The Structure of Quarks and Leptons

They have been considered the elementary particles of matter, but instead they may consist of still smaller entities confined within a volume less than a thousandth the size of a proton

by Haim Harari

In the past 100 years the search for the ultimate constituents of matter has penetrated four layers of structure. All matter has been shown to consist of atoms. The atom itself has been found to have a dense nucleus surrounded by a cloud of electrons. The nucleus in turn has been broken down into its component protons and neutrons. More recently it has become apparent that the proton and the neutron are also composite particles; they are made up of the smaller entities called quarks. What comes next? It is entirely possible that the progression of orbs within orbs has at last reached an end and that quarks cannot be more finely divided. The leptons, the class of particles that includes the electron, could also be elementary and indivisible. Some physicists, however, are not at all sure the innermost kernel of matter has been exposed. They have begun to wonder whether the quarks and leptons too might not have some internal composition.

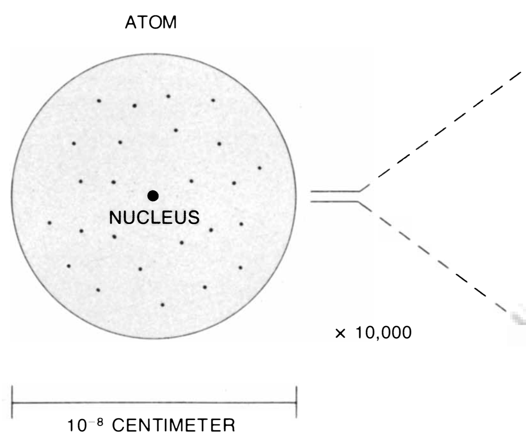
The main impetus for considering still another layer of structure is the conviction (or perhaps prejudice) that there should be only a few fundamental building blocks of matter. Economy of means has long been a guiding principle of physics, and it has served well up to now. The list of the basic constituents of matter first grew implausibly long toward the end of the 19th century, when the number of chemical elements, and hence the number of species of atoms, was approaching 100. The resolution of atomic structure solved the problem, and in about 1935 the number of elementary particles stood at four: the proton, the neutron, the electron and the neutrino. This parsimonious view of the world was spoiled in the 1950's and 1960's; it turned out that the proton and the neutron are representatives of a very large family of particles, the family now called hadrons. By the mid-1960's the number of fundamental forms of matter was again roughly 100. This time it was the quark model that brought relief. In the initial formulation of the model all hadrons could be explained as combinations of just three kinds of quarks.

Now it is the quarks and leptons themselves whose proliferation is beginning to stir interest in the possibility of a simpler scheme. Whereas the original model had three quarks, there are now thought to be at least 18, as well as six leptons and a dozen other particles that act as carriers of forces. Three dozen basic units of matter are too many for the taste of some physicists, and there is no assurance that more quarks and leptons will not be discovered. Postulating a still deeper level of organization is perhaps the most straightforward way to reduce the roster. All the quarks and leptons would then be composite objects, just as atoms and hadrons are, and would owe their variety to the number of ways a few smaller constituents can be brought together. The currently observed diversity of nature would be not intrinsic but combinatorial.

It should be emphasized that as yet there is no evidence quarks and leptons have an internal structure of any kind. In the case of the leptons, experiments have probed to within 10^{-16} centimeter and found nothing to contradict the assumption that leptons are pointlike and structureless. As for the quarks, it has not been possible to examine a quark in isolation, much less to discern any possible internal features. Even as a strictly theoretical conception, the subparticle idea has run into difficulty: no one has been able to devise a consistent description of how the subparticles might move inside a quark or a lepton and how they might interact with one another. They would have to be almost unimaginably small: if an atom were magnified to the size of the earth, its innermost constituents could be no larger than a grapefruit. Nevertheless, models of quark and lepton substructure make a powerful appeal to the aesthetic sense and to the imagination: they suggest a way of building a complex world out of a few simple parts.

Any theory of the elementary particles of matter must also take into account the forces that act between them and the laws of nature that govern the forces. Little would be gained in simplifying the spectrum of particles if the number of forces and laws were thereby increased. As it happens, there has been a subtle interplay between the list of particles and the list of forces throughout the history of physics.

In about 1800 four forces were thought to be fundamental: gravitation, electricity, magnetism and the short-range force between molecules that is responsible for the cohesion of matter. A series of remarkable experimental and theoretical discoveries then led to the recognition that electricity and magnetism are actually two manifestations of the same basic force, which was soon given the name electromagnetism. The discovery of atomic structure brought a further revision. Although an atom is



HIERARCHY OF PARTICLES in the structure of matter currently has four levels. All matter is made up of atoms; the atom con-

electrically neutral overall, its constituents are charged, and the short-range molecular force came to be understood as a complicated residual effect of electromagnetic interactions of positive nuclei and negative electrons. When two neutral atoms are far apart, there are practically no electromagnetic forces between them. When they are near each other, however, the charged constituents of one atom are able to "see" and influence the inner charges of the other, leading to various short-range attractions and repulsions.

As a result of these developments physics was left with only two basic forces. The unification of electricity and magnetism had reduced the number by one, and the molecular interaction had been demoted from the rank of a fundamental force to that of a derivative one. The two remaining fundamental forces, gravitation and electromagnetism, were both long-range. The exploration of nuclear structure, however, soon introduced two new short-range forces. The strong force binds protons and neutrons together in the nucleus, and the weak force mediates certain transformations of one particle into another, as in the beta decay of a radioactive nucleus. Thus there were again four forces.

The development of the quark model and the accompanying theory of quark interactions was the next occasion for revising the list of forces. The quarks in a proton or a neutron are thought to be held together by a new long-range fundamental force called the color force, which acts on the quarks because they bear a new kind of charge called color. (Neither the force nor the charge has any relation to ordinary colors.) Just as an atom is made up of electrically charged constituents but is itself neutral, so a proton or a neutron is made up of colored quarks but is itself colorless. When two colorless protons are far apart, there are essentially no color forces between them, but when they are near, the colored quarks in one proton "see" the color charges in the other proton. The short-range attractions and repulsions that result have been identified with the effects of the strong force. In other words, just as the short-range molecular force became a residue of the long-range electromagnetic force, so the short-range strong force has become a residue of the long-range color force.

One more chapter can be added to this abbreviated history of the forces of nature. A deep and beautiful connection has been found between electromagnetism and the weak force, bringing them almost to the point of full unification. They are clearly related, but the connection is not quite as close as it is in the case of electricity and magnetism, and so they must still be counted as separate forces. Therefore the current list of fundamental forces still has four entries: the long-range gravitational, electromagnetic and color forces and the short-range weak force. Within the limits of present knowledge all natural phenomena can be understood through these forces and their residual effects.

The evolution of ideas about particles and that of ideas about forces are clearly interdependent. As new basic particles are found, old ones turn out to be composite objects. As new forces are discovered, old ones are unified or reduced to residual status. The lists of particles and forces are revised from time to time as matter is explored at smaller scale and as theoretical understanding progresses. Any change in one list inevitably leads to a modification of the other. The recent speculations about quark and lepton structure are no exception; they too call for changes in the complement of forces. Whether the changes represent a simplification remains to be seen.

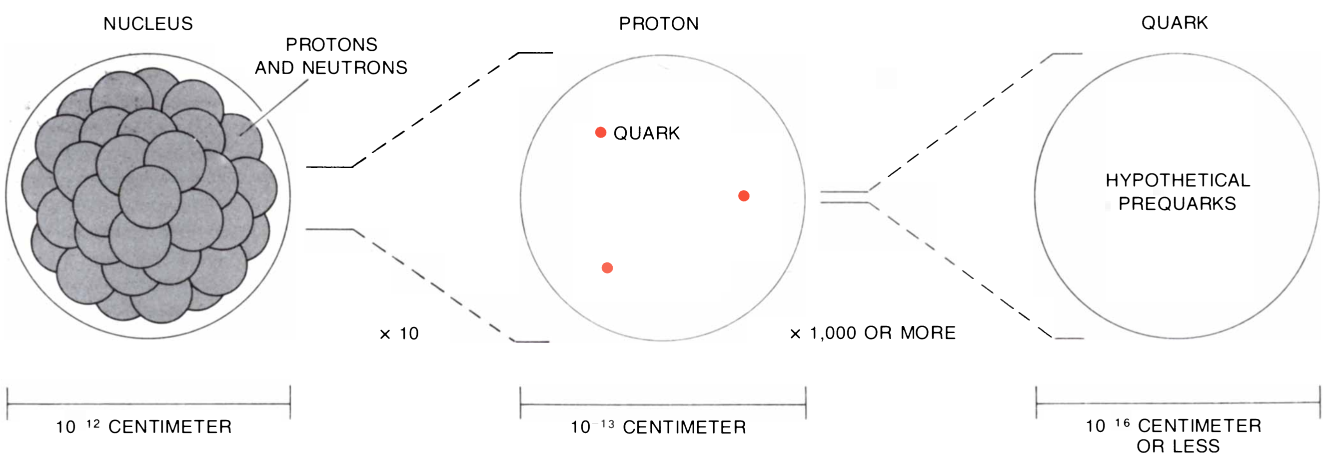
Of the four established fundamental forces, gravitation must be put in a category apart. It is too feeble even to be detected in the interactions of individual particles, and it is not understood in terms of microscopic events. For the other three forces successful theories have been developed and are now widely accepted. The three theories are distinct, but they are consistent with one another; taken together they constitute a comprehensive model of elementary particles and their interactions, which I shall refer to as the standard model.

In the standard model the indivisible constituents of matter are the quarks and the leptons. It is convenient to discuss the leptons first. There are six of them: the electron and its companion the electron-type neutrino, the muon and the muon-type neutrino and the tau and the tau-type neutrino. The electron, the muon and the tau have an electric charge of -1; the three neutrinos are electrically neutral.

There are also six basic kinds of quark, which have been given the names up, down, charmed, strange, top and bottom, or *u, d, c, s, t* and *b*. (The top quark has not yet been detected experimentally, and neither has the tau-type neutrino, but few theorists doubt their existence.) The *u, c* and *t* quarks have an electric charge of $+2/3$, the *d, s* and *b* quarks a charge of $-1/3$. In addition each quark type has three possible colors, which I shall designate red, yellow and blue. Thus if each colored quark is counted as a separate particle, there are 18 quark varieties altogether. Note that each quark carries both color and electric charge, but none of the leptons are colored.

For each particle in this scheme there is an antiparticle with the same mass but with opposite values of electric charge and color. The antiparticle of the electron is the positron, which has a charge of $+1$. The antiparticle of a red *u* quark, with a charge of $+2/3$, is an antired $\bar{u}$ antiquark, with a charge of $-2/3$.

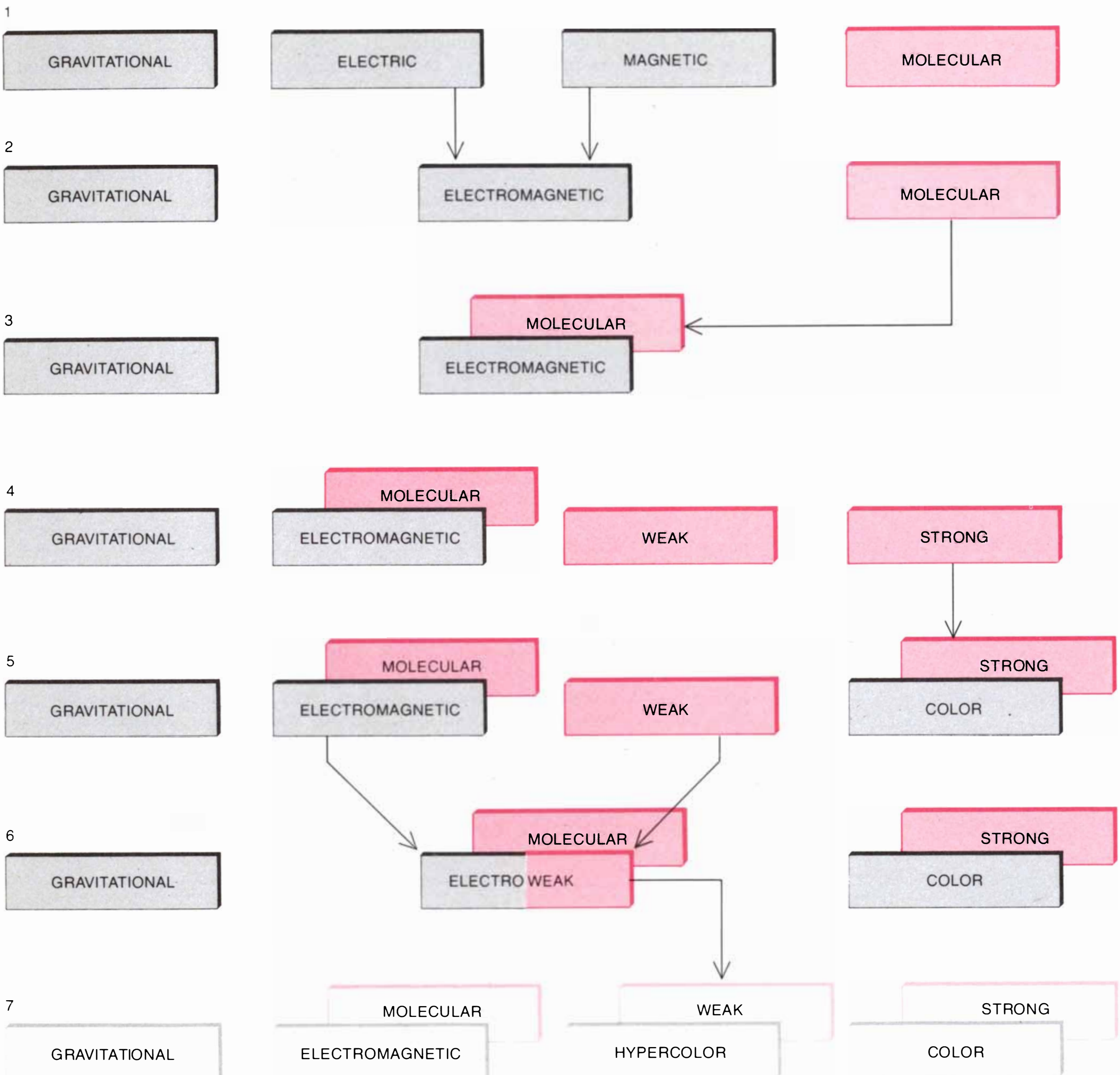
The color property of the quarks is analogous in many ways to electric charge, but because there are three pos-



sists of a nucleus surrounded by electrons; the nucleus is composed of protons and neutrons; each proton and neutron is thought to be composed of three quarks. Recent speculations might add a fifth level: the quark might be a composite of hypothetical finer constituents, which can be generically called prequarks. The leptons, the class of particles that includes the electron, could also consist of prequarks.

sible colors it is appreciably more complicated. Electrically charged particles can be brought together to form an electrically neutral system in only one way: by combining equal quantities of positive and negative charge. A colorless composite particle can be formed out of colored quarks in much the same way, namely by combining a colored quark and an anticolored antiquark. In the case of color, however, there is a second way to form a neutral state: any composite system with equal quantities of all three colors or of all three anticolors is also colorless. For this reason a proton consisting of one red quark, one yellow quark and one blue quark has no net color.

One further property of the quarks and leptons should be mentioned: each particle has a spin, or intrinsic angular momentum, equal to one-half the basic quantum-mechanical unit of angular momentum. When a particle with a spin of 1/2 moves along a straight line, its intrinsic rotation can be either clockwise or counterclockwise when the particle is viewed along the direction of motion. If the spin is clockwise, the particle is said to be right-handed, because when the fingers of the right hand curl in the same direction as the spin, the thumb indicates the direction of motion. For a par-



FUNDAMENTAL FORCES OF NATURE can be classified in a scheme that has evolved together with the list of elementary particles. Here long-range forces are shown in gray and short-range ones in color. Early in the 19th century three long-range forces were thought to be fundamental: the gravitational, the electric and the magnetic. One short-range force, the molecular force responsible for the cohesion of matter, also had fundamental status. James Clerk Maxwell unified electricity and magnetism, and with the discovery of atomic structure it became apparent that the molecular force is not fundamental but instead is a residual effect of electromagnetism. The discovery of the atomic nucleus introduced two short-range forces, the weak and the strong. In the quark model, however, the strong force becomes a residue of a new long-range force called the color force. Furthermore, a deep relation has been found between the weak force and electromagnetism, so that they can be considered partially unified. The sixth row of the chart represents the forces of nature as they are now understood in the "standard model" of elementary-particle physics. A successful model of quark and lepton structure could bring a further revision. In some models, for example, there is a new long-range force called hypercolor, and the weak force is a residue of it. In models of this kind all the fundamental forces of nature are long-range ones. Such models, however, are still highly speculative.

ticle with the opposite sense of spin a left-hand rule describes the motion, and so the particle is said to be left-handed.

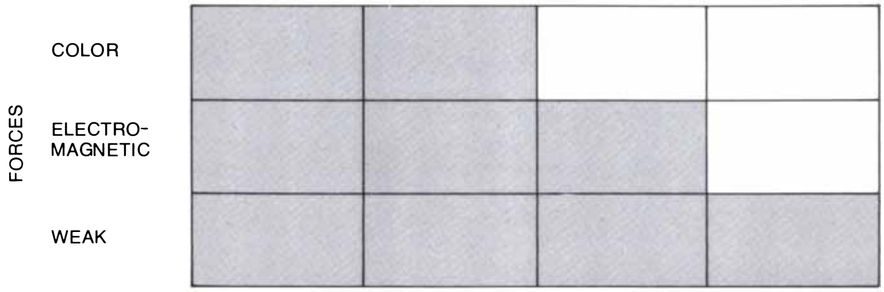
In the standard model the three forces that act on the quarks and leptons are described by essentially the same mathematical structure. It is known as a gauge-invariant field theory or simply a gauge theory. Each force is transmitted from one particle to another by carrier fields, which in turn are embodied in carrier particles, or gauge bosons.

The gauge theory of the electromagnetic force, called quantum electrodynamics or QED, is the earliest and simplest of the three theories. It was devised in the 1940's by Richard P. Feynman, Julian S. Schwinger and Sin-Itiro Tomonaga. QED describes the interactions of electrically charged particles, most notably the electron and the positron. There is one kind of gauge boson to mediate the interactions; it is the photon, the familiar quantum of electromagnetic radiation, and it is massless and has no electric charge of its own. QED is probably the most accurately tested theory in physics. For example, it correctly predicts the magnetic moment of the electron to at least 10 significant digits.

The theory of the color force was formulated by analogy to QED and is called quantum chromodynamics or QCD. It was developed over a period of almost two decades through the efforts of many theoretical physicists. In QCD particles interact by virtue of their color rather than their electric charge. The gauge bosons of QCD, which are responsible for binding quarks inside a hadron, are called gluons. Like the photon, the gluons are massless, but whereas there is just one kind of photon, there are eight species of gluons. A further difference between the photon and the gluons turns out to be even more important. Although the photon is the intermediary of the electromagnetic force, it has no electric charge and hence gives rise to no electromagnetic forces of its own (or at least none of significant magnitude). The gluons, in contrast, are not colorless. They transmit the color force between quarks but they also have color of their own and respond to the color force. This reflexiveness, whereby the carrier of the force acts on itself, makes a complete mathematical analysis of the color force exceedingly difficult.

One peculiarity that seems to be inherent in QCD is the phenomenon of color confinement. It is thought that the color force somehow traps colored objects (such as quarks and gluons) inside composite objects that are invariably colorless (such as protons and neutrons). The colored particles can never escape (although they can form new colorless combinations). It is because of color confinement, physicists suppose, that a quark or a gluon has never been seen in

		QUARKS		LEPTONS	
GENERATIONS	FIRST	u (UP)	d (DOWN)	e (ELECTRON)	ν_e (ELECTRON-TYPE NEUTRINO)
	SECOND	c (CHARMED)	s (STRANGE)	μ (MUON)	ν_μ (MUON-TYPE NEUTRINO)
	THIRD	t (TOP)	b (BOTTOM)	τ (TAU)	ν_τ (TAU-TYPE NEUTRINO)
CHARGES	ELECTRIC	+2/3	−1/3	−1	0
	COLOR	RED YELLOW BLUE	RED YELLOW BLUE	COLORLESS	COLORLESS



STANDARD MODEL of elementary particles includes three "generations" of quarks and leptons, although all ordinary matter can be constructed out of the particles of the first generation alone. The quarks are distinguished by fractional values of electric charge and by a property that is fancifully called color: each quark type comes in red, yellow and blue versions. The leptons have integer units of electric charge and are colorless. The two classes of particles also differ in their response to the various forces. Only the quarks are subject to the color force, and as a result they may be permanently confined inside composite particles such as the proton.

isolation. I must stress that although the idea of color confinement is now widely accepted, it has not been proved to follow from QCD. There may still be surprises in store.

The weak force is somewhat different from the other two, but it can nonetheless be described by a gauge theory of the same general kind. The theory was worked out, and the important connection between the weak force and electromagnetism was established, in the 1960's and the early 1970's by a large number of investigators. Notable contributions were made (in chronological order) by Sheldon Lee Glashow of Harvard University, Steven Weinberg of the University of Texas at Austin, Abdus Salam of the International Centre for Theoretical Physics in Trieste and Gerard 't Hooft of the University of Utrecht.

Curiously, the charges on which the weak force acts are associated with the handedness of a particle. Among both quarks and leptons left-handed particles and right-handed antiparticles have a weak charge, but right-handed particles and left-handed antiparticles are neutral with respect to the weak force. What is odder still, the weak charge is not conserved in nature: a unit of charge can be created out of nothing or can disappear into the vacuum. In contrast, the net quantity of electric charge in an isolated system of particles can never be altered, and neither can the net color. The weak force is also distinguished by its exceedingly short range; its effects extend only to a distance of about 10^{-16} centimeter, or roughly a thousandth of the diameter of a proton.

In the gauge theory of the weak force both the failure of the weak charge to be conserved and the short range of the force are attributed to a mechanism called spontaneous symmetry breaking, which I shall discuss in greater detail below. For now it is sufficient to note that the symmetry-breaking mechanism implies that the weak charge, and the associated handedness of particles, should be conserved at extremely high energy, where a particle's mass is a negligible fraction of its kinetic energy.

Spontaneous symmetry breaking also requires that the gauge bosons of the weak force be massive particles; indeed, they have masses approximately 100 times the mass of the proton. In the standard model there are three such bosons: two of them, designated W^+ and W^-, carry electric charge as well as weak charge; the third, designated Z^0, is electrically neutral. The large mass of the weak bosons accounts for the short range of the force. According to the uncertainty principle of quantum mechanics, the range of a force is inversely proportional to the mass of the particle that transmits it. Thus electromagnetism and the color force, being carried by massless gauge bosons, are effectively infinite in range, whereas the weak force has an exceedingly small sphere of influence. Spontaneous symmetry breaking has still another consequence: it predicts the existence of at least one additional massive particle, separate from the weak bosons. It is called the Higgs particle after Peter Higgs of the University of Edinburgh, who made an important contribution to the theory of spontaneous symmetry breaking.

In the past 10 years the successes of the standard model have given physicists a good deal of self-confidence. All known forms of matter can be constructed out of the 18 colored quarks and the six leptons of the model. All observed interactions of matter can be explained as exchanges of the 12 gauge bosons included in the model: the photon, the eight gluons and the three weak bosons. The model seems to be internally consistent; no one part is in conflict with any other part, and all measurable quantities are predicted to have a plausible, finite value. Internal consistency is not a trivial achievement in a conceptual system of such wide scope. So far the model is also consistent with all experimental results, that is to say, no clear prediction of the model has yet been contradicted by experiment. To be sure, there are some important predictions that have not yet been fully verified; most notably, the tau-type neutrino, the top quark, the weak bosons and the Higgs particle must be found. The first direct evidence of W bosons was recently reported by a group of experimenters at CERN, the European Laboratory for Particle Physics in Geneva. In the next several years new particle accelerators and more sensitive detecting apparatus will test the remaining predictions of the model. Most physicists are quite certain they will be confirmed.

If the standard model has proved so successful, why would anyone consider more elaborate theories? The primary motivation is not a suspicion that the standard model is wrong but rather a feeling that it is less than fully satisfying. Even if the model gives correct answers for all the questions it addresses, many questions are left unanswered and many regularities in nature remain coincidental or arbitrary. In short, the model itself stands in need of explanation.

The strongest hint of some organizing principle beyond the standard model is the proliferation of elementary particles. The known properties of matter are not so numerous or diverse that 24 particles are needed to represent them all. Indeed, there seems to be a great deal of repetition in the spectrum of quarks and leptons. There are three leptons with an electric charge of -1, three neutral leptons, three quarks with a charge of $+2/3$ and three quarks with a charge of $-1/3$. Everything is triplicated, and for no apparent reason. A world constructed by choosing one particle from each of the four groups would seem to have all the necessary variety.

As it turns out, all ordinary matter can indeed be formed from a subset that includes just the u quark, the d quark, the electron and the electron-type neutrino. These four particles and their antiparticles make up the "first generation" of quarks and leptons. The remaining quarks and leptons merely repeat the same pattern in two additional generations without seeming to add anything new. Corresponding particles in different generations are identical in all respects except one: they have different masses. The d, s and b quarks, for example, respond in precisely the same way to the electromagnetic, color and weak forces. For some unknown reason, however, the s quark is roughly 20 times as heavy as the d quark, and the b quark is approximately 600 times as heavy as the d. The mass ratios of the other quarks and of the charged leptons are likewise large and unexplained. (The masses of the neutrinos are too small to have been measured; it is not yet known whether the neutrinos are merely very light or are entirely massless.)

The presence of three generations of quarks and leptons begs for an explanation. Why does nature repeat itself? The pattern of particle masses is also mysterious. In the standard model the masses are determined by approximately 20 "free" parameters that can be assigned any values the theorist chooses; in practice the values are generally based on experimental findings. Is it possible the 20 parameters are all unrelated? Are they fundamental constants of nature with the same status as the velocity of light or the electric charge of the electron? Probably not.

A further tantalizing regularity can be perceived in the electric charges of the quarks and leptons: they are all related by simple ratios and are all integer multiples of one-third the electron charge. The standard model supplies no reason; in principle the charge ratios could have any values. It can be deduced from observation that the ratios of one-third and two-thirds that define the quark charges are not approximations. The proton consists of two u quarks and a d quark, with charges of $2/3 + 2/3 - 1/3$, or $+1$. If these values were not exact and the quarks instead had charges of, say, $+.617$ and $-.383$, the magnitude of the proton's charge would not be exactly equal to that of the electron's, and ordinary atoms would not be electrically neutral. Since atoms can be brought together in enormous numbers, even a slight departure from neutrality could be readily detected.

If the particles and antiparticles that make up a single generation are arranged according to their charge, it is found that every value from -1 to $+1$ in intervals of one-third is occupied by one particle (or, in the case of zero charge, by two particles, namely the neutrino and the antineutrino). The pattern formed raises still more questions. Why has nature favored these values of electric charge but no others, such as $+4/3$ or $-5/3$? It is apparent that all particles with integral charge are colorless and all those with fractional charge are colored. Is there some relation between the electric charge of a particle and its color or between the quarks and the leptons? The standard model implies no such relations, but they seem to exist.

Another motivation for looking beyond the standard model is the continuing desire to unify the fundamental forces, or at least to find some relation

ELECTRIC CHARGE

	+1	+2/3	+1/3	0	−1/3	−2/3	−1
ANTILEPTONS	$\bar{e}$			$\bar{\nu}_e$			
QUARKS		u			d		
ANTIQUARKS			$\bar{d}$			$\bar{u}$	
LEPTONS				ν_e			e

FIRST GENERATION of quarks and leptons forms an orderly pattern when the particles are arranged according to their electric charge. All values of charge from +1 to −1 in intervals of 1/3 are represented. All colored particles have fractional charge and all colorless ones have integral charge. The pattern is an arbitrary feature of the standard model, where charge and color are independent, but it might have some explanation if quarks and leptons are composite.

among them. The cause of parsimony would be served, for example, if two of the forces could be consolidated, as electricity and magnetism were, or if one force could be made a residue of another, as the strong force was made a residue of the color force. Ironically, it may turn out that a simplification of this kind can be attained only by introducing still more forces.

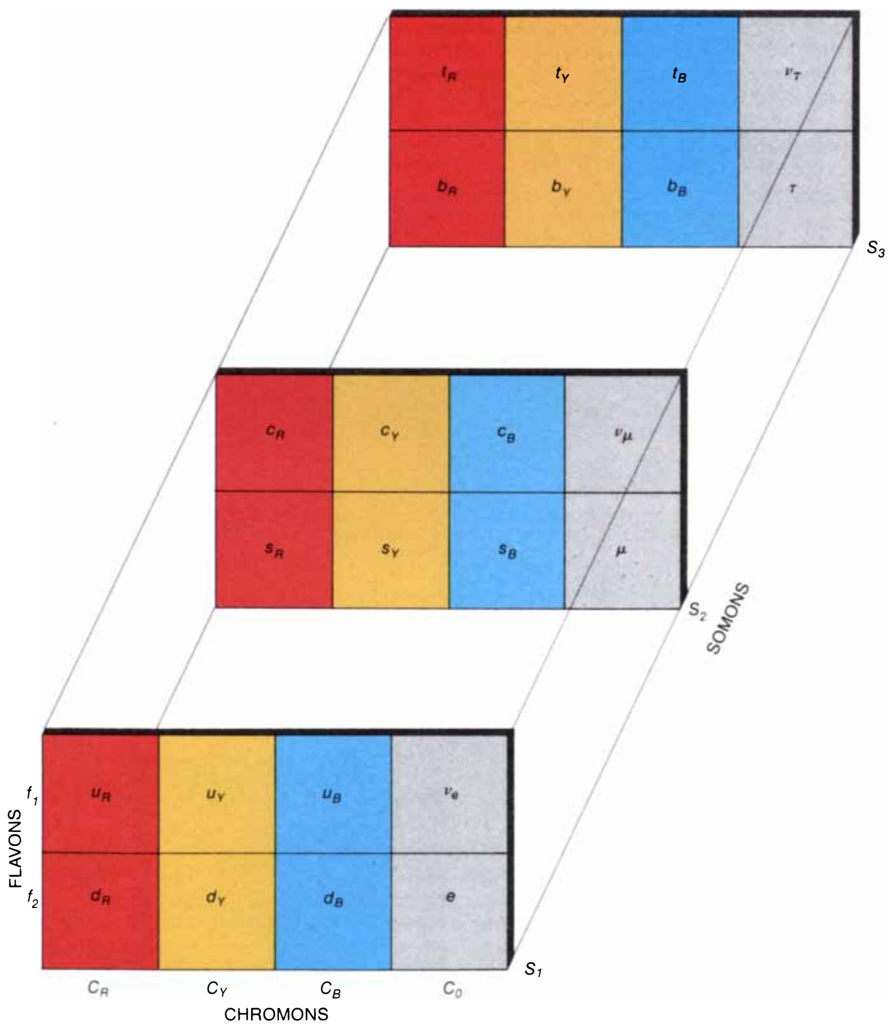
A theory that "goes beyond" the standard model need not contradict or invalidate it. The standard model may emerge as a very good approximation of the deeper theory. The standard model gives a remarkably successful description of all phenomena at distances no smaller than about 10^{-16} centimeter. A deeper theory should therefore focus on events at a still smaller scale. If there are new constituents to be discovered, they must exist within such minuscule regions of space. If there are new forces, their action must be effective only at a distance of less than 10^{-16} centimeter, either because the force is inherently short-range (following the example of the weak force) or because it is subject to some form of confinement (as the color force is).

The search for a theory beyond the standard model was launched almost 10 years ago, and by now several directions have been explored. One promising direction has led to the models known as grand unified theories, which incorporate the electromagnetic, color and weak forces into one fundamental force. The essential idea is to put all the quarks and leptons that make up one generation into a single family; new gauge bosons are then postulated to mediate interactions between the colored quarks and the colorless leptons. The theories account for the regularities noted in the distribution of electric charge and explain the exact commensurability of the quark and lepton charges. On the other hand, they do nothing to reduce the number of fundamental constants, they shed no light on the triplication of the generations and they create certain new theoretical difficulties of their own.

There have been several variations on the theme of grand unification. For example, the concept of horizontal symmetry tackles the triplication problem by establishing a symmetry relation among the generations. The mathematically beautiful idea called supersymmetry relates particles whose spin angular momentum is a half-integer (such as the quarks and leptons) to those with integer spin (such as the gauge bosons). The technicolor theory suggests that the Higgs particle of the standard model is a composite object made up of new fundamental entities; they would be bound together by a new force analogous to the color force and called technicolor. Each of these ideas answers some of the ques-

	PREON	ELECTRIC CHARGE	COLOR	GENERATION NUMBER
FLAVONS	f_1	+1/2	COLORLESS	0
	f_2	−1/2	COLORLESS	0
CHROMONS	C_R	+1/6	RED	0
	C_Y	+1/6	YELLOW	0
	C_B	+1/6	BLUE	0
	C_0	−1/2	COLORLESS	0
SOMONS	S_1	0	COLORLESS	1
	S_2	0	COLORLESS	2
	S_3	0	COLORLESS	3

PREON MODEL assigns three properties of quarks and leptons to three groups of hypothetical constituents called flavons, chromons and somons. A quark or a lepton is formed by choosing one preon from each group. The flavons have the primary responsibility for determining electric charge, the chromons determine color and the somons determine generation number. Ideally each kind of preon would carry just one property, but some adjustment is needed to differentiate the fractional electric charges of the quarks from the integral charges of the leptons. In the version of the model shown here the chromons carry electric charge as well as color.



COMBINATIONS OF PREONS give rise to the 24 quarks and leptons of the three generations. For example, the red s quark is made up of somon S_2 (signifying that the composite is a second-generation particle), in combination with the red chromon and the negative flavon.

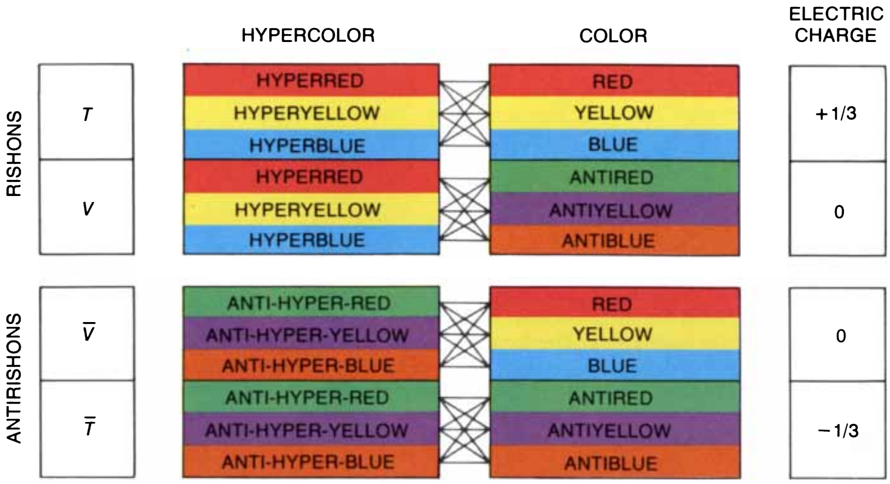
tions that remain open in the standard model. Each idea also fails to answer other questions, raises new difficulties and worsens existing ones, for example by further increasing the number of unrelated arbitrary constants.

In all the above schemes for grand unification it is explicitly assumed that the quarks, the leptons, the photon, the gluons and the weak bosons are the truly fundamental particles of the ultimate theory of nature. The alternative of suggesting that the quarks and leptons are themselves composite is in one sense the most conservative and the least original hypothesis. It is a strategy that has worked before, repeatedly, in going from the atom to the nucleus to the proton to the quark. In another sense the idea of quark and lepton substructure is a most radical proposal. The electron has now been studied for almost a century, and its pointlike nature has been established very well indeed. In the case of the neutrino, which may turn out to be entirely massless, it is even more difficult to imagine an internal structure. The assertion that these particles and the others like them are composites will clearly have to overcome formidable obstacles if it is to have any future.

Offsetting the difficulties of the undertaking are its potential rewards. A fully successful composite model might resolve all the questions left unsettled in the standard model. Such a hypothetical theory would begin by introducing a new set of elementary particles, which I shall refer to generically as prequarks. Ideally there would not be too many of them. Each quark and lepton in the standard model would be accounted for as a combination of prequarks, just as each hadron can be explained as a combination of quarks. The mass of a quark or a lepton would no longer be an arbitrary constant of nature; instead it would be determined by the masses of the constituent prequarks and by the strength of the force that binds the prequarks together. The exact ratios that relate the charge of a quark to that of a lepton would be explained in a similar way: both kinds of composite particles would derive their charges from those of the same constituent prequarks. The entire pattern of quarks and leptons within a generation would presumably reflect some simple rules for combining the prequarks.

The existence of multiple generations might also be explained in a natural way. The quarks and leptons in the higher generations might have an internal constitution similar to that of the corresponding particles of the first generation; the differences could be in the energy and the state of motion of the constituents. Thus the *s* and *b* quarks would be excited states of the *d* quark, and the muon and the tau lepton would be excited states of the electron. Similar excited states are known in all other composite systems, including atoms, nuclei and hadrons. For example, at least a dozen hadrons have been identified in experiments as excited states of the proton; they and the proton itself are all thought to have essentially the same quark composition, namely *uud*.

This imaginary, ideal prequark theory accomplishes everything one might ask of it except for unifying the fundamental forces. Even there some progress is conceivable, since a new force would very likely be introduced to bind the prequarks together; the new force might



RISHON MODEL constructs all the quarks and leptons out of just two species of fundamental particles and their antiparticles. The rishons carry both hypercolor, a property associated with the force that binds them to one another, and ordinary color, which they convey to the composite systems they form. One rishon is electrically charged and the other is neutral.

RISHON COMBINATION	PARTICLE	COLOR	ELECTRIC CHARGE
TTT	$\bar{e}$	COLORLESS	+1
TTV	u	RED YELLOW BLUE	+2/3
TVV	$\bar{d}$	ANTIRED ANTIYELLOW ANTIBLUE	+1/3
VVV	ν_e	COLORLESS	0
$\bar{V}\bar{V}\bar{V}$	$\bar{\nu}_e$	COLORLESS	0
$\bar{V}\bar{V}\bar{T}$	d	RED YELLOW BLUE	−1/3
$\bar{V}\bar{T}\bar{T}$	$\bar{u}$	ANTIRED ANTIYELLOW ANTIBLUE	−2/3
$\bar{T}\bar{T}\bar{T}$	e	COLORLESS	−1

COMBINATIONS OF RISHONS taken three at a time give a correct accounting of all the quarks and leptons (and antiquarks and antileptons) in any one generation. The pattern of electric charges noted in the standard model, and the apparent relation between fractional charge and color, emerge as natural consequences of the way the rishons combine. All the allowed combinations of three rishons or of three antirishons are neutral with respect to hypercolor.

lead to a new understanding of how the known forces are related. Imagining what a successful model might be like, however, is not at all the same thing as actually constructing a realistic and internally consistent one. So far no one has done it.

What has been lacking is a satisfactory theory of prequark dynamics, a theory that would describe how the prequarks move inside a quark or a lepton and that would enable one to calculate the mass and total energy of the system. As I shall set forth below, there are fundamental obstacles to the formulation of such a theory, although I would submit that they are not insurmountable. In the meantime, lacking any persuasive account of prequark motions, theorists have nonetheless been exploring the combinatorial possibilities of the prequark idea, that is, they have been examining the ways quarks and leptons might be built up as specific combinations of finer constituents.

In the past few years several dozen composite models have been proposed; they can be classified in perhaps four or five main groups. No single model solves all problems, answers all questions and is widely accepted. It would be unfair to describe only one scheme, but it is impractical to enumerate them all. I shall present a few of the central ideas.

The first explicit model of quark and lepton substructure was proposed in 1974 by Jogesh C. Pati of the University of Maryland at College Park and Salam, who have since returned to the topic several times in collaboration with John Strathdee of the International Centre for Theoretical Physics. It was they who introduced the term prequark, which I have adopted here as a generic name for hypothetical subconstituents of all kinds. The specific elementary particles of the model devised by Pati and Salam I shall call preons, which is another term of their invention.

The rationale for the preon model begins with the observation that every quark and lepton can be identified unambiguously by listing just three of its properties: electric charge, color and generation number. These properties, then, suggest a straightforward way of organizing a set of constituent particles. Three families of preons are needed. In one family the preons carry electric charge, in another they carry color and in the third they have some property that determines generation number. A given quark or lepton is assembled by selecting exactly one preon from each family.

The preons that determine generation number are called somons, from the Greek *soma*, meaning body, because they have a dominant influence on the mass of the composite system. Since there are three generations of quarks and leptons, there must be three somons. The color of the composite system is determined by preons called chromons; there are four of them, one with the color red, one yellow, one blue and one colorless. The remaining family of preons, which is assigned the role of defining electric charge, needs to have only two members in order for every quark and lepton to be uniquely identified. These last preons have been given the name flavons, after flavor, the whimsical term for whatever property it is that distinguishes the *u* quark from the *d* quark, the *c* from the *s*, the neutrino from the electron and so on.

In the preon model the classification of a composite particle follows directly from its complement of preons. All leptons, for example, are distinguished by a colorless chromon, and all first-generation particles must obviously have a first-generation somon. In the allocation of electric charge, however, a complication arises. If there are only two flavons and if they are the sole carriers of electric charge, not all the charge values observed in nature can be reproduced. The *u* quark and the neutrino, for example, must have the same charge (because they include the same flavon), and so must the *d* quark and the electron. The problem can be solved in any of several ways. In one scheme electric charge is assigned to both the flavons and the chromons, and the total charge of a composite particle is equal to the sum of the two values. Models of this kind can be made to yield the correct charge states, but only by abandoning the principle of having each kind of preon carry just one property.

Another troublesome feature of the preon model is the requirement that composites be formed only by drawing one preon from each family. Why are there no particles made up of three chromons, say, or of two somons and a flavon? The exotic properties of such particles would make them quite conspicuous. It seems likely that if they existed, they would have been detected by now.

Many variations of the preon model have been proposed by other physicists, using the same basic idea but slightly different sets of preons. Notable among the variations are the models suggested by Hidezumi Terazawa, Yoichi Chikashige and Keiichi Akama of the University of Tokyo and by O. Wallace Greenberg and Joseph Sucher of the University of Maryland.

Perhaps the simplest model of quark and lepton structure is the rishon model, which I proposed in 1979. A similar idea was put forward at about the same time by Michael A. Shupe of the University of Illinois at Urbana-Champaign. The model has since been further developed and studied in great detail by Nathan Seiberg and me at the Weizmann Institute of Science in Rehovot. The model postulates just two species of fundamental building blocks, called rishons. (*Rishon* is the Hebrew adjective meaning first or primary.) One rishon has an electric charge of $+1/3$ and the other is electrically neutral. I designate them respectively T and V, for *Tohu Vavohu*, Hebrew for "formless and void," the description of the initial state of the universe given in the first chapter of Genesis. The complementary antirishons have charges of $-1/3$ and zero and are designated $\bar{T}$ and $\bar{V}$.

The model has one simple rule for constructing a quark or a lepton: any three rishons can be assembled to form a composite system, or any three antirishons, but rishons and antirishons cannot be mixed in a single particle. The rule gives rise to 16 combinations, which reproduce exactly the properties of the 16 quarks, antiquarks, leptons and antileptons in the first generation. In other words, every quark and lepton in the first generation corresponds to some allowed combination of rishons or antirishons. (In this system of classification each color is counted separately.)

The pattern of quark and lepton charges is generated as follows. The TTT combination, with rishon charges of $1/3 + 1/3 + 1/3$, has a total charge of $+1$ and therefore corresponds to the positron; similarly, $\bar{T}\bar{T}\bar{T}$ has a total charge of -1 and is identified with the electron. The VVV and $\bar{V}\bar{V}\bar{V}$ combinations are both electrically neutral and represent the neutrino and the antineutrino respectively. The remaining allowed combinations yield fractionally charged quarks. TTV, with a charge of $+2/3$, is the u quark, and TVV, with a charge of $+1/3$, is the $\bar{d}$ antiquark. The analogous antirishon states $\bar{V}\bar{V}\bar{T}$ and $\bar{V}\bar{T}\bar{T}$ correspond to the d quark and the $\bar{u}$ antiquark.

The model also accounts successfully for the color of the composite systems. A T rishon can have any of the three colors red, yellow and blue, whereas a V rishon has an anticolor. Combinations such as $\bar{T}\bar{T}\bar{T}$ and VVV, which designate leptons, can be made colorless since they can include one rishon in each color or one in each anticolor. The other combinations, which yield quarks, must have a net color. For example, a TTV state might have the rishon colors red, blue and antiblue; the antiblue would cancel the blue, leaving the system with a net color of red. In this way the connection between color and electric charge, which was apparent but unexplained in the standard model, is readily understood. Because of the way electric charge and color are allotted to the rishons, all composite systems with fractional charge turn out to be colored, and all systems with an integer charge can be made colorless.

Other regularities of the standard

model also lose their air of mystery when rishons are introduced. Consider the hydrogen atom, made up of a proton and an electron, or in terms of quarks and leptons two *u* quarks, a *d* quark and an electron. The total rishon content of the quarks is four *T*'s, one $\overline{T}$, two *V*'s and two $\overline{V}$'s. The electric charge of the $\overline{T}$ cancels the charge of one *T* rishon, and the *V*'s and $\overline{V}$'s also cancel (they have no charge in any case), leaving the proton with a net charge equal to that of a *TTT* system. The electron's rishon content is just the opposite: $\overline{T}\overline{T}\overline{T}$. Thus it is evident why the proton and the electron have charges of equal magnitude and why the hydrogen atom is neutral: the ultimate sources of the charge are pairs of matched particles and antiparticles.

The rishon model and many other models that explain the pattern of the first generation have difficulty accounting for the second and third generations. It would seem that such models lend themselves well to the scheme of forming each particle in the higher generations as an excited state of the corresponding particle in the first generation. The simplest idea would be to describe the muon, for example, as having the same prequark constituents as the electron, but in the muon the prequarks would have some higher-energy configuration. It is an elegant idea but, regrettably, it appears to be unworkable. The scheme implies differences in energy between the successive excited states that are much larger than the actual differences. The flaw is a fundamental one, and there seems to be no remedy.

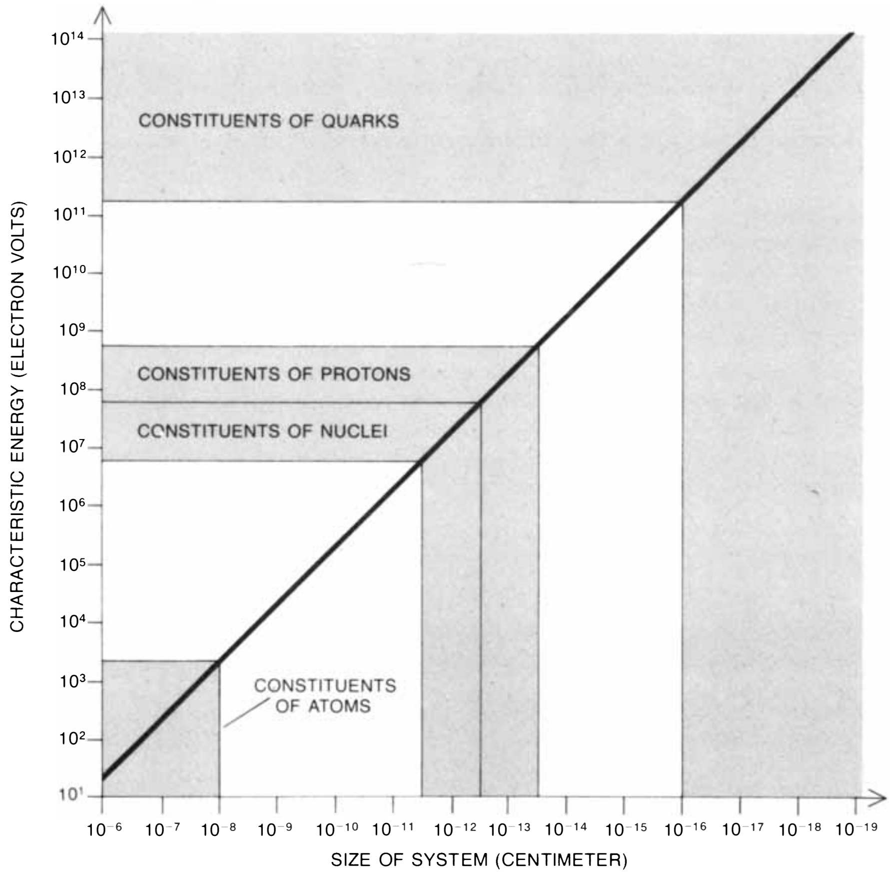
Other possible mechanisms for creating multiple generations have been considered. Several physicists have suggested that the higher-generation relatives of a given state might be created by adding a Higgs particle, the "extra" particle associated with the weak bosons in the standard model. Because a Higgs particle has no electric charge or color or even spin angular momentum, adding one to a composite system would alter only the mass. Hence an electron might be converted into a muon by adding one Higgs particle or into a tau by adding two or more Higgs particles. Seiberg and I have proposed another possible mechanism: a higher-generation particle could be formed by the addition of pairs of prequarks and antiprequarks. All charges and other properties must cancel in such a pair, and so again only the mass would be affected.

These ideas are currently at the stage of unrestrained speculation. No one knows what distinguishes the three generations from one another, or why there are three or whether there may be more. No explanation can be given of the mass difference between the generations. In short, the triplication of the generations is still a major unsolved puzzle.

A third kind of substructure model deserves mention. It tries to relate the possibility of quark and lepton structure to another fundamental problem: understanding the relativistic quantum theory of gravitation. Ideas of this kind have been explored by John Ellis, Mary K. Gaillard, Luciano Maiani and Bruno Zumino of CERN. One approach to their ideas is to consider the distances at which prequarks interact: the experimental limit is less than 10^{-16} centimeter, but the actual distance could be several orders of magnitude smaller still. At about 10^{-34} centimeter the gravitational force becomes strong enough to have a significant effect on individual particles. If the scale of the prequark interactions is this small, gravitation cannot be neglected. Ellis, Gaillard, Maiani and Zumino have outlined an ambitious program that aims to unify all the forces, including gravitation, in a scheme that treats not only the quarks and leptons but also the gauge bosons as composite particles. Like other composite models, however, this one has serious flaws.

Any prequark model, regardless of its details, must supply some mechanism for binding the prequarks together. There must be a powerful attractive force between them. One strategy is to postulate a new fundamental force of nature analogous in its workings to the color force of the standard model. To emphasize the analogy the new force is called the hypercolor force and the carrier fields are called hypergluons. The prequarks are assumed to have hypercolor, but they combine to form hypercolorless composite systems, just as quarks have ordinary color but combine to form colorless protons and neutrons. The hypercolor force presumably also gives rise to the property of confinement, again in analogy to the color force. Hence all hypercolored prequarks would be trapped inside composite particles, which would explain why free prequarks are not seen in experiments. An idea of this kind was first proposed by 't Hooft, who studied some of its mathematical implications but also expressed doubt that nature actually follows such a path.

The typical radius of hypercolor con-



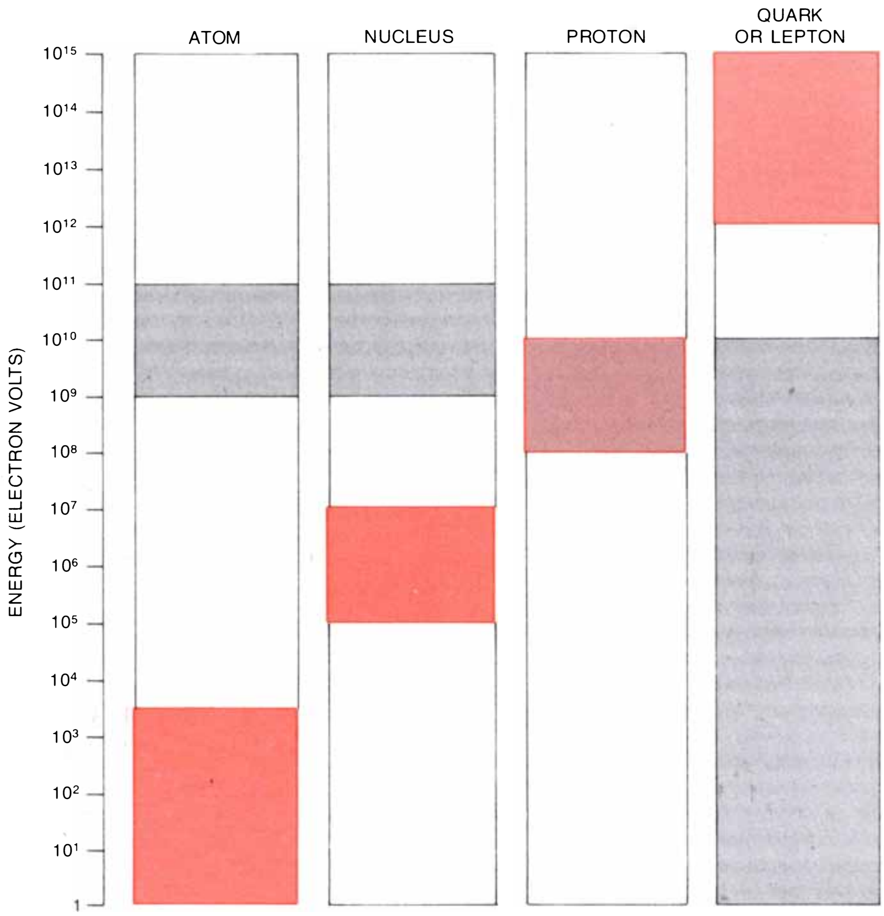
SIZE AND ENERGY have a reciprocal relation in the quantum theory, indicating that the constituents of composite quarks and leptons must have an exceedingly high kinetic energy. The size of an atom implies that its constituents can have energies ranging from a few electron volts to a few thousand. (An electron volt is the energy gained by an electron accelerated through a potential difference of one volt.) In a nucleus the protons and neutrons move with an energy of several million electron volts, and in a proton or a neutron the quarks have energies of several hundred million electron volts. Any constituents of quarks and leptons must be confined to a radius of less than 10^{-16} centimeter, and possibly much less. As a result the kinetic energy of the hypothetical prequarks can be no less than a few hundred billion electron volts.

finement must be less than 10^{-16} centimeter. Only when matter is probed at distances smaller than this would it be possible to see the hypothetical prequarks and their hypercolors. At a range of 10^{-14} or 10^{-15} centimeter hypercolor effectively disappears; the only objects visible at this scale of resolution (the quarks and leptons) are neutral with respect to hypercolor. At a range of 10^{-13} centimeter ordinary color likewise fades away, and the world seems to be made up entirely of objects that lack both color and hypercolor: protons, neutrons, electrons and so on.

The notion of hypercolor is well suited to a variety of prequark models, including the rishon model. In addition to their electric charge and color the rishons are assumed to have hypercolor and the antirishons to have antihypercolor. Only combinations of three rishons or three antirishons are allowed because only those combinations are neutral with respect to hypercolor. A mixed three-particle system, such as $TT\bar{T}$, cannot exist because it would not be hypercolorless. The assignment of hypercolors thereby explains the rule for forming composite rishon systems. Similar rules apply in other hypercolor-based prequark models.

If the aim of a prequark model is to simplify the understanding of nature, postulating a new basic force does not seem very helpful. In the case of hypercolor, however, there may be some compensation. Consider the neutrino: it has neither electric charge nor color, only weak charge. According to the standard model, two neutrinos can act on each other only through the short-range weak force. If neutrinos are composites of hypercolored prequarks, however, there could be an additional source of interactions between neutrinos. When two neutrinos are far apart, there are practically no hypercolor forces between them, but when they are at close range, the hypercolored prequarks inside one neutrino are able to "see" the inner hypercolors of the other one. Complicated short-range attractions and repulsions are the result. The mechanism, of course, is exactly the same as the one that explains the molecular force as a residue of the electromagnetic force and the strong force as a residue of the color force.

The conclusion may also be the same. Seiberg and I, and independently Greenberg and Sucher, were the first to suggest that the short-range weak force may actually be a residual effect of the hypercolor force. According to this hypothesis, the weak bosons W^+, W^- and Z^0 must also be composite objects, presumably made up of certain combinations of the same prequarks that compose the quarks and leptons. If this idea is confirmed, the list of fundamental forces will still have four entries: gravitation, electromagnetism, color and hypercolor. It should be noted, however, that all these forces are long-range ones; the short-range molecular, strong and weak forces will have lost their fundamental status.



MISMATCH OF ENERGY AND MASS makes it difficult to devise a theory of how prequarks might move and interact. In an atom or a nucleus the kinetic energy of the constituents (*color*) is much less than the total mass of the system (*gray*). In a proton the two quantities are of comparable magnitude. In a composite quark, however, the energy of the prequarks greatly exceeds the total mass. Indeed, compared with the kinetic energy, the mass is essentially zero. Somehow virtually all mass is canceled, a development that is unlikely to be accidental.

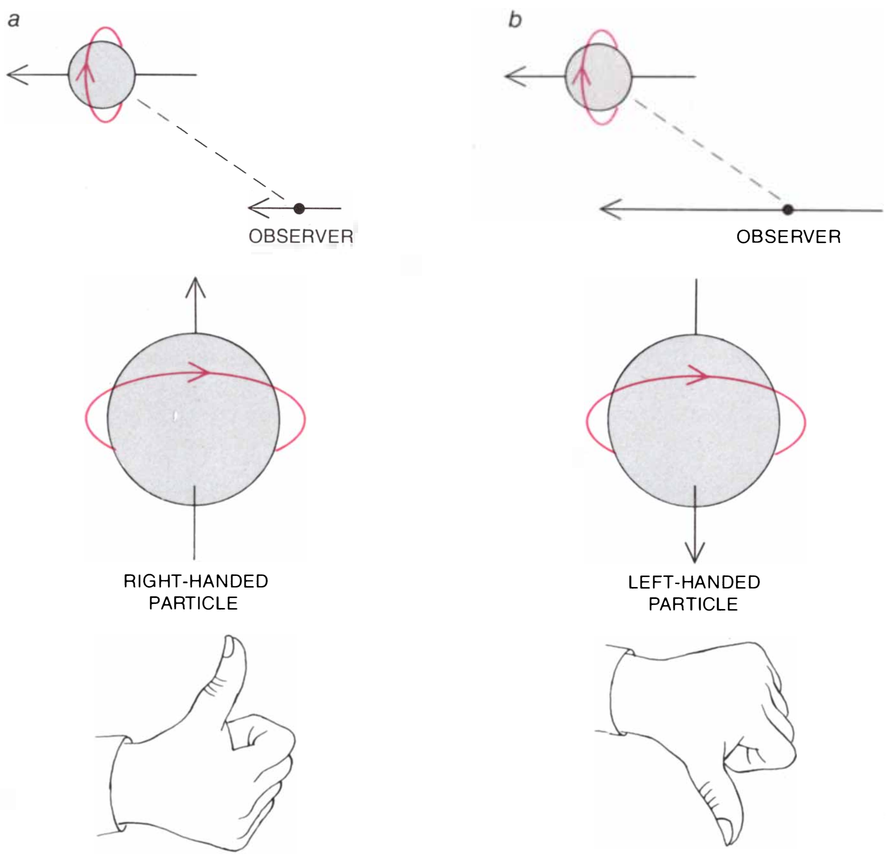
For now hypercolor remains a conjecture, and so does the notion of explaining the weak force as a residue of the hypercolor force. It may yet turn out that the weak force is fundamental. A careful measurement of the mass, lifetime and other properties of the weak bosons should provide important clues in this matter.

Hypercolor is not the only candidate for a prequark binding force. Another interesting possibility was suggested by Pati, Salam and Strathdee. Instead of introducing a new hypercolor force, they borrowed an idea that has long been familiar, namely the magnetic force, and adapted it to a new purpose. An ordinary magnet invariably has two poles, which can be thought of as opposite magnetic charges. For 50 years there have been theoretical reasons for supposing there could also be isolated magnetic charges, or monopoles. Pati, Salam and Strathdee have argued that the prequarks could be particles with charges resembling both magnetic and electric charges. If they are, the forces binding them may be of a new and interesting origin.

None of the ideas I have just described constitutes a theory of prequark dynamics. Indeed, there is a serious impediment to the formulation of such a theory; it is the requirement that the prequarks be exceedingly small. The most stringent limit on their size is set indirectly by measurements of the magnetic moment of the electron, which agree with the calculations of quantum electrodynamics to an accuracy of 10 significant digits. In the calculations it is assumed that the electron is pointlike; if it had any spatial extension or internal structure, the measured value would differ from the calculated one. Evidently any such discrepancy can at most affect the 11th digit of the result. It is this constraint that implies the characteristic distance scale of the electron's internal structure must be less than 10^{-16} centimeter. Roughly speaking, that is the maximum radius of an electron, and any prequarks must stay within it. If they strayed any wider, their presence would already have been detected.

Why should the small size of the electron inhibit speculation about its internal structure? The uncertainty principle establishes a reciprocal relation between the size of a composite system and the kinetic energy of any components moving inside it. The smaller the system, the larger the kinetic energy of the constituents. It follows that the prequarks must have enormous energy: more than 100 GeV (100 billion electron volts), and possibly much more. (One electron volt is the energy acquired by an electron when it is accelerated through a potential difference of one volt.) Because mass is fundamentally equivalent to energy, it can be measured in the same system of units. The mass of the electron, for example, is equivalent to .0005 GeV. There is a paradox here, which I call the energy mismatch: the mass of the composite system (if it is indeed composite) is much smaller than the energy of its constituents.

The oddity of the situation can be illuminated by considering the relations of mass and kinetic energy in other composite systems. In an atom the kinetic energy of a typical electron is smaller than the mass of the atom by many orders of magnitude. In hydrogen, for example, the ratio is roughly one part in 100 million. The energy needed to change the orbit of the electron and thereby put the atom into an excited state is likewise a negligible fraction of the atomic mass. In a nucleus the kinetic energy of the protons and neutrons is also small compared with the nuclear mass, but it is not completely negligible. The motion of the particles gives them an energy equivalent to about 1 percent of the system's mass. The energy needed to create an excited state is also about 1 percent of the mass.



CHIRAL SYMMETRY offers a possible explanation of the "miraculous" cancellation of mass in quarks and leptons. Chirality, or handedness, describes the relation of a particle's spin angular momentum to its direction of motion. Suppose an observer is overtaken by a faster-moving electron (*a*). From the observer's point of view the electron obeys a right-hand rule: When the fingers of the right hand curl in the same direction as the spin, the thumb gives the direction of motion. If the observer speeds up, however, so that he overtakes the electron (*b*), the handedness of the particle changes. In the observer's frame of reference the electron is now approaching instead of receding, but its spin direction has not changed; as a result its motion is described by a left-hand rule. Chirality, therefore, is not conserved. There is one kind of particle to which this argument cannot be applied, namely a massless particle, which must always move with the speed of light. No observer can move faster than a massless particle, and so its handedness is an invariant property. If a theory of prequarks had a chiral symmetry, in which handedness must be conserved, the low mass of the quarks and leptons might not be accidental. They would have to be virtually massless for the chiral symmetry to be maintained.

With the proton and its quark constituents the energy-mass relation begins to get curious. From the effective radius of the proton the typical energy of its component quarks can be calculated; it turns out to be comparable to the mass of the proton itself, which is a little less than 1 GeV. The energy that must be invested to create an excited state of the quark system is of the same order of magnitude: the hadrons identified as excited states of the proton exceed it in mass by from 30 to 100 percent. Nevertheless, the ratio of kinetic energy to total mass is still in the range that seems intuitively reasonable. Suppose one knew only the radius of the proton, and hence the typical energy of whatever happens to be inside it, and one were asked to guess the proton's mass. Since the energy of the constituents is generally a few hundred million electron volts, one would surely guess that the total mass of the system is at least of the same order of magnitude and possibly greater. The guess would be correct.

For the atom, the nucleus and the proton, then, the mass of the system is at least as large as the kinetic energy of the constituents and in some cases is much larger. If quarks and leptons are composite, however, the relation of energy to mass must be quite different. Since the prequarks have energies well above 100 GeV, one would guess that they would form composites with masses of hundreds of GeV or more. Actually the known quarks and leptons have masses that are much smaller; in the case of the electron and the neutrinos the mass is smaller by at least six orders of magnitude. The whole is much less than the sum of its parts.

The high energy of the prequarks is also what spoils the idea of viewing the higher generations of quarks and leptons as excited states of the same set of prequarks that form the first-generation particles. As in the other composite systems, the energy needed to change the orbits of the prequarks should be of the same order of magnitude as the kinetic energy of the constituents. One would therefore expect the successive generations to differ in mass by hundreds of GeV, whereas the actual mass differences are as small as .1 GeV.

At this point one might well adopt the view that the energy mismatch cannot be accepted, indeed that it simply demonstrates the elementary and structureless nature of the quarks and leptons. Many physicists hold this view. The energy mismatch, however, contradicts no basic law of physics, and I would argue that the circumstantial evidence for quark and lepton compositeness is sufficiently persuasive to warrant further investigation.

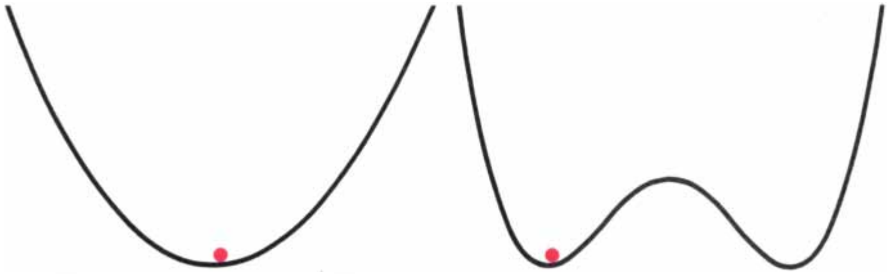
What is peculiar about the quark and lepton masses is not merely that they are small but that they are virtually zero when measured on the energy scale defined by their constituents' energy. In other composite systems a small amount of mass is "lost" by being converted into the binding energy of the system. The total mass of a hydrogen atom, for example, is slightly less than that of an isolated proton and electron; the difference is equal to the binding energy. In a nucleus this "mass defect" can reach a few percent of the total mass. In a quark or a lepton, it seems, the entire mass of the system is canceled almost exactly. Such a "miraculous" cancellation is certainly not impossible, but it seems most unlikely to happen by accident. Similar large cancellations are known elsewhere in physics, and they have always been found to result from some symmetry principle or conservation law. If there is to be any hope of constructing a theory of prequark dynamics, it is essential to find such a symmetry in this case.

There is a likely candidate: chiral symmetry, or chirality. The name is derived from the Greek word for hand, and the symmetry has to do with handedness, the property defined by a particle's spin and direction of motion. Like other symmetries of nature, chiral symmetry has a conservation law associated with it, which gives the clearest account of what the symmetry means. The law states that the total number of right-handed particles and the total number of left-handed ones can never change.

In the ordinary world of protons, electrons and similar particles handedness or chirality clearly is not conserved. A violation of the conservation law can be demonstrated by a simple thought experiment. Imagine that an observer is moving in a straight line when he is overtaken by an electron. As the electron recedes from him he notes that its spin and direction of motion are related by a right-hand rule. Now suppose the observer speeds up, so that he is overtaking the electron. In the observer's frame of reference the electron seems to be approaching; in other words, it has reversed direction. Because its spin has not changed, however, it has become a left-handed particle.

There is one kind of particle to which this thought experiment cannot be applied: a massless particle. Because a massless particle must always move with the speed of light, no observer can ever go faster. As a result the handedness of a massless particle is an invariant property, independent of the observer's frame of reference. Furthermore, it can be shown that none of the known forces of nature (those mediated by the photon, the gluons and the weak bosons) can alter the handedness of a particle. Thus if the world were made up exclusively of massless particles, the world could be said to have chiral symmetry.

Chiral symmetry is the root of an idea that might conceivably account for the small mass of the quarks and leptons. The argument runs as follows. If the prequarks are massless particles, if they have a spin of 1/2 and if they interact with one another only through the exchange of gauge bosons, any theory describing their motion is guaranteed to have a chiral symmetry. If the massless prequarks then bind together to form composite spin-1/2 objects (namely the quarks and leptons), the chiral symmetry might ensure that the composite particles also remain massless compared with the huge energy of the prequarks inside them. Hence the small mass of the quarks and leptons is not an accident. They must be essentially massless with respect to the energy of their constituents if the chiral symmetry of the theory is to be maintained.



SPONTANEOUS SYMMETRY BREAKING is a mechanism that could spoil a prequark theory even if it has a chiral symmetry. Both of the physical systems shown here—a simple trough and a trough with a bump in the bottom—can be described as symmetrical in the sense that exchanging left and right leaves the system unaltered. For the simple trough the system remains symmetrical when a ball is put in the trough; the ball comes to rest in the center, so that exchanging left and right still has no effect. In the trough with a bump, however, the ball takes up a position on one side or the other, and the symmetry is inevitably broken. Similarly, a prequark theory that has a chiral symmetry might nonetheless give rise to composite systems that do not observe the symmetry. Showing that a chiral symmetry can definitely remain unbroken is currently the principal challenge in formulating a theory of how prequarks move.

The crucial step in this argument is the one extending the chiral symmetry from a world of massless prequarks to one made up of composite quarks and leptons. It is essential that the symmetry of the original physical system survive in and be respected by the composite states formed out of the massless constituents. It may seem self-evident that if a theory is symmetrical in some sense, the physical systems described by the theory must exhibit that symmetry; actually, however, the spontaneous breaking of symmetries is commonplace. A familiar example is the roulette wheel. A physical theory of the roulette wheel would show it is completely symmetrical in the sense that each slot is equivalent to any other slot. The physical system formed by putting a ball in the roulette wheel, however, is decidedly asymmetrical: the ball invariably comes to rest in just one slot.

In the standard model it is the spontaneous breaking of a symmetry that makes the three weak bosons massive and leaves the photon massless. The theory that describes these gauge bosons is symmetrical, and in it the four bosons are essentially indistinguishable, but because of the symmetry breaking the physical states actually observed are quite different. Chiral symmetries are notoriously susceptible to symmetry breaking. Whether the chiral symmetry of prequarks breaks or not when the prequarks form composite objects can be determined only with a detailed understanding of the forces acting on the prequarks. For now that understanding does not exist. In certain models it can be shown that a chiral symmetry does exist but is definitely broken. No one has yet succeeded in constructing a composite model of quarks and leptons in which a chiral symmetry is known to remain unbroken. Neither the preon model nor the rishon model succeeds in solving the problem. The task is probably the most difficult one facing those attempting to demonstrate that quarks and leptons are composite.

If a consistent prequark theory can be worked out, it will still have to pass the test of experiment. First, it is important to establish in the laboratory whether or not quarks and leptons have any internal structure at all. If they do, experiments might then begin to discriminate among the various models. The experiments will have to penetrate the unknown realm of distances smaller than 10^{-16} centimeter and energies higher than 100 GeV. There are two basic ways to explore this region: by doing experiments with particles accelerated to very high energy and by making precise measurements of low-energy quantities that depend on the physics of events at very small distances.

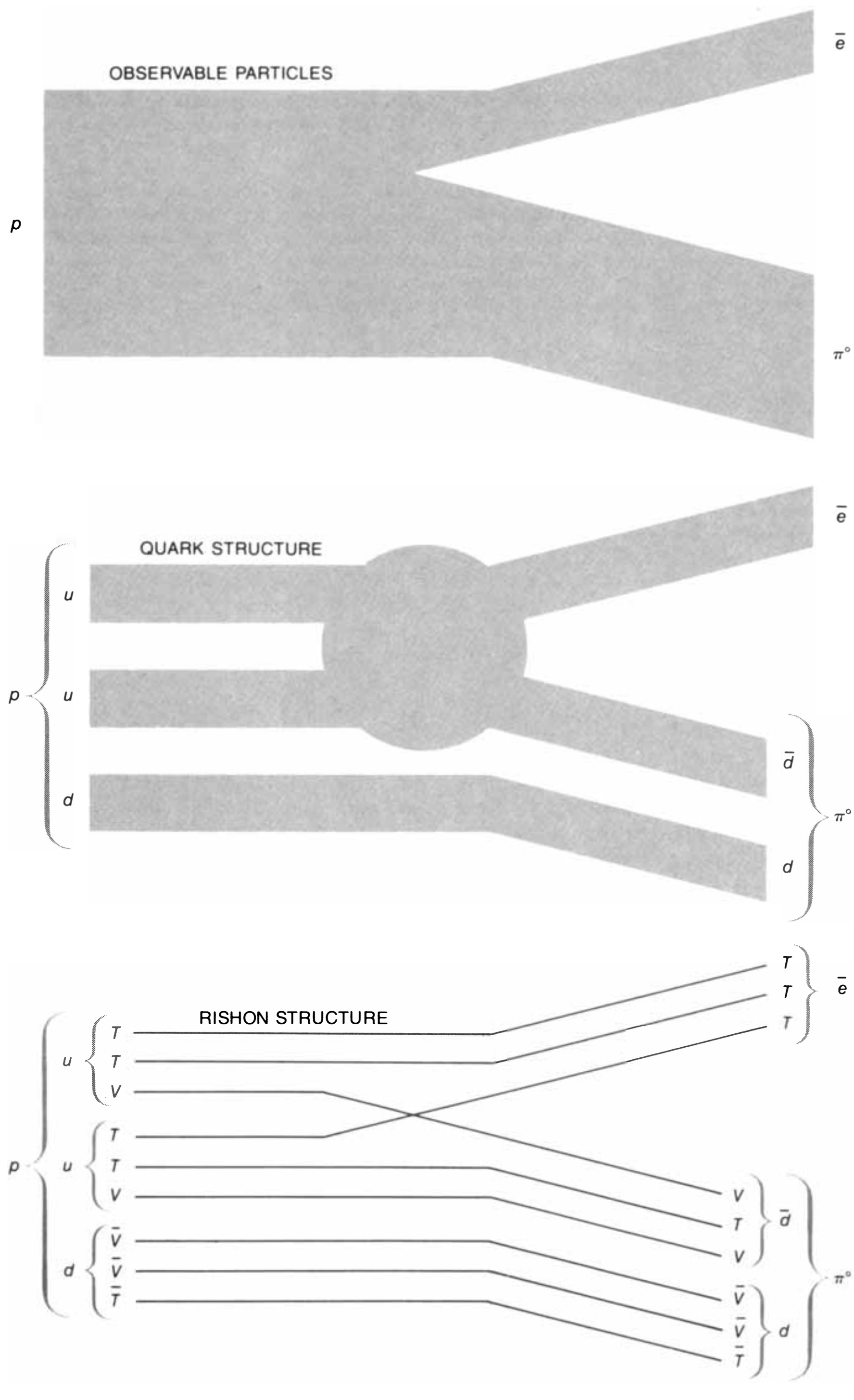
Experiments of the first kind include the investigation of the weak bosons and the search for the Higgs particles of the standard model. When such particles can be made in sufficient numbers, a careful look at their properties should reveal much about the physics of very small distances. New accelerators now being planned or built in the U.S., Europe and Japan are expected to yield detailed information about the weak bosons and will also continue the ongoing investigation of the quarks and leptons themselves.

Equally interesting are the high-precision, low-energy experiments. One of these is the search for the decay of the proton, a particle that is known to have an average lifetime of at least 10^{30} years. Several experiments are now monitoring large quantities of matter, incorporating substantially more than 10^{30} protons, in an attempt to detect the signals emitted when a proton disintegrates. None of the forces of the standard model can induce such an event, but none of the rules of the standard model absolutely forbids it. Both the grand unified theories and the prequark models, on the other hand, include mechanisms that could convert a proton into other particles that would ultimately leave behind only leptons and photons. If the decay is detected, its rate and the pattern of decay products could offer an important glimpse beyond the standard model.

There is similar interest in the hypothetical process in which a muon emits a photon and is thereby converted into an electron. Again none of the forces of the standard model can bring about an event of this kind, but again too no fundamental law forbids it. Some of the composite models allow the transition and others do not, so that a search for the process might offer a means of choosing among the models. Experiments done up to now put a limit of less than one in 10 billion on the probability that any given muon will decay in this way. Detection of such events and a determination of their rate might illuminate the mysterious distinction between the generations.

A third class of precision experiments are those that continue to refine the measurement of the magnetic moment of the electron and of the muon. Further improvements can be expected both in experimental accuracy and in the associated calculations of quantum electrodynamics. If the results continue to agree with the predictions of the standard model, the limit on the possible size of any quark and lepton substructure will become remoter. If a discrepancy between theory and experiment is detected, it will represent a strong hint that quarks and leptons are not elementary.

It may well be a decade or two before the next level in the structure of matter comes clearly into view (if, again, there is another level). What is needed is a sound theoretical picture, one that is self-consistent, that agrees with all experiments and that is simple enough to explain all the features of the standard model in terms of a few principles and a few fundamental particles and forces. The correct picture, whether it is a grand unified theory or a composite model of the quarks and leptons, may already exist in some embryonic form. On the other hand, it is also possible the correct theory will emerge only from some totally new idea. In the words of Niels Bohr, it may be that our present ideas "are not sufficiently crazy to be correct."



DECAY OF THE PROTON is a conjectured event that might be interpreted as experimental evidence for a grand unified theory or for a model of quark substructure. In one form of decay the proton would be observed to disintegrate into a positron ($\bar{e}$) and a neutral pion (π^0). The event can be understood in terms of the proton's quark constituents: an interaction of the two *u* quarks converts one of them into a positron and the other into a $\bar{d}$ antiquark; the latter combines with the remaining *d* quark of the proton to form the neutral pion. Grand unified theories suggest that the interaction of the *u* quarks is mediated by a new force of nature. The rishon model provides an alternative explanation: the two *u* quarks merely exchange a *T* and a *V* rishon.