter the charge of interacting particles, the emission or absorption of a gluon can change a quark's color; each of the eight gluons mediates a different transformation. The mediating gluon is itself colored, bearing both a color and an anticolor.

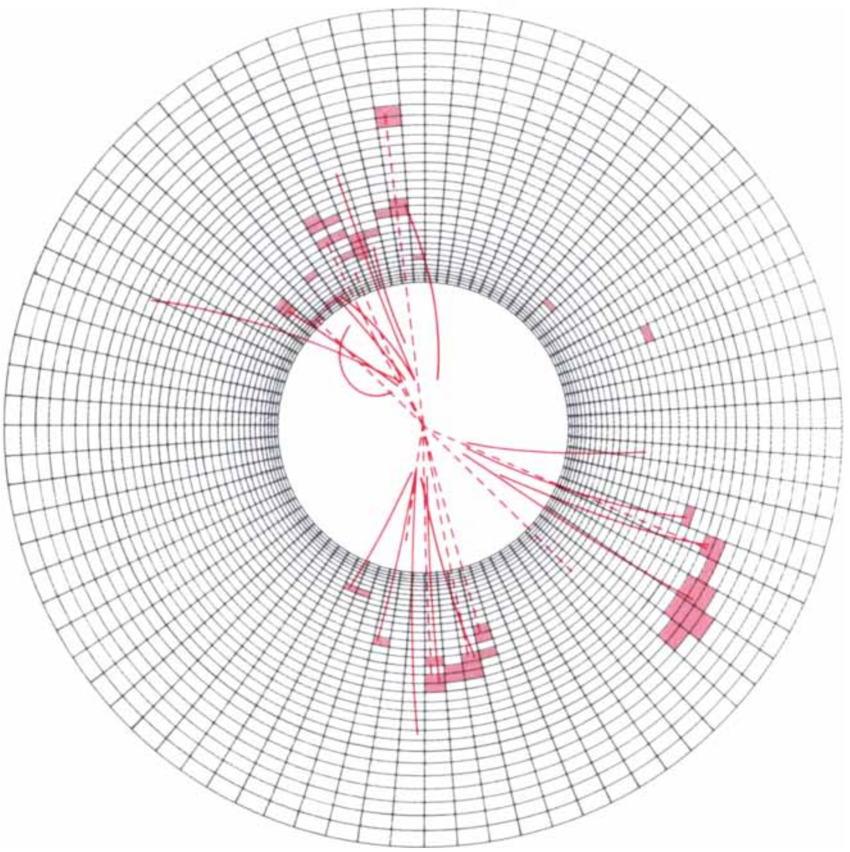
The fact that the gluons are color-charged, in contrast to the electrically neutral photons of QED, accounts for the differing behaviors over distance of the electromagnetic and strong interactions. In QCD two competing effects govern the effective charge: screening, analogous to the screening of QED, and a new effect known as camouflage. The screening, or vacuum polarization, resembles that in electromagnetic interactions. The vacuum of QCD is populated by pairs of virtual quarks and antiquarks, winking into and out of existence. If a quark is introduced into the vacuum, virtual particles bearing contrasting color charges will be attracted to the quark; those bearing a like charge will be repelled. Hence the quark's color charge will be hidden within a cloud of unlike colors, which serves to reduce the effective charge of the quark at greater distances.

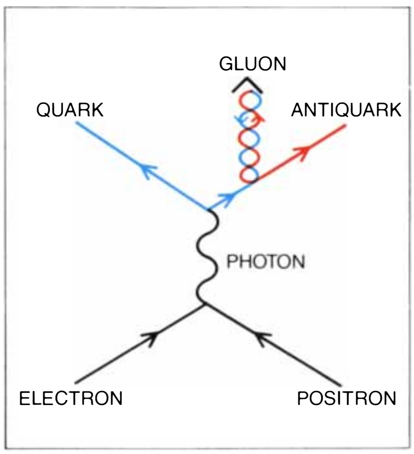
Camouflage

Within this polarized vacuum, however, the quark itself continuously emits and reabsorbs gluons, thereby changing its color. The color-charged gluons propagate to appreciable distances. In effect they spread the color charge throughout space, thus camouflaging the quark that is the source of the charge. The smaller an arbitrary region of space centered on the quark is, the smaller will be the proportion of the quark's color charge contained in it. Thus the color charge felt by a quark of another color will diminish as it approaches the first quark. Only at a large distance will the full magnitude of the color charge be apparent.

In QCD the behavior of the strong force represents the net effect of screening and camouflage. The equations of QCD yield a behavior that is consistent with the observed paradox of quarks: they are both permanently confined and asymptotically free. The strong interaction is calculated to become extraordinarily strong at appreciable distances, resulting in quark confinement, but to weaken and free quarks at very close range.

In the regime of short distances that is probed in high-energy collisions, strong interactions are so enfeebled that they can be described using the methods developed in the context of QED for the much weaker electromagnetic interaction. Hence some of the same precision that characterizes QED can be imparted to QCD. The evolution of jets of hadrons from a quark and an antiquark generated in electron-positron annihilation, for example, is a strong interaction. QCD predicts that if the energy of the collision is high enough, the quark and the antiquark moving off in opposite directions may generate not two but three jets of hadrons. One of the particles will radiate a gluon, moving in a third direction. It will also evolve into



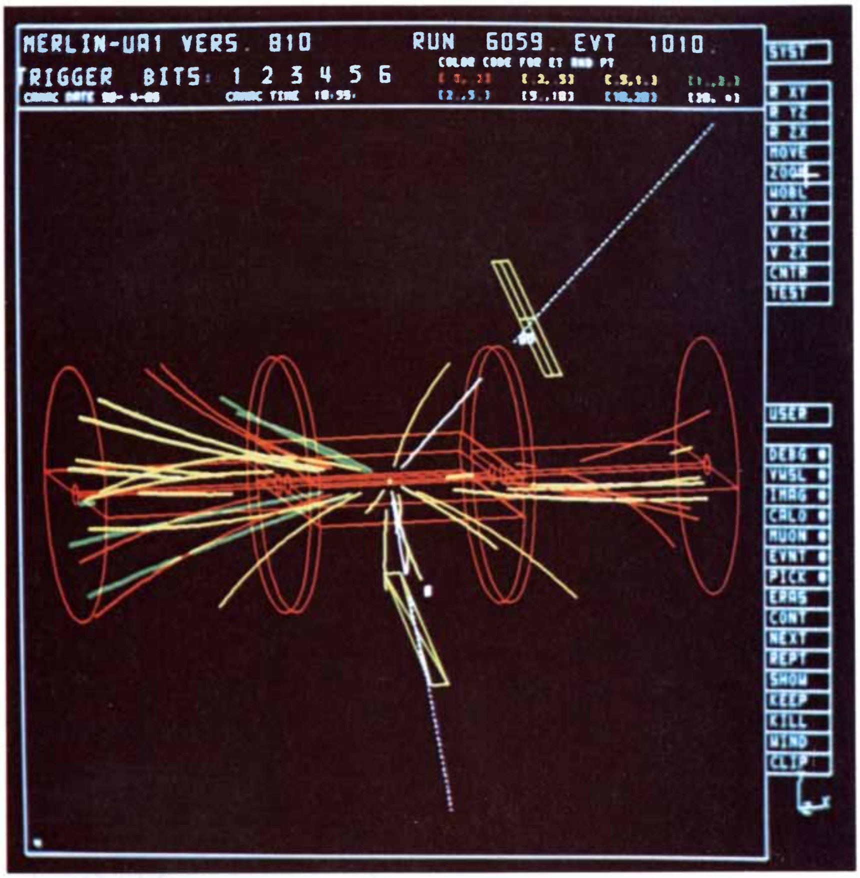


THREE-JET EVENT, recorded in the JADE detector, confirms the existence of the gluon, the mediating particle of the color force. An electron and a positron collided at high energy, creating a quark and an antiquark, as in the event shown on page 87. In this case one of the quarks radiated a gluon (*above*). The quarks and the gluon diverged; each promptly gave rise to a shower of particles, which preserved the trajectory of the original entity (*left*). The event reveals the asymptotic freedom of quarks and gluons: their ability to move independently within a very small region in spite of the enormous strength of the color force across larger distances.

hadrons, giving rise to a third distinct jet—a feature that indeed is commonly seen in high-energy collisions.

The three jets continue along paths set by quarks and gluons moving within an extremely confined space, less than 10^{-13} centimeter. The quark-antiquark pair cannot proceed as isolated particles beyond that distance, the limit of asymptotic freedom. Yet the confinement of quarks and of their interactions is not absolute. Although a hadron as a whole is color-neutral, its quarks do respond to the individual color charges of quarks in neighboring hadrons. The interaction, feeble compared with the color forces within hadrons, generates the binding force that holds the protons and neutrons together in nuclei.

Moreover, it seems likely that when hadronic matter is compressed and heated to extreme temperatures, the hadrons lose their individual identities. The hadronic bubbles of the image used above overlap and merge, possibly freeing their constituent quarks and gluons to migrate over great distances. The resulting state of matter, called quark-gluon plasma, may exist in the cores of collapsing supernovas and in neutron stars. Workers are now studying the possibility of creating quark-gluon plasma in the laboratory through collisions of heavy nuclei at very high energy [see "Hot Nuclear Matter," by Walter Greiner and Horst Stöcker; SCIENTIFIC AMERICAN, January].



SIGNATURE OF THE Z^0 PARTICLE is visible on a computer-synthesized display from the UA1 detector of the Super Proton Synchrotron Collider at CERN, the European laboratory for particle physics in Geneva, where the existence of the W^+ and W^- particles was also established. The Z^0, W^+ and W^- are the particles that transmit the weak force; their existence was predicted by the unified theory of the weak and the electromagnetic interactions, and their discovery vindicated the theory. The tracks depicted within the detector correspond to particles detected following the high-energy collision of a proton and an antiproton. The tracks displayed in white are those of an electron and a positron, the characteristic decay products of the Z^0, which disintegrated soon after it materialized in the collision.

Electroweak Symmetry

Understanding of the third interaction that elementary-particle physics must reckon with, the weak interaction, also has advanced by analogy with QED. In 1933 Enrico Fermi constructed the first mathematical description of the weak interaction, as manifested in beta radioactivity, by direct analogy with QED. Subsequent work revealed several important differences between the weak and the electromagnetic interactions. The weak force acts only over distances of less than 10^{-16} centimeter (in contrast to the long range of electromagnetism), and it is intimately associated with the spin of the interacting particles. Only particles with a left-handed spin are affected by weak interactions in which electric charge is changed, as in the beta decay of a neutron, whereas right-handed ones are unaffected.

In spite of these distinctions theorists extended the analogy and proposed that the weak interaction, like electromagnetism, is carried by a force particle, which came to be known as the intermediate boson, also called the *W* (for weak) particle. In order to mediate decays in which charge is changed, the *W* boson would need to carry electric charge. The range of a force is inversely proportional to the mass of the particle that transmits it; because the photon is massless, the electromagnetic interaction can act over infinite distances. The very short range of the weak force suggests an extremely massive boson.

A number of apparent connections between electromagnetism and the weak interaction, including the fact that the mediating particle of weak interactions is electrically charged, encouraged some workers to propose a synthesis. One immediate result of the proposal that the two interactions are only different manifestations of a single underlying phenomenon was an estimate for the mass of the *W* boson. The proposed unification implied that at very short distances and therefore at very high energies the weak force is equal to the electromagnetic force. Its apparent weakness in experiments done at lower energies merely reflects its short range. Therefore the whole of the difference in the apparent strengths of the two interactions must be due to the mass of the *W* boson. Under that assumption the *W* boson's mass can be estimated at about 100 times the mass of the proton.

To advance from the notion of a synthesis to a viable theory unifying the weak and the electromagnetic interactions has required half a century of experiments and theoretical insight, culminating in the work for which Sheldon Lee Glashow and Steven Weinberg, then at Harvard University, and Abdus Salam of the Imperial College of Science and Technology in London and the International Center for Theoretical Physics in Trieste won the 1979 Nobel prize in physics. Like QED itself, the unified, or electroweak, theory is a gauge theory derived from a symmetry principle, one that is manifested in the family groupings of quarks and leptons.

Not one but three intermediate bosons, along with the photon, serve as force particles in electroweak theory. They are the positively charged W^+ and negatively charged W^- bosons, which respectively mediate the exchange of positive and negative charge in weak interactions, and the Z^0 particle, which mediates a class of weak interactions known as neutral current processes. Neutral current processes such as the elastic scattering of a neutrino from a proton, a weak interaction in which no charge is exchanged, were predicted by the electroweak theory and first observed at CERN in 1973. They represent a further point of convergence between electromagnetism and the weak interaction in that electromagnetic interactions do not change the charge of participating particles either.

To account for the fact that the electromagnetic and weak interactions, although they are intimately related, take different guises, the electroweak theory holds that the symmetry uniting them is apparent only at high energies. At lower energies it is concealed. An analogy can be drawn to the magnetic behavior of iron. When iron is warm, its molecules, which can be regarded as a set of infinitesimal magnets, are in hectic thermal motion and therefore randomly oriented. Viewed in the large the magnetic behavior of the iron is the same from all directions, reflecting the rotational symmetry of the laws of electromagnetism. When the iron cools below a critical temperature, however, its molecules line up in an arbitrary direction, leaving the metal magnetized along one axis. The symmetry of the underlying laws is now concealed.

The principal actor in the breaking of the symmetry that unites electromagnetism and the weak interaction at high energies is a postulated particle called the Higgs boson. It is through interactions with the Higgs boson that the symmetry-hiding masses of the intermediate bosons are generated. The Higgs boson is also held to be responsible for the fact that quarks and leptons within the same family have different masses. At very high energies all quarks and leptons are thought to be massless; at lower energies interactions with the Higgs particle confer on the quarks and leptons their varying masses. Because the Higgs boson is elusive and may be far more massive than the intermediate bosons themselves, experimental energies much higher than those of current accelerators probably will be needed to produce it.

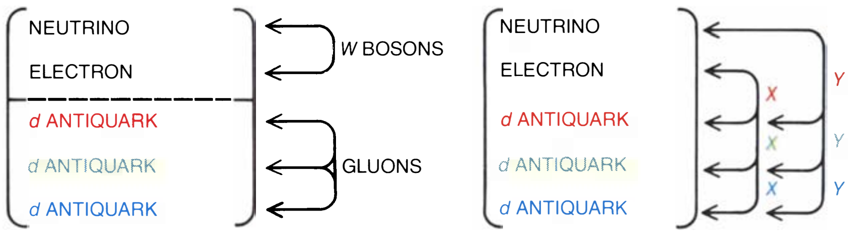
The three intermediate bosons required by the electroweak theory, however, have been observed. Energies high enough to produce such massive particles are best obtained in head-on collisions of protons and antiprotons. In one out of about five million collisions a quark from the proton and an antiquark from the antiproton fuse, yielding an intermediate boson. The boson disintegrates less than 10^{-24} second after its formation. Its brief existence, however, can be detected from its decay products.

In a triumph of accelerator art, experimental technique and theoretical reasoning, international teams at CERN led by Carlo Rubbia of Harvard and Pierre Darriulat devised experiments that in 1983 detected the W bosons and the Z^0 particle. An elaborate detector identified and recorded in the debris of violent proton-antiproton collisions single electrons whose trajectory matched the one expected in a W^- particle's decay; the detector also recorded electrons and positrons traveling in precisely opposite directions, unmistakable evidence of the Z^0 particle. For their part in the experiments and in the design and construction of the proton-antiproton collider and the detector Rubbia and Simon van der Meer of CERN were awarded the 1984 Nobel prize in physics.

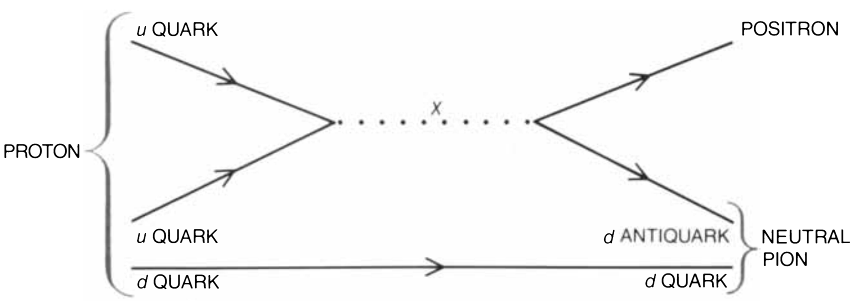
Unification

With QCD and the electroweak theory in hand, what remains to be understood? If both theories are correct, can they also be complete? Many observations are explained only in part, if at all, by the separate theories of the strong and the electroweak interactions. Some of them seem to invite a further unification of the strong, weak and electromagnetic interactions.

Among the hints of deeper patterns is the striking resemblance of quarks and leptons. Particles in both groups are structureless at current experimental resolution. Quarks possess color



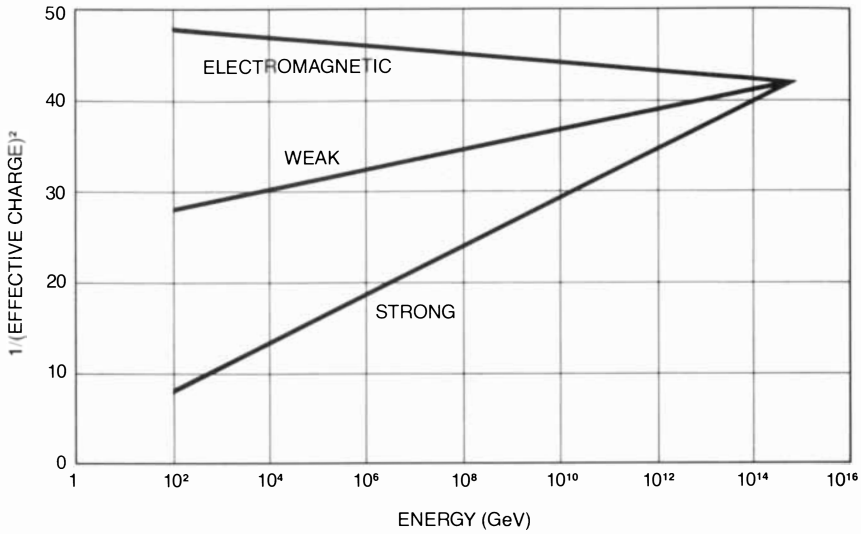
KINSHIP OF ALL MATTER is implied by unified theories of the fundamental forces; one branch of a unified family of elementary particles is shown here. Particles that are equivalent within a theory can metamorphose into one another. Because leptons, such as the electron and the neutrino, respond to the electroweak force alone whereas quarks also respond to the strong force, the two kinds of particle are not equivalent in current theory, and transformations of one into the other have not been observed (*left*). If the simplest unified theories are correct and the fundamental forces are ultimately identical, then at some very high energy quarks and leptons are interconvertible (*right*). Known transformations are mediated by force particles such as the *W* bosons and the gluons; transitions between the quark and lepton groups would be mediated by new force particles, here given as *X* and *Y*.



DECAY OF THE PROTON is a possible consequence of transformations of quarks into leptons, a phenomenon unified theories would allow. The diagram shows one of several proposed decay routes. The proton's constituent *u* quarks combine to form an *X* particle, which disintegrates into a *d* antiquark and a positron (a lepton). The *d* antiquark combines with the remaining quark of the proton, a *d* quark, to form a neutral pion. Because pions are composed of matter and antimatter, they are short-lived; the mutual annihilation of their constituents will release energy in the form of two photons. The positron is also ephemeral: an encounter with a stray electron, its antiparticle, will convert it into energy as well.

charges whereas leptons do not, but both carry a half unit of spin and take part in electromagnetic and weak interactions. Moreover, the electroweak theory itself suggests a relation between quarks and leptons. Unless each of the three lepton families (the electron and its neutrino, for example) can be linked with the corresponding family of quarks (the *u* and *d* quarks, in their three colors) the electroweak theory will be beset with mathematical inconsistencies.

What is known about the fundamental forces also points to a unification. All three can be described by gauge theories, which are similar in their mathematical structure. Moreover, the strengths of the three forces appear likely to converge at very short distances, a phenomenon that would be apparent only at extremely large energies. We have seen that the electromagnetic charge grows strong at short distances, whereas the strong, or color, charge becomes increasingly feeble. Might all the interactions become comparable at some gigantic energy?



CONVERGENCE OF FORCES at extremely high energies, which are equivalent to very small scales of distance, is expected in unified theories. The graph gives an inverse measure of the forces' intrinsic strength; that of the strong and weak forces diminishes with energy, whereas that of electromagnetism increases. The simplest unified theory predicts that the fundamental identity of the three forces is revealed in interactions taking place at an energy of more than 10^{15} GeV, which corresponds to a distance of less than 10^{-29} centimeter.

If the interactions are fundamentally the same, the distinction between quarks, which respond to the strong force, and leptons, which do not, begins to dissolve. In the simplest example of a unified theory, put forward by Glashow and Howard Georgi of Harvard in 1974, each matched set of quarks and leptons gives rise to an extended family containing all the various states of charge and spin of each of the particles.

The mathematical consistency of the proposed organization of matter is impressive. Moreover, regularities in the scheme require that electric charge be apportioned among elementary particles in multiples of exactly 1/3, thereby accounting for the electrical neutrality of stable matter. The atom is neutral only because when quarks are grouped in threes, as they are in the nucleus, their individual charges combine to give a charge that is a precise integer, equal and opposite to the charge of an integral number of electrons. If quarks were unrelated to leptons, the precise relation of their electric charges could only be a remarkable coincidence.

In such a unification only one gauge theory is required to describe all the interactions of matter. In a gauge theory each particle in a set can be transformed into any other particle. Transformations of quarks into other quarks and of leptons into other leptons, mediated by gluons and intermediate bosons, are familiar. A unified theory suggests that quarks can change into leptons and vice versa. As in any gauge theory, such an interaction would be mediated by a force particle: a postulated *X* or *Y* boson. Like other gauge theories, the unified theory describes the variation over distance of interaction strengths. According to the simplest of the unified theories, the separate strong and electroweak interactions converge and become a single interaction at a distance of 10^{-29} centimeter, corresponding to an energy of 10^{24} electron volts.

Such an energy is far higher than may ever be attained in an accelerator, but certain consequences of unification might be apparent even in the low-energy world we inhabit. The supposition that transformations can cross the boundary between quarks and leptons implies that matter, much of whose mass consists of quarks, can decay. If, for example, the two *u* quarks in a proton were to approach each other closer than 10^{-29} centimeter, they might combine to form an *X* boson, which would disintegrate into a positron and a *d* antiquark. The antiquark would then combine with the one remaining quark of the proton, a *d* quark, to form a neutral pion, which itself would quickly decay into two photons. In the course of the process much of the proton's mass would be converted into energy.

The observation of proton decay would lend considerable support to a unified theory. It would also have interesting cosmological consequences. The universe contains far more matter than it does antimatter. Since matter and antimatter are equivalent in almost every respect, it is appealing to speculate that the universe was formed with equal amounts of both. If the number of baryons—three-quark particles such as the proton and the neutron, which constitute the bulk of ordinary matter—can change, as the decay of the proton would imply, then the current excess of matter need not represent the initial state of the universe. Originally matter and antimatter may indeed have been present in equal quantities, but during the first instants after the big bang, while the universe remained in a state of extremely high energy, processes that alter baryon number may have upset the balance.

A number of experiments have been mounted to search for proton decay. The large unification energy implies that the mean lifetime of the proton must be extraordinarily long—10^{30} years or more. To have a reasonable chance of observing a single decay it is necessary to monitor an extremely large number of protons; a key feature of proton-decay experiments has therefore been large scale. The most ambitious experiment mounted to date is an instrumented tank of purified water 21 meters on a side in the Morton salt mine near Cleveland. During almost three years of monitoring none of the water's more than 10^{33} protons has been observed to decay, suggesting that the proton's lifetime is even longer than the simplest unified theory predicts. In some rival theories, however, the lifetime of the proton is considerably longer, and there are other theories in which protons decay in ways that would be difficult to detect in existing experiments. Furthermore, results from other experiments hint that protons can indeed decay.

Open Questions

Besides pointing the way to a possible unification the standard model, consisting of QCD and the electroweak theory, has suggested numerous sharp questions for present and future accelerators. Among the many goals for current facilities is an effort to test the predictions of QCD in greater detail. Over the next decade accelerators with the higher energies needed to produce the massive W and Z^0 bosons in adequate numbers will also add detail to electroweak theory. It would be presumptuous to say these investigations will turn up no surprises. The consistency and experimental successes of the standard model at familiar energies strongly suggest, however, that to resolve fundamental issues we need to take a large step up in interaction energy from the several hundred GeV (billion electron volts) attainable in the most powerful accelerators now being built.

Although the standard model is remarkably free of inconsistencies, it is incomplete; one is left hungry for further explanation. The model does not account for the pattern of quark and lepton masses or for the fact that although weak transitions usually observe family lines, they occasionally cross them. The family pattern itself remains to be explained. Why should there be three matched sets of quarks and leptons? Might there be more?

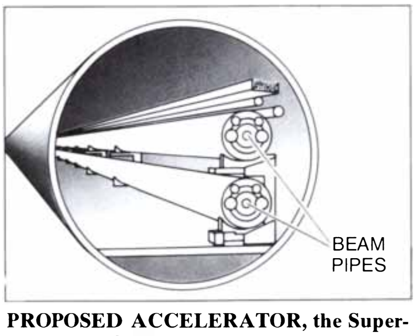
Twenty or more parameters, constants not accounted for by theory, are required to specify the standard model completely. These include the coupling strengths of the strong, weak and electromagnetic interactions, the masses of the quarks and leptons, and parameters specifying the interactions of the Higgs boson. Furthermore, the apparently fundamental constituents and force particles number at least 34: 15 quarks (five flavors, each in three colors), six leptons, the photon, eight gluons, three intermediate bosons and the postulated Higgs boson. By the criterion of simplicity the standard model does not seem to represent progress over the ancient view of matter as made up of earth, air, fire and water, interacting through love and strife. Encouraged by historical precedent, many physicists account for the diversity by proposing that these seemingly fundamental particles are made up of still smaller particles in varying combinations.

There are two other crucial points at which the standard model seems to falter. Neither the separate theories of the strong and the electroweak interactions nor the conjectured unification of the two takes any account of gravity. Whether gravity can be described in a quantum theory and unified with the other fundamental forces remains an open question. Another basic deficiency of the standard model concerns the Higgs boson. The electroweak theory requires that the Higgs boson exist but does not specify precisely how the particle must interact with other particles or even what its mass must be, except in the broadest terms.

The Superconducting Supercollider

What energy must we reach, and what new instruments do we need, to shed light on such fundamental problems? The questions surrounding the Higgs boson, although they are by no means the only challenges we face, are particularly well defined, and their answers will bear on the entire strategy of unification. They set a useful target for the next generation of machines.

It has been proposed that the Higgs boson is not an elementary particle at all but rather a composite object made up of elementary constituents analogous to quarks and leptons but subject to a new kind of strong interaction, often called technicolor, which would confine them within about 10^{-17} centimeter. The phenomena that would reveal such an interaction would become apparent at energies of about 1 TeV (trillion electron volts). A second approach to the question of the Higgs boson's mass and behavior employs a postulated principle known as supersymmetry, which relates particles that differ in spin. Supersymmetry entails the existence of an entirely new set of elusive, extremely massive particles. The new particles would correspond to known quarks, leptons and bosons but would differ in their spins. Because of their mass, such particles would reveal themselves fully only in interactions taking place at very



PROPOSED ACCELERATOR, the Superconducting Supercollider, will make it possible to study interactions at energies of more than 1 TeV. In the design depicted (one of many) the accelerator ring has a diameter of 30 kilometers and is buried 100 meters underground; smaller rings feed protons into the large ring. A cross section of the main tunnel (*above*) shows the two pipes, each about five centimeters in diameter, which will contain the counterrotating beams of protons. Superconducting magnets supercooled with liquid helium to increase their power and efficiency surround each of the pipes, focusing and confining the beams.

high energy, probably about 1 TeV.

Our best hope for producing interactions of fundamental particles at energies of 1 TeV is an accelerator known as the Superconducting Supercollider (SSC). Formally recommended to the Department of Energy in 1983 by the High Energy Physics Advisory Panel, it would incorporate proved technology on an unprecedented scale. A number of designs have been put forward, but all envision a proton-proton or proton-antiproton collider. High-energy beams of protons are produced more readily with current technology than beams of electrons and positrons, although electron-positron collisions are generally simpler to analyze; because protons are composite particles, their collisions yield a larger variety of interactions than collisions of electrons and positrons. Another common feature of the designs is the use of superconducting magnets, first employed on a large scale in the Tevatron Collider at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill. The technology increases the field strength and lowers the power consumption of the magnets that bend and confine the beam.

One of the more compact designs incorporates niobium-titanium alloy magnets cooled to 4.4 degrees Celsius above absolute zero. If the magnets generated fields of five tesla (100,000 times the strength of the earth's magnetic field), two counterrotating beams of protons accelerated to energies of 20 TeV (needed to produce 1-TeV interactions of the quarks and gluons within the protons) could be confined within a loop about 30 kilometers in diameter. In other designs magnetic fields are lower and the proposed facility is correspondingly larger.

It is believed such a device could be operational in 1994, at a cost of $3 billion. The Department of Energy has encouraged the establishment of a Central Design Group to formulate a specific construction proposal within three years and is currently funding the development of magnets for the SSC at several laboratories.

The SSC represents basic research at unprecedented cost on an unmatched scale. Yet the rewards will be proportionate. The advances of the past decade have brought us tantalizingly close to a profound new understanding of the fundamental constituents of nature and their interactions. Current theory suggests that the frontier of our ignorance falls at energies of about 1 TeV. Whatever clues about the unification of the forces of nature and the constituents of matter wait beyond that frontier, the SSC is likely to reveal them.