The Confinement of Quarks

How is it that these elementary particles of matter that explain so much about other particles are not seen? It may be that they are held inside other particles by forces inherent in their nature

by Yoichiro Nambu

An elementary particle of matter, strictly defined, is one that has no internal structure, one that cannot be broken up into smaller constituent particles. In the past decade or so it has become apparent that many particles long thought to be elementary, including such familiar ones as the proton and the neutron, are not elementary at all. Instead they appear to be composite structures made up of the more fundamental entities named quarks, in much the same way that an atom is made up of a nucleus and electrons.

The quark model amounts to an impressive simplification of nature. In the initial formulation of the theory there were supposed to be just three species of quark, and those three were enough to account for the properties of an entire class of particles with several dozen members. Every known member of that class could be understood as a combination of quarks; moreover, every allowed combination of the quarks gave rise to a known particle. The correspondence between theory and observation seemed too close to be coincidental, and experiments were undertaken with the aim of detecting the quarks themselves.

If the quarks are real particles, it seems reasonable that we should be able to see them. We know that the atom consists of a nucleus and a surrounding cloud of electrons because we can take the atom apart and study its constituents in isolation. We know that the nucleus in turn consists of protons and neutrons because the nucleus can be split into fragments and the constituent particles identified. It is easy to imagine a similar experiment in which particles thought to be made of quarks, such as protons, are violently decomposed. When that is attempted, however, the debris consists only of more protons and other familiar particles. No objects with the properties attributed to quarks are seen. Physicists have searched high and low, but free quarks have not been found.

It is possible, of course, that no experiment has yet looked in the right place or with the right instruments, but that now seems unlikely. It is also possible that the quarks simply do not exist, but physicists are reluctant to abandon a theory that carries such explanatory force. The successes of the theory represent compelling evidence that quarks exist inside particles such as the proton; on the other hand, the repeated failure of experimental searches to discover a free quark argues that the quarks do not exist independently. This paradox can be resolved, but only by making further theoretical assumptions about the quarks and the forces that bind them together. It must be demonstrated that quarks exist, but that for some reason they do not show themselves in the open. Theorists, who invented the quarks in the first place, are now charged with explaining their confinement within the particles they make up.

The particles thought to be made up of quarks are those called hadrons; they are distinguished by the fact that they interact with each other through the strong force, the force that binds together the particles in the atomic nucleus. ("Hadron" is derived from the Greek *hadros,* meaning stout or strong.) No other particles respond to the strong force.

The hadrons are divided into the two large subgroups named the baryons and the mesons. These two kinds of particle differ in many of their properties, and indeed they play different roles in the structure of matter, but the distinction between them can be made most clearly in the context of the quark model. All baryons consist of three quarks, and there are also antibaryons consisting of three antiquarks. The proton and the neutron are the least massive and the most familiar of the baryons. Mesons have a different structure: they consist of a quark bound to an antiquark. The pi meson, or pion, is the least massive of the mesons.

The properties of the hadrons can perhaps be best illustrated by considering them in contrast with the remaining major group of particles: the leptons. The leptons are not susceptible to the strong force (or else they would be hadrons). There are just four of them: the electron, the muon, the electron-type neutrino and the muon-type neutrino (along with the four corresponding antiparticles). The leptons seem to be truly elementary: they have no internal structure. Indeed, they apparently have no size. They can be represented as dimensionless points, so that it would not seem possible for them to have an internal structure.

The hadrons differ from the leptons in many respects, and they give several clues to their composite nature. The hadrons have a finite size, even if it is exceedingly small: about 10^{-13} centimeter. Experiments in which protons or neutrons collide at high energy with other particles give fairly direct evidence of an internal structure: electric and magnetic fields and the field associated with the strong force all seem to emanate from point sources within the particles. Finally, there are a great many hadrons. Well over 100 are known, most of them very short-lived, and there is every indication that many more exist and have not yet been observed only because the particle accelerators available today cannot supply enough energy to create them. There is no obvious limit to the number of hadrons that might be found as larger accelerators are built.

It was the great multiplicity of the hadrons that led to the formulation of the quark model. Without some organizing principle such a large collection of particles seemed unwieldy, and the possibility that they might all be elementary offended those who hold the conviction, or at least the fond wish, that nature should be simple. The quark hypothesis replaced the great variety of hadrons with just three fundamental building blocks from which all the hadrons could be constructed. It was proposed in 1963, independently by Murray Gell-Mann and George Zweig, both of the California Institute of Technology. It was Gell-Mann who supplied the name quark, from a line in James Joyce's *Finnegans Wake:* "Three quarks for Muster Mark!"

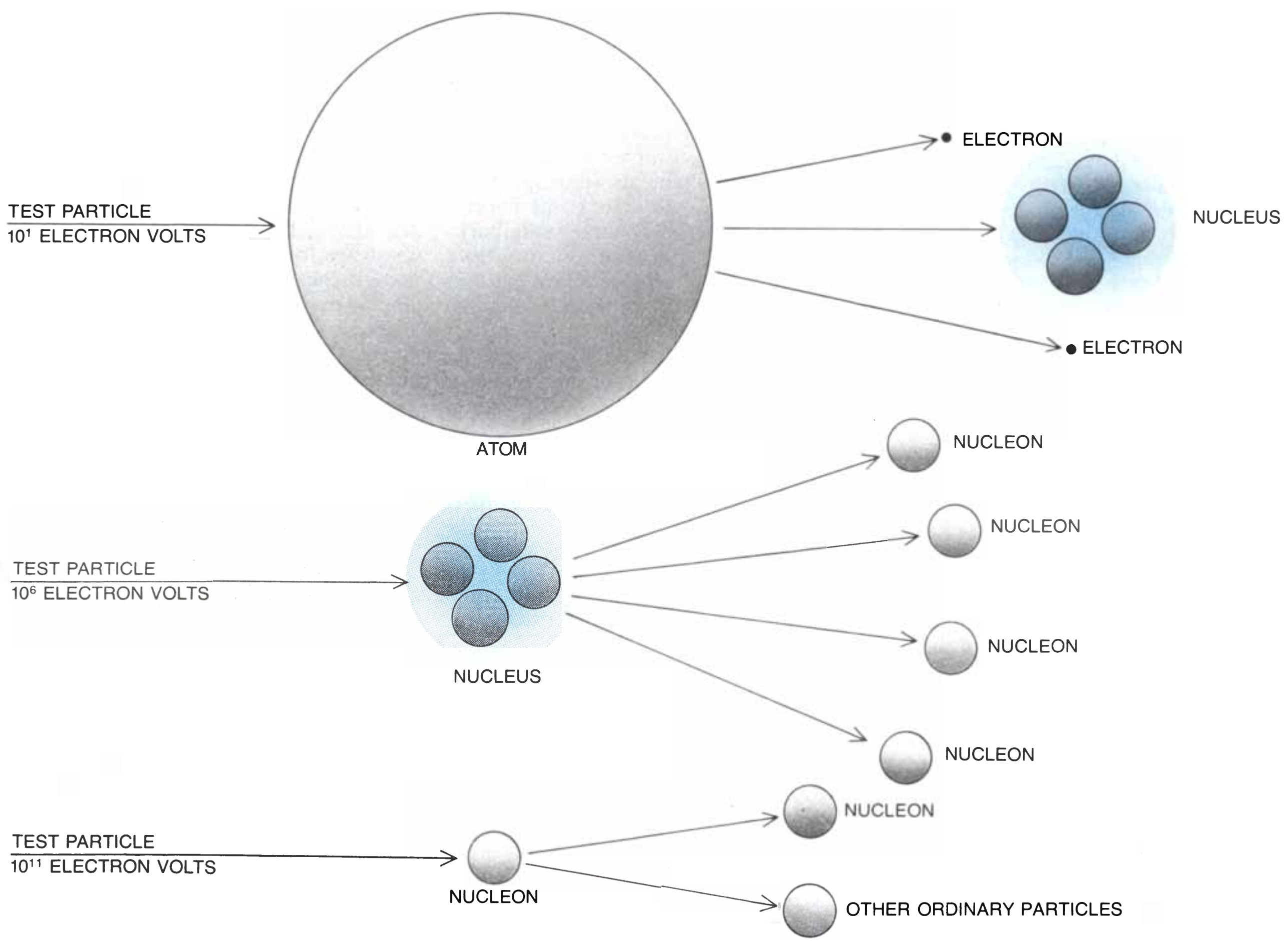
The immediate inspiration for the quark hypothesis was the discovery, made by Gell-Mann and by Yuval Ne'eman of Tel-Aviv University, that all the hadrons can be grouped logically in families of a few members each. The mesons form families of one particle and of eight particles; the baryons form families of one, eight and 10.

The classification of particles is made easier by tabulating their properties in numerical form. Each number refers to a single property, and it can assume only certain discrete values. Since the numbers are assigned in discrete units, or quanta, they are called quantum numbers. A complete list of a particle's quantum numbers identifies it uniquely and defines its behavior.

Electric charge is a typical quantum number. The fundamental unit of measurement is the electric charge of the proton or the electron, and in those units the charges of all observed particles can be expressed as simple integers (such as 0, +1 and −1). Another quantum number is called baryon number. Baryons are arbitrarily assigned a value of +1 and antibaryons a value of −1. Mesons have a baryon number of 0. Strangeness, the property of hadrons introduced in the 1950's to explain the strangely long lifetimes of some massive particles, is also accounted for through a quantum number with only integer quantities.

One of the most important quantum numbers is spin angular momentum. Under the rules of quantum mechanics a particle's state of rotation is one of its intrinsic properties, and the particle must therefore always have a specified and unvarying angular momentum. (The angular momentum is measured in units of Planck's constant divided by 2π, Planck's constant being 6.6×10^{-27} erg-second.) A crucial distinction is made between particles whose spins have a half-integer value (that is, half an odd integer, such as 1/2 or 3/2) and those with integer spin (such as 0, 1 or 2). As we shall see, this distinction determines the behavior of the particles when they are brought together in a bound system, but for now it is enough to note that all baryons have half-integer spins and all mesons have integer spins.

The families of hadrons defined by Gell-Mann and Ne'eman are related by spin angular momentum. All the members of a given family have the same quantity of spin. Within the families the members are distinguished from one another by two other quantum numbers: isotopic spin and hypercharge. In spite of its name, isotopic spin has nothing to



STRUCTURE OF MATTER has been examined at progressively finer scale by a process of violent decomposition. The atom can be reduced to its component parts by striking it with a projectile carrying relatively little energy: a few electron volts. This is the process called ionization, and in the extreme case it results in the isolation of free electrons and a nucleus. The nucleus can also be dismembered, although higher energy is required. The nucleus splits into free protons and neutrons, which are collectively called nucleons. Nucleons in turn seem to be composed of the pointlike entities called quarks, and it would seem that the quarks might be liberated by smashing a nucleon with a test particle of sufficient energy. When that experiment is attempted, however, free quarks are not seen, even at the highest energies now attainable (a few hundred billion electron volts). Instead other ordinary particles are created, including many that are thought to be made up of quarks. A possible explanation of this effect is that the quarks are permanently confined within the nucleon.

do with angular momentum; it is determined by the number of particles included in a given group. Hypercharge is determined by the electric charges of those particles, and it is also related to both baryon number and strangeness. From the various possible combinations of the values that these two quantum numbers can assume it is possible to construct an array for each family of hadrons. These arrays, having in each case one, eight or 10 positions, predict the existence of all the known hadrons and of no others. The formation of these arrays can be described formally in the branch of mathematics called group theory. The arrays are said to be representations of the symmetry group SU(3), which stands for special unitary group for matrixes of size 3×3.

The quarks are also described by an SU(3) symmetry group. Gell-Mann designated the quarks by the arbitrary labels *u, d* and *s*, for "up," "down" and "sideways." All of them have the same spin angular momentum, 1/2 unit, and in the SU(3) group they form a family of their own; it is, obviously, a family of three. The three members of the quark family are distinguished by having different values of isotopic spin and hypercharge, and they differ in other quantum numbers as well. The electric charges assigned to them are particularly unusual. The *u* quark has a charge of $+2/3$, and the *d* quark and the *s* quark each have a charge of $-1/3$. The baryon numbers of the quarks are also fractional: all the quarks have a baryon number of $+1/3$. Strangeness, on the other hand, remains an integer quantum number; the *u* and *d* quarks have zero strangeness and the *s* quark has a strangeness of -1. For the corresponding antiquarks, whose symbols are $\bar{u}$, $\bar{d}$ and $\bar{s}$, the magnitude of each of these quantum numbers is the same but the sign is changed.

The fundamental rule for the construction of hadrons from quarks is disarmingly simple: it states that all the quantum numbers of the hadron can be found by adding up the quantum numbers of the constituent quarks. The proton, for example, consists of two *u* quarks and one *d* quark, a configuration written *uud*. The electric charges are therefore $2/3 + 2/3 - 1/3$, for a total value of $+1$. The baryon number is $1/3 + 1/3 + 1/3$, or $+1$, and since the strangeness of each of these quarks is zero, the total is also zero. All the sums are in accord with the measured properties of the proton.

The positively charged pi meson is made up of a *u* quark and a $\bar{d}$ antiquark. The electric charges of the quarks are $+2/3$ and $+1/3$, for a total of $+1$, and the baryon numbers are $+1/3$ and $-1/3$, for the total baryon number of zero required of a meson. The strangeness again is zero. The spin-angular-momentum quantum number calls for a slightly more elaborate calculation because the spins of the quarks can be aligned in either of two ways, and the alignment determines the signs that must be supplied for the spin quantum numbers when they are summed. In all possible cases, however, combinations of three quarks or three antiquarks (baryons and antibaryons) must have half-integer spin, whereas combinations of a quark and an antiquark (mesons) must have integer spin.

The great strength of the quark model is that through this simple additive procedure the model correctly predicts all the quantum numbers of the known hadrons. In particular it should be pointed out that all allowed combinations of the quarks yield integer values of electric charge and baryon number, and that no other combinations do so (except in the trivial case of multiples of the allowed combinations). Furthermore, all the known hadrons can be constructed out of either three quarks or a quark and an antiquark.

In the past few years it has become apparent that there may be a fourth species of quark, bearing a new quantum number somewhat similar to strangeness and given the arbitrary name charm. The new quark (labeled *c*) adds another dimension to the symmetry group that describes the hadrons, and it predicts the existence of a multitude of new particles, some of which may already have been found. The addition of charm to the quark model, which seems increasingly to be justified by the experimental evidence, has a number of attractive features and can be considered to strengthen the model, but it has little effect on the problem of quark confinement.

In many respects quarks are like leptons. Both kinds of particle can apparently be represented as dimensionless points, and if they are without extension, they are also presumably without internal structure. All the quarks and all the leptons also share the property of having a spin of 1/2 unit. Finally, if the charm hypothesis is correct, then there are four members of each group; indeed, the appeal of that symmetry was one of the principal motivations for introducing the concept of charm. (On the other hand, four need not be the ultimate number of quarks and leptons. Both groups could have additional, undiscovered members.)

The resemblance between quarks and leptons is not a superficial one, but there are important differences between these two kinds of fundamental particle. In the first place, quarks participate in strong interactions, whereas leptons do not. The quarks also form aggregations of particles (hadrons), whereas there are no analogous composite structures made up of leptons. Why is it, however, that the quarks form only certain well-defined aggregations, those made up either of three quarks or of a quark and an antiquark? Many other combinations are conceivable—four quarks, two quarks, a quark and two antiquarks, even states made up of hundreds or thousands of quarks—but there is no evidence that any of them exist. A state of particular interest is the one represented by a solitary quark. Isolated leptons are commonplace; what distinguishing property of quarks prohibits them from appearing in isolation?

The concept that has provided the first, speculative answers to these questions was introduced in order to mend a conspicuous flaw in the quark theory.

		SPIN (J)	ELECTRIC CHARGE (Q)	BARYON NUMBER (B)	STRANGENESS (S)	CHARM (C)
QUARKS	u (UP)	½	+⅔	⅓	0	0
	d (DOWN)	½	−⅓	⅓	0	0
	s (STRANGE)	½	−⅓	⅓	−1	0
	c (CHARMED)	½	+⅔	⅓	0	+1
ANTIQUARKS	$\bar{u}$ (UP)	½	−⅔	−⅓	0	0
	$\bar{d}$ (DOWN)	½	+⅓	−⅓	0	0
	$\bar{s}$ (STRANGE)	½	+⅓	−⅓	+1	0
	$\bar{c}$ (CHARMED)	½	−⅔	−⅓	0	−1

PROPERTIES OF QUARKS are accounted for by assigning them quantum numbers, which can assume only certain discrete values. In the original quark model there were three kinds of quark, labeled *u* and *d* (for "up" and "down") and *s* (for "sideways" or "strange"). There is now evidence for a fourth quark species, labeled *c* (for "charm"). The quarks have fractional electric charge and fractional values of baryon number, a quantum number that distinguishes between two groups of particles. The spin quantum number reflects the intrinsic angular momentum of the quarks; the strangeness and charm quantum numbers recognize special properties of *s* and *c* quarks respectively. For each quark there is an antiquark with opposite quantum numbers.

QUARK FLAVORS	QUARK COLORS: RED	GREEN	BLUE
u (UP)	Q = +⅔ B = +⅓	Q = +⅔ B = +⅓	Q = +⅔ B = +⅓
	Q = 0 B = 0	Q = +1 B = 0	Q = +1 B = +1
d (DOWN)	Q = −⅓ B = +⅓	Q = −⅓ B = +⅓	Q = −⅓ B = +⅓
	Q = −1 B = 0	Q = 0 B = 0	Q = 0 B = +1
s (STRANGE)	Q = −⅓ B = +⅓	Q = −⅓ B = +⅓	Q = −⅓ B = +⅓
	Q = −1 B = 0	Q = 0 B = 0	Q = 0 B = +1
c (CHARM)	Q = +⅔ B = +⅓	Q = +⅔ B = +⅓	Q = +⅔ B = +⅓
	Q = 0 B = 0	Q = +1 B = 0	Q = +1 B = +1

ADDITIONAL QUANTUM NUMBER of quarks is called color, and it can assume three possible values, represented here by the primary colors red, green and blue. In contrast to color the original quark designations *u, d, s* and *c* are sometimes called quark flavors. (Both color and flavor are arbitrary terms; they do not have their usual meaning.) Each flavor of quark is assumed to exist in each of the three colors. In one model (*white boxes*) red, green and blue quarks of a given flavor are indistinguishable; they have the same values of electric charge (*Q*) and baryon number (*B*) and of all other quantum numbers. In an alternative theory (*gray boxes*) proposed by the author and M.-Y. Han quarks of different colors differ in electric charge and baryon number, and these quantum numbers can be given integer values. The Han-Nambu model cannot be excluded with certainty, but in this article fractional charges are assumed.

The flaw involves an apparent conflict between the behavior of the quarks and one of their quantum numbers, spin angular momentum. The assignment of a spin of 1/2 unit to each of the quarks is essential if the spins of the hadrons are to be predicted correctly. Quantum mechanics, however, specifies rules for the behavior of particles with half-integer spins, and the quarks do not seem to obey them.

The quantum-mechanical rules postulate a connection between the spin of a particle and its "statistics," the set of rules that mandates how many identical particles can occupy a given state. Particles with integer spin are said to obey Bose-Einstein statistics, which allow an unlimited number of particles to be brought together in one state. Particles with half-integer spins obey Fermi-Dirac statistics, which require that no two identical particles occupy a state. This is the exclusion principle formulated by Wolfgang Pauli, the quantum-mechanical equivalent of the intuitive notion that no two things can be in the same place at the same time.

The most familiar application of Fermi-Dirac statistics and of the related exclusion principle is in atomic physics. There it governs the way electrons (which, being leptons, have a spin of 1/2) fill the orbitals, or energy levels, surrounding the nucleus. If an orbital contains one electron, one more can be added, provided that its spin is aligned in the direction opposite to that of the first electron's. With opposite spins the electrons do not have identical quantum numbers, and so they can occupy the same state, in this case an atomic orbital. Since there are only two possible directions for the spin, however, all other electrons are permanently excluded from the orbital.

The connection between spin and statistics is not well understood at a theoretical level, but it is not in doubt. In fact, formal proofs have been presented showing that the exclusion principle must be obeyed by all particles with half-integer spin, without exception. Like electrons, quarks move in orbitals, although their motion is measured not with respect to a nucleus but with respect to one another or to their common center of mass. For the least massive families of hadrons all the quarks should be in the same orbital: the smallest one. It follows that no two quarks in a hadron can have exactly the same quantum numbers.

In the quark model of the meson the requirements of Fermi-Dirac statistics can readily be accommodated. The two particles that compose a meson are a quark and an antiquark, and their quantum numbers are therefore different (in some cases they are exactly opposite). In the baryon, however, spin and statistics issue conflicting imperatives. In at least three baryons (*uuu, ddd* and *sss*) all three quarks have identical quantum numbers. Because there are three particles in the baryon, at least two of them must have their spins aligned the same way, and in many cases all three spins must point in the same direction. The exclusion principle seems to be violated.

A strategy for avoiding this uncomfortable conclusion was first proposed by O. W. Greenberg of the University of Maryland. Greenberg suggested that the quarks might not obey Fermi-Dirac statistics but could instead be governed by an unconventional set of rules he called para-Fermi statistics of order 3. Whereas in Fermi-Dirac statistics a state can be occupied by only one particle, in para-Fermi statistics it can be occupied by three particles, but no more.

Another approach to the problem was later suggested by M.-Y. Han of Duke University and me, and independently by A. Tavkhelidze of the Joint Institute for Nuclear Research in the U.S.S.R. and Y. Miyamoto of the Tokyo University of Education. Instead of changing the rules we changed the quarks. By assigning each quark an extra quantum number with three possible values, it is possible to arrange for all the quarks in a baryon to be of different species and therefore in different quantum-mechanical states. All that is necessary is some mechanism that will ensure that in every case each quark has a different value of the new quantum number. This extra quantum number has come to be known as color. For the three values of the quantum number it is convenient to adopt the three primary colors red, green and blue; the antiquarks have anticolors, which can be represented by the complements of the primaries, respectively cyan, magenta and yellow. (None of these terms, of course, has any connection with its conventional meaning; they are arbitrary labels.)

The para-Fermi statistics can be regarded as a special case of the color hypothesis. The two theories are equivalent if the assumption is that color is completely unobservable. In that case quarks of different colors would appear to be identical in all their properties, and since there would be no way of telling one from another it would seem that identical quarks were obeying unconventional statistics. Color would be invisible, or, to put it another way, nature would be color-blind. The color hypothesis allows, however, for the possibility that color might be visible under some circumstances.

The introduction of color necessarily triples the number of quarks. If only the original three quarks are considered, then with color there is a total of nine; if the charmed quark is included, it too must have red, green and blue varieties, and the total number of quarks is 12. The number of hadrons, however, is not increased; the color hypothesis does not predict any new particles. The number of hadrons is unchanged because of the special way the colors are allotted to the quarks in a hadron. If the colors are to solve the problem of quark statistics, it is essential that a baryon contain one quark of each color; if a baryon could be made of three red quarks, for example, then the quantum numbers of all the quarks could well be identical. Only if all three colors are equally represented can obedience to the exclusion principle be ensured. Since we have assigned the quarks primary colors such a combination could be termed white, or colorless. As we shall see, the theory implies that all hadrons, both baryons and mesons, are colorless. The baryons are made up of equal quantities of red, green and blue; the mesons are equal mixtures of each color with its anticolor.

The formal treatment of the quark colors involves postulating another SU(3) symmetry group, exactly analogous to the one that determines the other properties of the quarks. The two quantum numbers that determine the quark colors are named, again by analogy to the original SU(3) group, color isotopic spin and color hypercharge. The properties determined by the original SU(3) symmetry are sometimes called quark flavors, and flavor, unlike color, is readily observed in experiments; it is, as it were, tasteable. The labels *u, d, s* and *c* represent the quark flavors, and they determine all the observable properties, such as electric charge, of the hadrons they compose. The symmetry among the flavors is not a perfect one, and quarks that differ in flavor have slightly different masses. Color, on the other hand, is an exact symmetry; in the usual formulation of the theory a quark of a given flavor has the same properties and the same mass regardless of its color.

Color was introduced into the quark theory as an ad hoc element to solve the problem of quark statistics. It has since become a central feature of the model. In particular it is thought to determine the forces that bind quarks together inside a hadron, and hence to have a profound influence on quark confinement. In this context the qualitative distinction between quarks and leptons begins to seem comprehensible. An important element in the distinction is that leptons do not form strongly bound states. If it is the color quantum number that is responsible for binding quarks together, then the absence of strong binding in leptons is readily understood, since the leptons do not have color.

In order to understand the forces between quarks it is helpful to consider first a more familiar force: electromagnetism. The electromagnetic force is described by Coulomb's law, which states that the force between two charged bodies declines as the square of the distance between them. For example, the force between a proton in the nucleus of an atom and one of the electrons surrounding the nucleus is described by this law. The force can be regarded as being transmitted by a field or by discrete particles: photons, the quanta of the electromagnetic field. Ultimately both the field and the force are derived from the electric charges of the particles; since those charges are unlike, the force is attractive.

The forces between quarks are in many respects similar, but they are somewhat more complicated. In the case of the electromagnetic field only one quantum number (electric charge)

PROPERTIES	CONSTITUENT QUARKS u		u		d		HADRONS PROTON (p)
SPIN (J)	$(\frac{1}{2},\frac{1}{2})$	+	$(\frac{1}{2},\frac{1}{2})$	+	$(\frac{1}{2},-\frac{1}{2})$	=	$(\frac{1}{2},\frac{1}{2})$
ELECTRIC CHARGE (Q)	$\frac{2}{3}$	+	$\frac{2}{3}$	−	$\frac{1}{3}$	=	+1
BARYON NUMBER (B)	$\frac{1}{3}$	+	$\frac{1}{3}$	+	$\frac{1}{3}$	=	+1
STRANGENESS (S)	0	+	0	+	0	=	0
CHARM (C)	0	+	0	+	0	=	0

			u		$\bar{d}$		PION (π^+)
SPIN (J)			$(\frac{1}{2},\frac{1}{2})$	+	$(\frac{1}{2},-\frac{1}{2})$	=	(0,0)
ELECTRIC CHARGE (Q)			$\frac{2}{3}$	+	$\frac{1}{3}$	=	+1
BARYON NUMBER (B)			$\frac{1}{3}$	−	$\frac{1}{3}$	=	0
STRANGENESS (S)			0	+	0	=	0
CHARM (C)			0	+	0	=	0

	$\bar{u}$		$\bar{d}$		$\bar{d}$		ANTINEUTRON ($\bar{n}$)
SPIN (J)	$(\frac{1}{2},-\frac{1}{2})$	+	$(\frac{1}{2},\frac{1}{2})$	+	$(\frac{1}{2},\frac{1}{2})$	=	$(\frac{1}{2},\frac{1}{2})$
ELECTRIC CHARGE (Q)	$-\frac{2}{3}$	+	$\frac{1}{3}$	+	$\frac{1}{3}$	=	0
BARYON NUMBER (B)	$-\frac{1}{3}$	−	$\frac{1}{3}$	−	$\frac{1}{3}$	=	−1
STRANGENESS (S)	0	+	0	+	0	=	0
CHARM (C)	0	+	0	+	0	=	0

	u		d		s		LAMBDA (Λ^0)
SPIN (J)	$(\frac{1}{2},\frac{1}{2})$	+	$(\frac{1}{2},-\frac{1}{2})$	+	$(\frac{1}{2},\frac{1}{2})$	=	$(\frac{1}{2},\frac{1}{2})$
ELECTRIC CHARGE (Q)	$\frac{2}{3}$	−	$\frac{1}{3}$	−	$\frac{1}{3}$	=	0
BARYON NUMBER (B)	$\frac{1}{3}$	+	$\frac{1}{3}$	+	$\frac{1}{3}$	=	+1
STRANGENESS (S)	0	+	0	−	1	=	−1
CHARM (C)	0	+	0	+	0	=	0

			c		$\bar{u}$		CHARMED MESON (D^0)
SPIN (J)			$(\frac{1}{2},\frac{1}{2})$	+	$(\frac{1}{2},-\frac{1}{2})$	=	(0,0)
ELECTRIC CHARGE (Q)			$\frac{2}{3}$	−	$\frac{2}{3}$	=	0
BARYON NUMBER (B)			$\frac{1}{3}$	−	$\frac{1}{3}$	=	0
STRANGENESS (S)			0	+	0	=	0
CHARM (C)			1	+	0	=	+1

QUARKS COMBINE to make up the class of observed particles called hadrons. Two kinds of quark combination are possible. In one of them three quarks bind together to form a baryon (such as the proton) or three antiquarks bind to form an antibaryon (such as the antineutron). In the other kind of quark binding a quark and an antiquark make up a meson (such as the pion). The properties of these hadrons are determined by the simple rule that the quantum numbers of the hadron are the sums of the quark quantum numbers. All the allowed combinations of quarks give integer values of electric charge. The baryon numbers add in such a way that all baryons have a value of +1, antibaryons −1 and mesons 0. Strange particles, such as the lambda baryon, are those that have at least one *s* quark; charmed particles have at least one *c* quark. The spin quantum number is a vector and requires a more complicated arithmetic, but the result of the addition is that all baryons and antibaryons have half-integer spin and all mesons have integer spin. The great success of the quark theory is that all the allowed combinations yield known hadrons and no other combinations do so. The problem of quark confinement is why only these combinations should exist, and why solitary quarks are not observed.

is involved in generating the field; the fields between quarks are generated by two quantum numbers: color isotopic spin and color hypercharge. To continue the analogy with electromagnetism, these quantum numbers can be regarded as two varieties of "color charge."

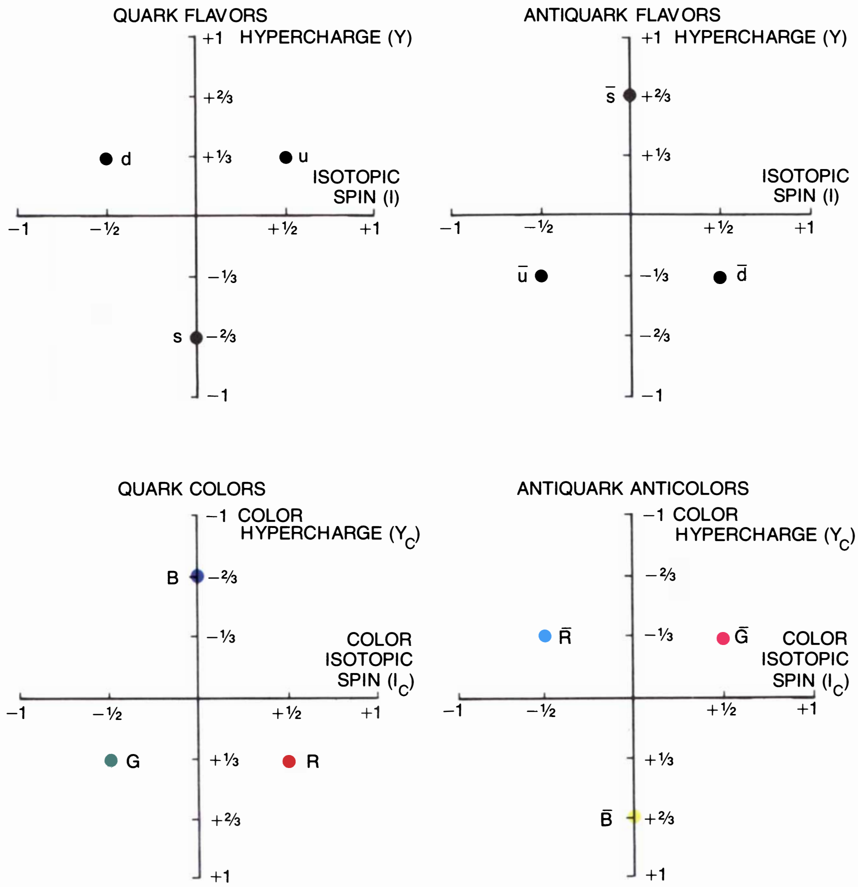
If a combination of quarks is to be stable, it is obvious that the forces between them must be attractive. That can be arranged by ensuring that the quarks in a baryon, for example, are all of different colors, since the quarks will then have unlike values of the two kinds of color charge. A red quark and a green quark will be bound together because their color-isotopic-spin numbers are of opposite sign; the blue quark will be bound to both of the others because of a difference in the sign of the color-hypercharge quantum number. A similar mechanism generates an attractive force between a quark of one color and an antiquark of the corresponding anticolor, as in a meson. The forces favor just those combinations that have been identified as white, or colorless.

Actually the situation is still more complicated. Whereas the electromagnetic force is transmitted by a single kind of particle, the photon, the force associated with quark colors requires eight fields and eight intermediary particles. These particles have been named gluons because they glue the quarks together. Like the photon, all of them are massless and have a spin of 1; like the quarks themselves, they have not been detected as free particles.

The eight gluons can be regarded as having composite colors, made up of the various combinations of three colors and three anticolors. All together there are nine such combinations, but one of them receives equal contributions from red combined with antired, green combined with antigreen and blue combined with antiblue. Since that combination is effectively colorless it is a trivial case and is excluded, leaving eight colored gluons.

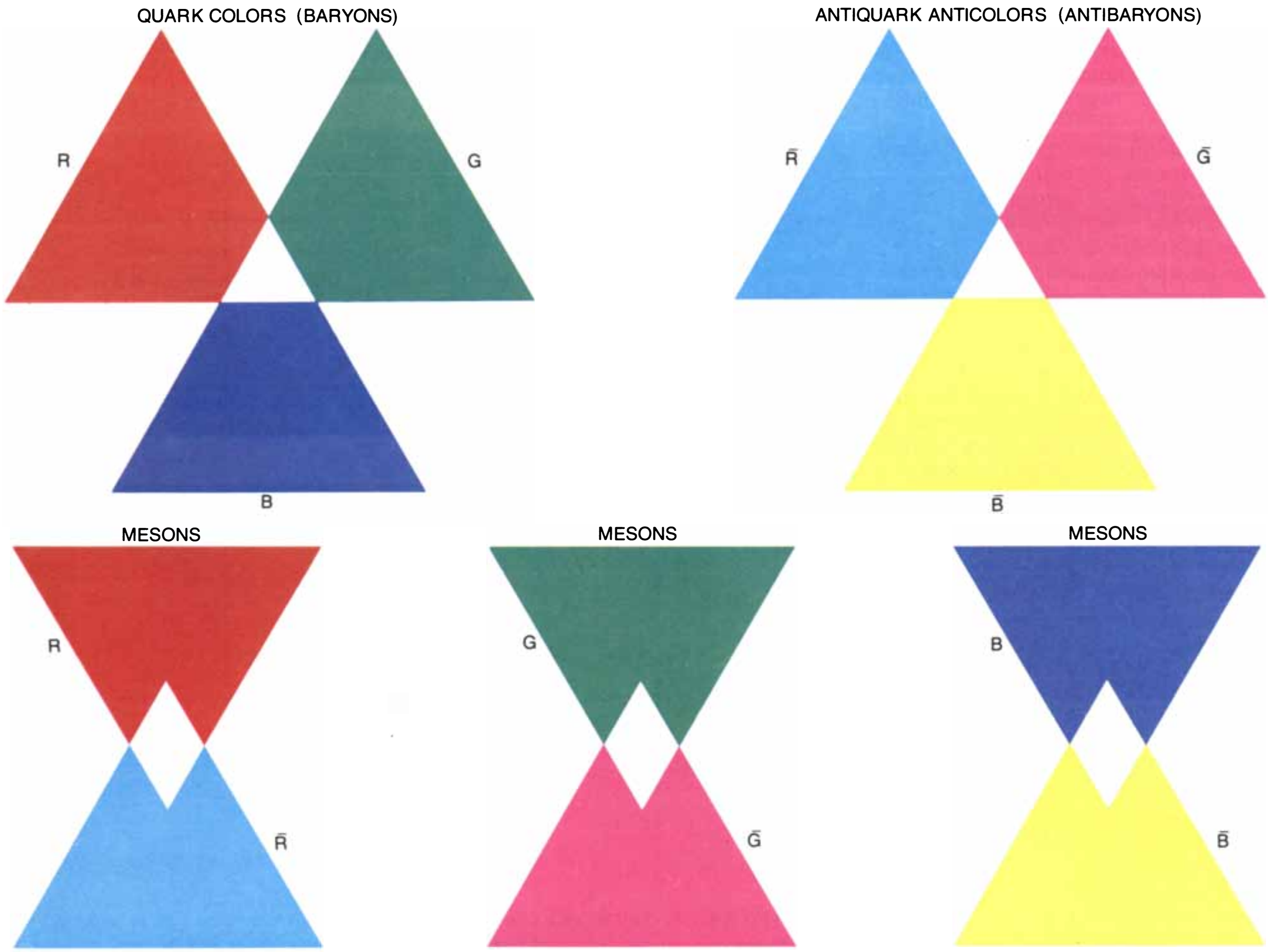
Quarks interact by the exchange of gluons; when they do so, they can change their colors but not their flavors. At all times a baryon contains red, green and blue quarks, but because gluons are continually exchanged it is not possible to say at any given moment which quark is which color. Similarly, a meson always consists of a quark of one color and an antiquark of the complementary anticolor, but the three possible combinations of color and anticolor are equally represented. In quantum mechanics we can have no certain knowledge of quark colors; rather, we can know only the probability that a quark is a given color. If all hadrons are colorless, the probabilities for the three colors are equal.

The model of hadrons in which these

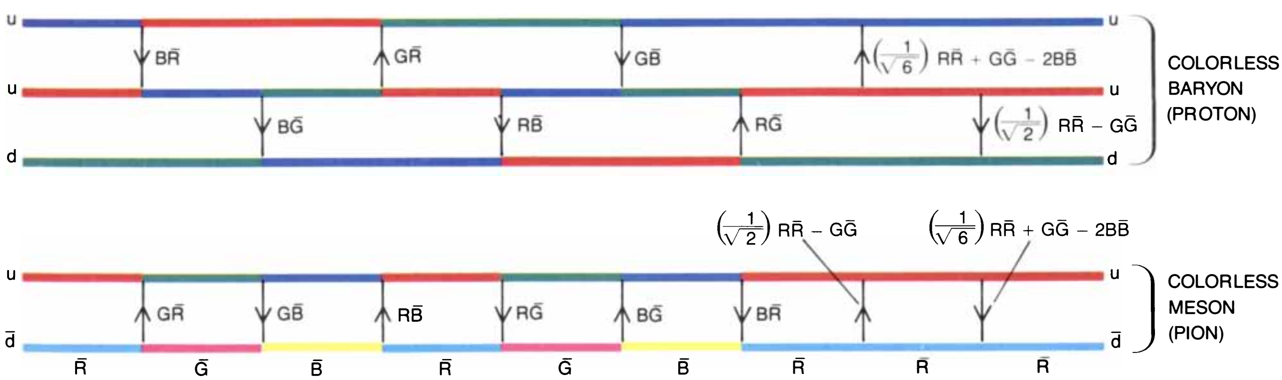


CLASSIFICATION OF QUARKS is governed by a fundamental symmetry of nature. The quark flavors are determined by two quantum numbers, isotopic spin and hypercharge; each quark or antiquark represents a unique combination of these numbers. Color is determined by two other quantum numbers, named by analogy color isotopic spin and color hypercharge. Both flavor and color can be described by means of the concept of a symmetry group. Flavor is a "broken symmetry" because quarks with different flavors differ in properties such as mass and electric charge. Color is an exact symmetry: two quarks of the same flavor but of different colors differ only in their colors and are otherwise indistinguishable. The quark colors are thought to generate forces binding quarks together. These forces result from two kinds of field, or color charge, associated with quantum numbers color isotopic spin and color hypercharge.

COLORED GLUONS are the particles that transmit forces between colored quarks; they are the quanta of the fields generated by the color quantum numbers just as the photon is the quantum of the electromagnetic field. The gluons can be regarded as combinations of color and anticolor. In the first analysis there are nine possible combinations of three colors and three anticolors; six of these combinations (*white squares*) are straightforward but three require special treatment (*gray squares*). The three involve combinations of a single color with the corresponding anticolor, and in each combination all quantum numbers cancel out. States with null quantum numbers can be combined at will, but only three of these combinations of combinations need be considered. One is $R\bar{R} + G\bar{G} + B\bar{B}$, in which the quantum numbers are still null; the case is trivial and can be eliminated. The remaining two are $R\bar{R} - G\bar{G}$ and $R\bar{R} + G\bar{G} - 2B\bar{B}$, which can be treated like the other six gluons except that numerical correction factors are required.



COLORLESS HADRONS are formed by properly combining the colored quarks. A baryon consists of three quarks, one each of red, green and blue color. (The quarks can have any flavor, and their flavors determine all the observable properties of the particle.) Similarly, an antibaryon is made up of three antiquarks having each of the three anticolors. The anticolors are shown here as the complements of the corresponding primary colors. In mesons the colors and anticolors are equally represented. In each of these combinations the net color quantum numbers are zero; in figurative terms the hadrons are white or colorless. No other combinations of colors can give the same result. It is thus possible to explain why only these combinations of quarks exist in nature, and why single quarks are prohibited, by postulating that only colorless particles are observable. The problem of quark confinement is then reduced to the problem of explaining this postulate.



EXCHANGE OF GLUONS binds together the quarks in a hadron and can simultaneously change their colors. In these diagrams the vertical dimension represents the spatial separation between the quarks and the horizontal dimension represents time. At each vertex where a gluon is emitted or absorbed the color quantum numbers must balance. Hence at the upper left, where a blue quark emits a blue-antired gluon, the "bluishness" of the quark is carried off by the gluon, and the quark changes to red, balancing the antired of the gluon. When the gluon is absorbed, the antired of the gluon and the red of the absorbing quark annihilate each other, and the quark is left with a net color of blue. The gluons at the far right, which have null quantum numbers, do not change the quark colors, and no gluons have any effect on quark flavors. At all times the baryon contains a red, a green and a blue quark; in the meson the color of the quark is balanced at each of the instants shown here by the anticolor of the antiquark. In practice it is not possible to determine the colors of the quarks; only the probability of each color can be calculated. In hadrons that are colorless the probabilities of the colors are equal.

particles are composed of quarks bound together by the exchange of gluons can be given an elegant mathematical formulation. The model is an example of a non-Abelian gauge theory, a kind of theory invented by C. N. Yang of the State University of New York at Stony Brook and Robert L. Mills of Ohio State University. A gauge theory is one modeled on the theory of electromagnetism developed by James Clerk Maxwell. A characteristic of such theories is that any particle carrying a given quantum number, or charge, generates a long-range field whose strength is proportional to the quantum number. In Maxwell's theory the quantum number in question is electric charge; in the model of hadron structure there are two such numbers, those associated with the quark colors.

Maxwell's theory is an Abelian gauge theory; non-Abelian gauge theories are distinguished from it by the fact that the fields themselves carry quantum numbers. A field can therefore act as a source of itself. Einstein's theory of gravitation is also a non-Abelian gauge theory in that the gravitational field itself generates gravity. Electromagnetism and the weak force, which is responsible for certain kinds of radioactive decay, have recently been combined in another non-Abelian gauge theory by Steven Weinberg of Harvard University and by Abdus Salam of the International Centre for Theoretical Physics in Trieste. The colored-quark model could now provide a similar framework for understanding the strong force. These four forces—strong, weak, electromagnetic and gravitational—are the only ones known in nature. It would bring great aesthetic satisfaction if all four could be understood through the same kind of theory.

Before describing schemes for the confinement of quarks it would be well to consider the possibility that they are not confined at all. Perhaps they have been there all the time but we have not been able to detect their presence, or perhaps we have confused them with some ordinary particle. If a fractionally charged quark could escape from a hadron, it would almost certainly be stable in isolation. One quark might decay to yield another quark, perhaps along with some ordinary particles, but at least one quark species—the one with the smallest mass—must be stable. It could not decay because all particles other than quarks have integer charges, which cannot be created from the decay of a fractionally charged quark.

Such free, stable quarks could well come to rest among the atoms of ordinary matter. Similarly, if they can escape, they should be found in the debris produced by high-energy collisions of hadrons, both in particle accelerators and when cosmic rays collide with atoms in the atmosphere. The principal argument against the existence of such free quarks is that they have not been found in ordinary matter, even in minute concentrations, and they have not been seen in the aftermath of hadron collisions.

If fractionally charged quarks were present, they could readily be detected and recognized. Charged particles are detected by the ionization they cause in the atoms surrounding them. The extent of the ionization is proportional to the square of the particle's electric charge. Thus a quark with a charge of 1/3 would produce only one-ninth the ionization of a particle with a charge of 1, and it could easily be distinguished from ordinary particles.

Perhaps, however, the quarks do not have fractional charges. With the addition of color to the quark theory it becomes possible to assign each quark integer values of both electric charge and baryon number, and Han and I proposed such a model in 1965. The model has the effect of making color visible, in the sense that quarks of different colors carry different masses, electric charges and baryon numbers and can therefore be distinguished. For each flavor of quark all the electric charge ($+1$ or -1) would be assigned to one color, and the other two colors would have zero charge. If all colors must be represented equally, then the total charge of the hadron would be correct. If the quarks do have integer charges, then a free quark in the laboratory would not look much different from an ordinary baryon and might easily be misidentified. This possibility cannot yet be excluded with certainty.

Another hypothesis suggests that it is difficult to extract quarks from hadrons, but not impossible. Perhaps they are simply very massive and the accelerators operating today are not powerful enough to liberate them. That hypothesis, however, requires that the mass of a free quark and that of a bound quark be quite different. Indeed, a single isolated quark might be more massive than a baryon composed of three quarks, a notion that is difficult to understand if it is not inconceivable.

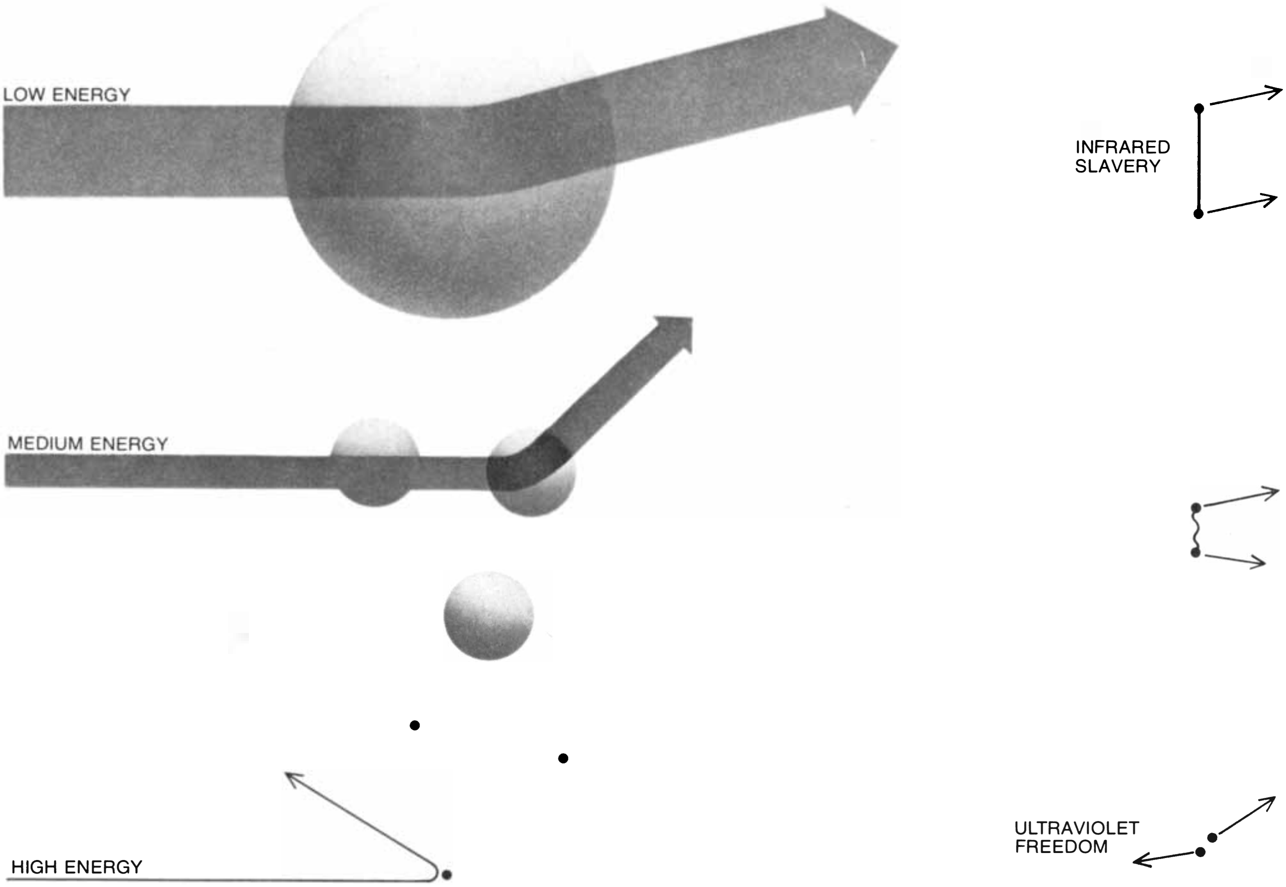
The color theory of hadron construction leads naturally to at least a partial confinement of the quarks. An atom is stablest when it is electrically neutral, that is, when it has attracted just enough electrons to balance the positive charge of the nucleus. Any attempt to add an extra electron or to remove one of those already bound is resisted. In the same way a system of quarks is stablest when all three colors, or a color and an anticolor, are present; then the hadron is neutral with respect to the two kinds of color charge. This result is hardly surprising: the color quantum numbers were introduced precisely in order to achieve an equal representation of the colors in baryons. It follows that since an isolated quark is necessarily a colored particle, it is an energetically unfavorable configuration. Free quarks will tend to associate to form colorless hadrons, just as free electrons and ionized atoms will tend to recombine. This aspect of the quark colors does not exclude the possibility of there being free quarks, but it does strongly inhibit their formation. It requires that a free quark or any other colored state be less stable, or more massive, than colorless states.

The quark model has changed significantly and grown far more elaborate since it was proposed in 1963. There is every reason to believe it will go on evolving, and it is entirely possible the present perceived need to explain the confinement of quarks will be altered by subsequent events—including, perhaps, the discovery of a free quark. The fact remains that experimental searches for quarks, guided by reasonable conjectures about their properties, have failed to reveal their presence. The consistently negative results demand explanation. One approach is to postulate a mechanism that permanently confines the quarks to the interior of a hadron, so that free quarks are not merely discouraged but are absolutely prohibited. Several theories can provide such a mechanism, and some of them exhibit exceptional ingenuity.

One of these ideas grows directly out of the underlying gauge theory of the interactions between colored quarks. Once again the principle can be effectively illustrated by considering first the analogous phenomena observed in electromagnetic interactions of matter.

The inverse-square relation of Coulomb's law has been verified with great precision at large distances, but it is not valid when the force between charged particles, such as electrons, is measured at extremely short range. The discrepancy is caused by the spatial distribution of the electron's charge. At the core of the electron there is a negative charge, called the bare charge, of very large magnitude; indeed, it may well be infinite. This charge induces in the vacuum surrounding it a halo of positive charge, which almost cancels the bare charge. The effective charge of the electron, when measured from a distance, is simply the difference between these two charges. A test particle able to approach the electron at close range will penetrate the shielding of positive charge and will begin to perceive the large bare charge.

Electromagnetism, it will be remembered, is an Abelian gauge theory, whereas the colored-quark theory of the strong force is a non-Abelian one. In this context the distinction is a crucial one, a fact that has been demonstrated by H.



INFRARED SLAVERY, one proposed explanation of quark confinement, is a concept derived directly from the field theory that describes interactions of colored quarks and gluons. The theory holds that quarks at large distances (about the size of a hadron, 10^{-13} centimeter) are bound tightly together and move in concert. The long-distance behavior of the quarks is examined by low-energy probes of the hadron, and indeed at these energies the hadron appears to be a cohesive, unified body. When the quarks are close together, on the other hand, they are only weakly bound and can move independently. The forces between quarks at this range are investigated by high-energy probes, and such experiments have observed centers of mass in the hadron that seem to move freely. The names infrared slavery and ultraviolet freedom were applied to these phenomena through analogy with the relative energies of infrared and ultraviolet radiation.

David Politzer of Harvard and David Gross and Frank Wilczek of Princeton University. In the non-Abelian theory the bare charge does not induce a shielding charge but an "antishielding" one. Thus a quark with a color charge induces around it additional charges of the same polarity. As a result the color charge of the quark is smallest at close range; as a particle recedes from the quark the charge gets larger. The corresponding force law is dramatically different from Coulomb's law: as the distance separating two color-charged particles increases, the force between them could remain constant or could even increase.

A test particle colliding with a hadron at high energy inspects the behavior of the constituent quarks over very small distances and during a very brief interval. This fact is established mathematically by the uncertainty principle, which relates the time and distance in which a measurement is performed to the energy and momentum of the test particle. It can be understood intuitively by remembering that a high-energy particle moves at nearly the speed of light and that it "sees" the quarks for only a brief moment, during which they can move only a short distance. The non-Abelian gauge theory predicts that such a high-energy probe will reveal the quarks to be essentially free particles, moving independently of one another, since at small distances the color charge declines and the quarks are only loosely bound together.

A low-energy investigation of a hadron, on the other hand, should see quarks that are rigidly tied together and therefore move as a unit. At these comparatively low energies the quarks are being observed during a more extended period, and they can interact over greater distances. Hence the more powerful long-range effects of the color gauge fields grip the quarks and bind them to one another.

Since the theory is a non-Abelian one, the gluons are subject to the same constraints as the quarks, and they are confined just as efficiently. The gluons, or the fields they represent, generate fields of their own that have the same character as the color fields of the quarks. The resulting behavior of the gluons contrasts sharply with that of photons, the quanta of the gauge fields in the Abelian theory of electromagnetism. Photons do not themselves give rise to an electromagnetic field, and they escape from such a field without hindrance.

These two opposing aspects of the color gauge theory have been given the picturesque names infrared slavery and ultraviolet freedom. The terms do not refer to those particular regions of the electromagnetic spectrum but are simply intended to suggest low-energy and high-energy phenomena respectively. Ultraviolet freedom is also known as asymptotic freedom, because the state of completely independent movement is approached asymptotically and never actually achieved. The effect may have been observed in collisions of electrons with protons, where it has been found that at very high energy the proton behaves as if it were a collection of free quarks.

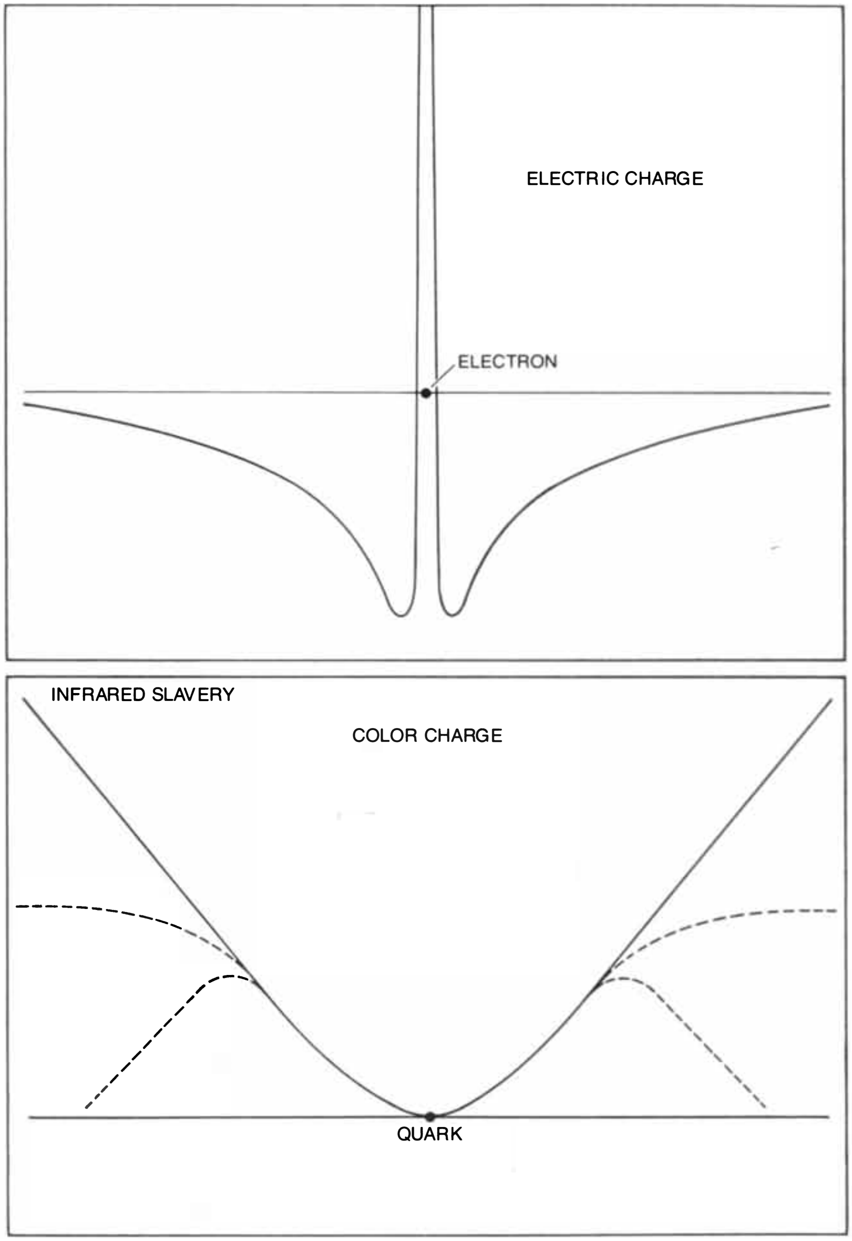
The concept of infrared slavery provides an obvious means of explaining the confinement of quarks. If the effective color charge continues to increase indefinitely with increasing distance, then so does the energy needed to pull two quarks apart. Achieving a macroscopic separation would require an enormous input of energy and would surely be a practical impossibility.

The spatial distribution of the color charge is not known, however, for macroscopic distances; indeed, nothing is known of it for any distance greater than the approximate size of a hadron: 10^{-13} centimeter. Whether or not infrared slavery can account for quark confinement depends on the details of the charge distribution. It should be pointed out, however, that the charge need not increase indefinitely to entrap the quarks permanently. It need only increase to the point where the energy required to further separate the quarks is equal to the energy needed to create a quark and an antiquark. When that energy is reached, the quark-antiquark pair can materialize. The newly created quark replaces the one extracted, and the antiquark binds to the displaced quark, forming a meson. The result is that a quark is removed from the hadron but is not set free; all we can observe is the creation of the meson.

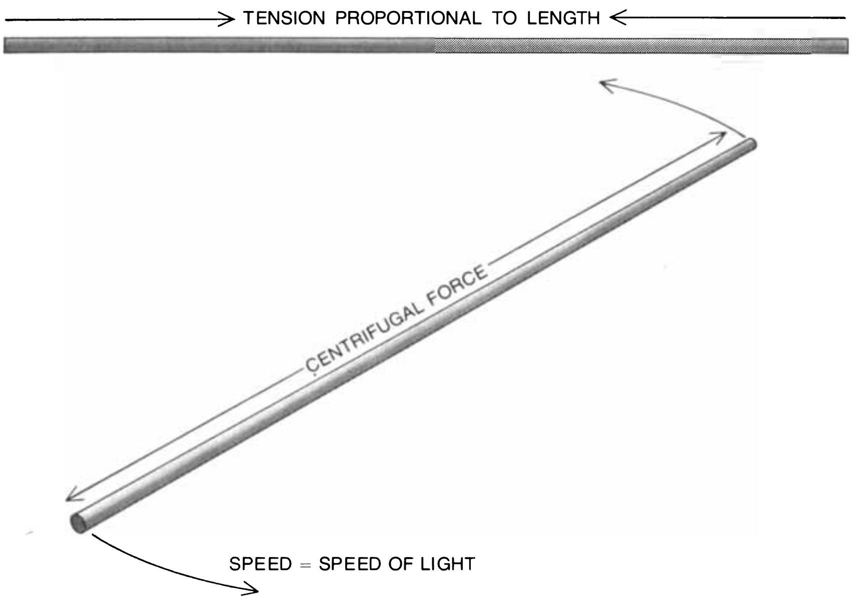
A kind of charge that increases with distance and a force that remains constant with distance seem to contradict an intuitive sense of how matter ought to behave. Quantum mechanics has contradicted intuition before, and made no apology for it, but in this case an explanation, and even a pictorial representation, of how the effects might arise may be possible. This explanation is a feature of another model of quark confinement, called the string model.

The string model grew out of mathematical formulas introduced by Gabriele Veneziano of the Weizmann Institute of Science. In the model hadrons are regarded as flexible, extensible strings in rapid rotation. The string is massless, at least in that it has no material "beads" along its length, although it does have potential and kinetic energy. The string is given a certain fixed tension as one of its intrinsic properties, so that the ends of the string tend to pull toward each other with constant force. The tension represents potential energy (just as the tension of a stretched spring does), and the magnitude of that energy is exactly proportional to the length of the string. If the string were stationary, its intrinsic tension would cause it to collapse, but the system can be kept in equilibrium by spinning the string. As the string spins it stretches, and when its length is such that its ends move with the speed of light, the centrifugal force balances the tension. (The ends are allowed to move with the speed of light, and indeed are required to do so since they are massless.)

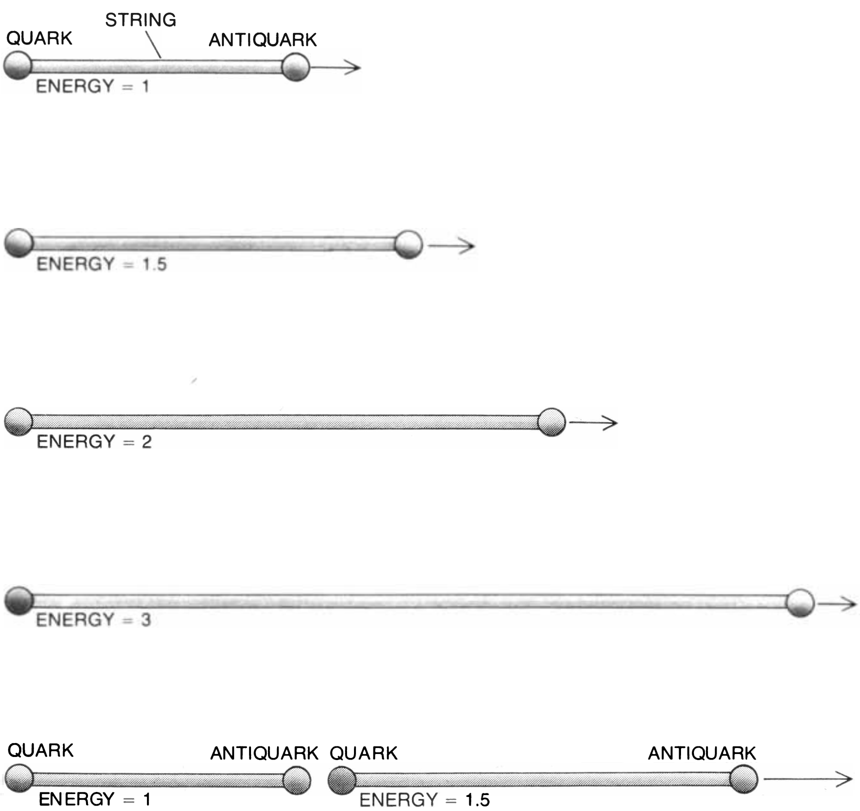
Because of the relations between length, energy and rotation that have been built into the string model, the angular momentum of the system is proportional to the square of the total energy. In this respect the model reflects an important observed property of hadrons: When the angular momentum of hadrons is plotted against the square of



DISTRIBUTION OF THE COLOR CHARGE might explain the effects of infrared slavery and ultraviolet freedom. The distribution seems to be quite different from that of the more familiar electric charge. The electron has at its core a large and possibly infinite negative charge, called the bare charge, which induces in the vacuum surrounding it a positive charge of almost equal magnitude; the effective charge of the electron observed at a distance is the difference between these charges. The bare color charge, in contrast, is thought to be very small and possibly zero, but it induces a surrounding charge of the same polarity, so that the effective charge increases, perhaps without limit, as it spreads out in space. From these charge distributions it follows that electrically charged particles obey Coulomb's law: the force between them declines as the square of the distance. Particles bearing a color charge, on the other hand, obey a very different law: the force between them remains constant, regardless of distance, and the energy with which they are bound together (or the energy that must be supplied in order to pull them apart) increases with distance. The actual distribution of the color charge has not been measured at large distances, so that several continuations of graph are possible (*broken lines*).



STRING MODEL of hadron structure leads to another possible explanation of quark confinement. The model assumes that a hadron is made of a massless, one-dimensional string that has as one of its intrinsic properties a constant tension per unit length. Because of its tension the string tends to collapse, but it can be kept in equilibrium by centrifugal force if it is made to spin so that its ends move with exactly the speed of light. These properties of the string imply that its energy is proportional to its length and that its angular momentum is proportional to the square of its energy, a relation that has been experimentally verified for the hadrons.



QUARKS WELDED TO STRINGS might be effectively confined. In order to separate the quarks it is necessary to stretch the string, but since the energy of the string is proportional to its length the energy required to pull the quarks apart increases in proportion to the separation. A macroscopic separation could be obtained only at the cost of enormous energy. In fact, isolation of a quark might not be possible at any energy, since as soon as enough energy had been supplied to create a quark and an antiquark the string might snap and these new particles appear at the ends. Thus the result is not the liberation of a quark but the creation of a meson.

their mass or energy, the result is a series of parallel lines, named Regge trajectories after the Italian physicist Tullio Regge. The relation between angular momentum and energy embodied in the string model provides a possible explanation for the observation that all the Regge trajectories are straight lines.

Quarks can be incorporated into the string model simply by attaching them to the ends of the strings. The quarks are then assumed to carry the quantum numbers of the hadron while the string carries most of the energy and momentum. Quark confinement follows as a natural consequence of the properties of the string. It is assumed that the quarks cannot be pulled off, and so the only way they can be separated is by stretching the string. Any increase in the length of the string, however, demands a proportionate increase in its energy, so that once again large separations are impossible. Nevertheless, even if the string cannot be stretched without an inordinate supply of energy, it might be snapped in two. At the breaking point a newly created quark and antiquark would be welded to the broken ends, with the result that a meson would be created. In all these interactions the string model can be seen to give results equivalent to those of the infrared-slavery hypothesis, even though the underlying description of the hadron has a quite different form.

What is the stuff of the massless spinning string? One appealing interpretation has been proposed by Holger B. Nielsen and P. Olesen of the Niels Bohr Institute in Denmark; in explaining it we shall return again to the consideration of electromagnetism. Coulomb's law describes an electromagnetic field in three-dimensional space, and if the field is represented by discrete lines of force, it is apparent that the strength of the field declines with distance because the lines spread out in space. Their density decreases as the square of the distance, giving the familiar force law. If all the lines of force could be compressed into a thin tube, the lines could not spread out and the force would remain constant, regardless of the distance.

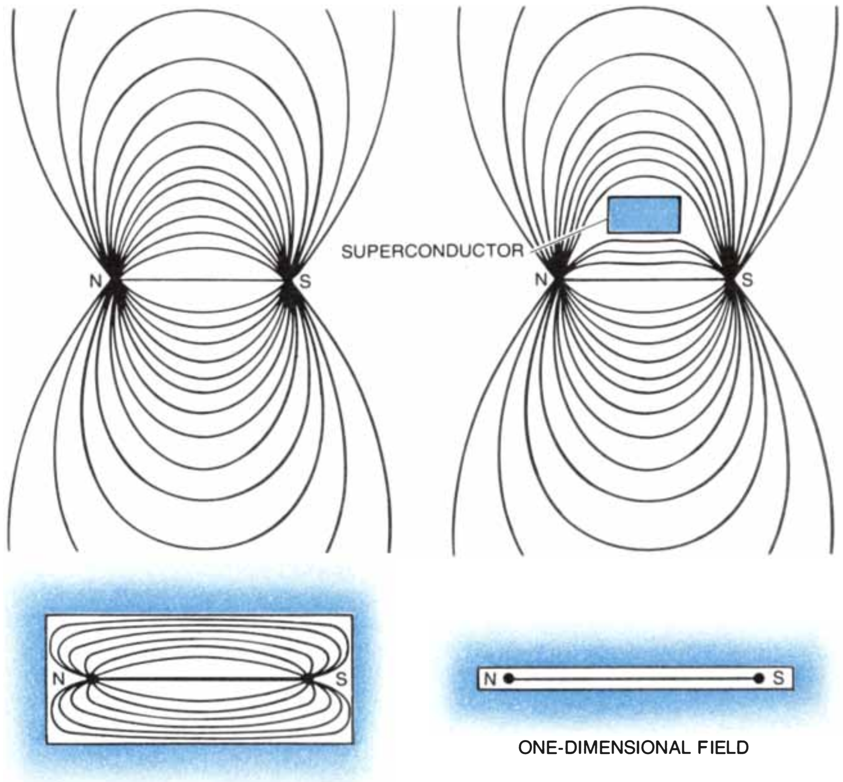
The distinctive geometry of the string suggests that it might be regarded as such a one-dimensional gauge field. The properties of the string itself—in particular the inherent tensile force and the variation of energy with length—are then as predicted by the model. Furthermore, the bizarre properties of the color gauge field are given a simple and intuitively appealing explanation. It is no longer the force itself that is peculiar; the force is a conventional one, obeying the same kind of law as electromagnetism. The peculiar properties all derive from the geometry imposed on the field.

Fields that are virtually one-dimensional can actually be created on a macroscopic scale. If a superconductor (an electrical conductor cooled to the superconducting state) is put into a magnetic field, the lines of force are expelled from the superconducting medium. If the two poles of a magnet are completely immersed in a superconductor, the lines of force are confined to a thin tube between the poles, where the superconductivity is destroyed. The tube of flux lines carries a fixed amount of magnetic energy per unit length, and the amount of magnetic flux is quantized. An exact analogy requires only that we assume that the effects of a superconducting medium on the magnetic field are duplicated in the effects of the vacuum on the color gauge field. A theory based on this comparison has been described mathematically; in it the quarks are likened to the hypothetical carriers of magnetic charge, the magnetic monopoles.

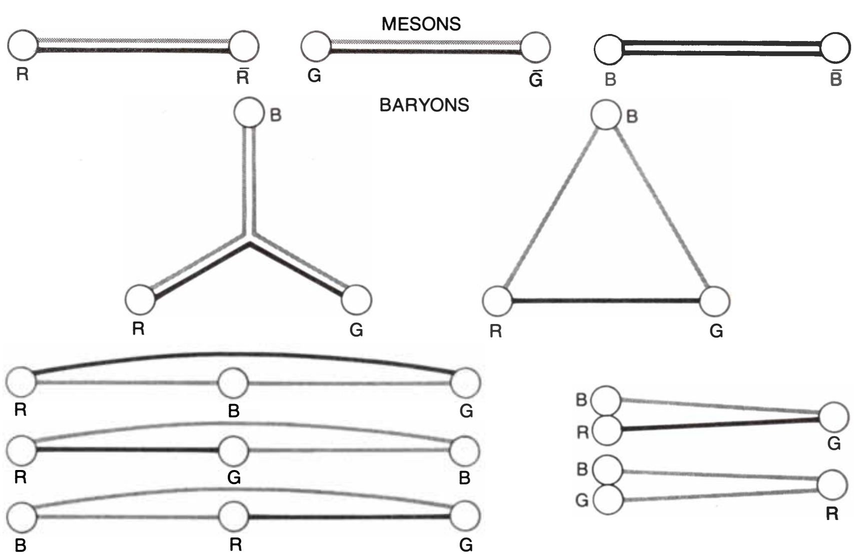
The string is a novel and amusing model of hadron structure, but attempts to make a complete and quantitative theory of it have encountered difficulties. The placement of the quarks at the ends of the string is rather arbitrary. This raises no serious problems in the case of the meson, which can be regarded as a single hank of string with a quark and an antiquark at the ends, but it is not clear what structure should be assigned to the baryon. Several configurations are possible, such as a three-pointed star, or a triangle with a quark at each vertex. The relation of mass or energy to angular momentum is very similar in baryons and mesons (that is, their Regge trajectories are nearly parallel), which implies that the internal dynamics of the two kinds of particle are also similar. This observation favors yet another possible baryon structure: a single string with a quark at one end and two quarks at the other end. In such a model, however, the colors can be assigned to the quarks in three ways, which are not equivalent to one another. Perhaps the baryon resonates between these configurations, much as the benzene ring resonates between its various possible structures.

The color-isotopic-spin and color-hypercharge quantum numbers can be accommodated in the string model by assuming that there are two kinds of string, each carrying the field associated with one of the quantum numbers. All together, though, there are eight gauge fields, represented by the eight color-anticolor combinations of the gluons. Are there then eight kinds of string also? How are we to describe the changes in the quark colors resulting from the emission or absorption of a gluon? These questions have yet to be answered satisfactorily. It may be that the simple, pictorial character of the string model is too naïve for a system in which quantum-mechanical effects are essential.

The third major attempt to account for the confinement of quarks takes a



GEOMETRY OF THE STRING might be explained through an analogy with the behavior of a magnetic field in the vicinity of a superconductor. The strength of a magnetic field declines as the square of the distance because the lines of force spread out in three-dimensional space. The flux lines are expelled by a superconductor, and if two magnetic poles are surrounded by a superconducting medium, the field is confined to a thin tube. Under these circumstances the force between the poles is constant and the energy required to pull them apart increases linearly with their separation. A string might be a similar one-dimensional field, confined not by a superconducting medium but by the vacuum. Quark confinement could then be explained even if the color charge does not increase with distance but obeys a law like that of the electric charge.



CONFIGURATION OF STRINGS linking quarks is not obvious in all cases and represents a serious impediment to the further development of the string model. It is convenient to consider two kinds of string, one associated with each of the color quantum numbers, color isotopic spin (*black*) and color hypercharge (*gray*). The binding together of a quark and an antiquark in a meson by these strings is straightforward, but baryons demand a more complex structure, for which there are several alternatives. The baryon might resonate between the various possible structures, but not all of them are satisfactory. The quarks must be able to interchange their colors without altering the mass or other properties of the hadron, but that condition is not invariably satisfied. Moreover, quark colors actually give rise to eight fields, associated with the eight gluons, rather than to two, and there is no obvious way of incorporating all into the model.

somewhat different approach but reaches a similar conclusion. This model has been proposed by Kenneth A. Johnson of the Massachusetts Institute of Technology and by others. It takes as one of its given initial conditions that the quarks are confined and from that assumption attempts to calculate known properties of the hadrons.

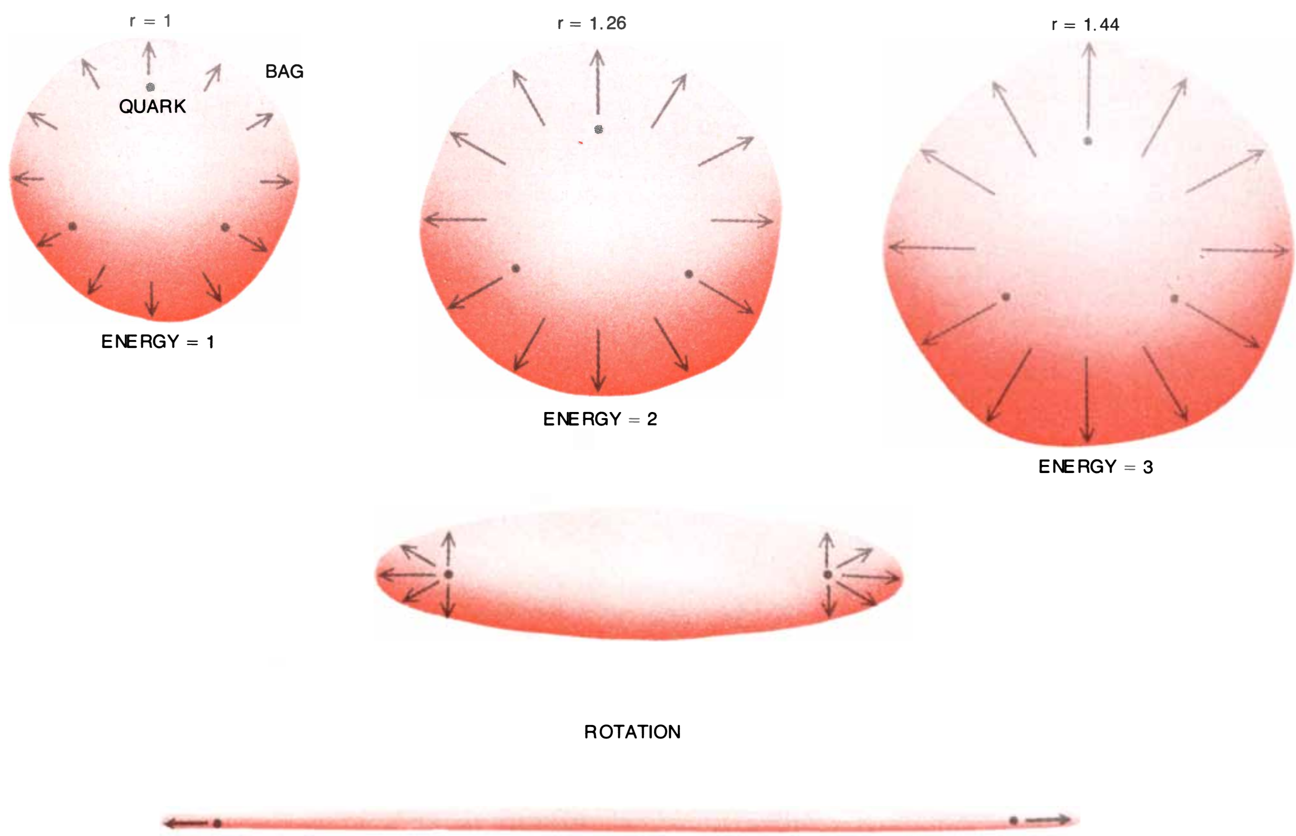
To provide containment the model employs what is perhaps the most obvious device: the quarks are trapped inside a bag, or bubble. It is a feature of the model that the quarks cannot penetrate the fabric of the bag, but by exerting pressure from inside they can inflate it. The energy of the bag itself, however, is proportional to its volume, so that large and potentially unlimited amounts of energy are required to separate the quarks. The system reaches equilibrium when the bag's tendency to shrink, in order to minimize its energy, is balanced by the pressure of the quarks inside, which move freely like the molecules of a gas. Interactions of the quarks inside the bag are governed by the standard non-Abelian gauge theory.

From the bag model it is possible to compute various properties of the proton and the neutron and of other hadrons with reasonable accuracy. The model is not very different in spirit from the Nielsen-Olesen description of the string. In one case the critical relation is between length and energy, in the other it is between volume and energy, but the effect is the same. The bag might be regarded as a string that is as thick as it is long. Conversely, if a round bag is spun fast enough, it elongates, that is, it turns into a string. Perhaps the bag will prove to be the appropriate model for discussing the ground states of hadrons, and the string will be applied to their excited, rotating states.

Each of these three models achieves its objective: it provides a mechanism for sequestering quarks inside hadrons. Each model can also account for a few properties of hadrons, but none can be considered definitive. Perhaps the comprehensive theory that will ultimately emerge will combine features of several models; for example, it would be useful to have the concept of ultraviolet freedom in the string models.

One approach to such a synthesis is being attempted by Kenneth G. Wilson of Cornell University. In Wilson's model the continuous space-time of the real world is approximated by a lattice in which the cells are the size of a hadron. Quarks can occupy any of the lattice sites and the color gluon fields propagate along straight lines (strings) linking them. Quark confinement is automatic.

Quarks are a product of theoretical reasoning. They were invented at a time when there was no direct evidence of their existence. The charm hypothesis added an extra quark explaining the properties of another large family of particles when those particles had themselves never been seen. Color, a concept of even greater abstraction, postulates three varieties of quark that may be distinct but completely indistinguishable. Now theories of quark confinement suggest that all quarks may be permanently inaccessible and invisible. The very successes of the quark model lead us back to the question of the reality of quarks. If a particle cannot be isolated or observed, even in theory, how will we ever be able to know that it exists?

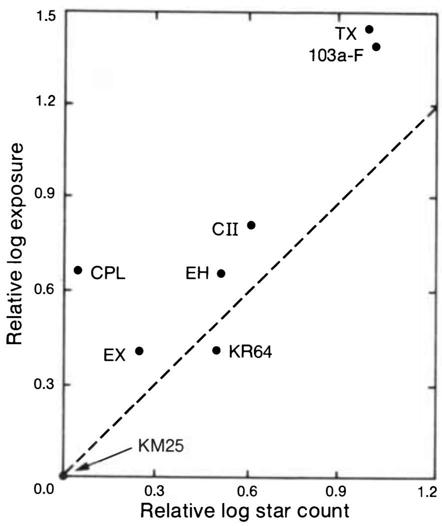


BAG MODEL of hadron structure offers a third mechanism for confining quarks. Indeed, in this model confinement is one of the initial assumptions: the quarks are assumed to be trapped inside a bag whose surface they cannot penetrate. The bag is kept inflated by the pressure of the quarks inside it, much as a balloon is inflated by the pressure of the gas inside it. The quarks can be separated only by increasing this inflation. The energy of the bag itself, however, is proportional to its volume, so that every increase in the distance between the quarks requires an additional application of energy. The bag model and the string model are closely related, and the connection between them becomes obvious when the bag is rotated rapidly: it then elongates to form an object essentially indistinguishable from a string.

How many stars are there?

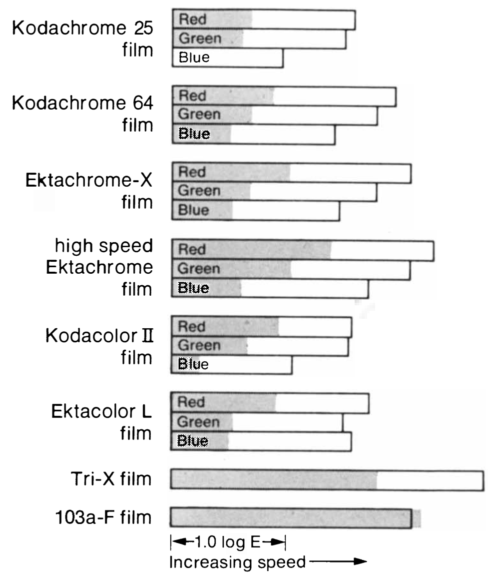
A picture is to be taken. No, several pictures. Guided exposures successively longer from "one chimpanzee, two chimpanzees, three chimpanzees" all the way to 5 minutes. In the next exciting chapter it will be found that the longer the exposure, the more stars.

The number of stars depends on the kind of film. Here is what we found when we tried it ourselves:



The origin represents one of the most available of 35 mm films, Kodachrome 25 film; *KR64,* Kodachrome 64 film; *EX,* Kodak Ektachrome-X film; *EH,* Kodak high speed Ektachrome film daylight (5033); *CII,* Kodacolor II film (5035); *CPL,* Kodak Ektacolor professional film 6102, type L; *TX,* Kodak Tri-X pan film (5063); *103a-F,* Kodak spectroscopic film, type 103a-F, acetate rem jet. For the first four of these, reversal color films, the ordinate represents threshold film speed for 5-minute exposures, specifically the logarithm of the ratio of the exposure required to create a reversed density of 3.0 on Kodachrome 25 film to that required for the same density on the plotted film; for the remaining four, negative films, the divisor is the exposure to create a density of 0.1 above minimum density. Only the blue response of the color films was used, and star counts were made from enlarged negative prints bearing a background sky density of 0.6. The color films were processed as recommended by Kodak; the two black-and-white films were developed 5 minutes in Kodak developer D-19. All points would fall on the 45° line if star count depended only on film sensitivity.

For astrophotography not requiring accommodation to the patience of youngsters and for other technical photography calling for long exposure to weak intensity—bioluminescence, for example—exposures longer than 5 minutes are often needed. Then one becomes more aware of low-intensity reciprocity failure, an effect that requires disproportionately large increases in exposure time. Emulsions vary in this respect, as shown here:



Bar length represents logarithm of speed increase for a 1-second exposure, as compared with the blue-light speed of Kodachrome 25 film for a 1000-second exposure. The unshaded portion of each bar represents speed gain when the energy is delivered over one second of time, as compared with 1000 seconds. Speed measurements of the color reversal films are on the basis of exposure required to yield an absolute density of 2.0 in the processed film; for the negative films, exposure to give a density of 0.6 above D_{min}. Overlapping of shaded area in bottom bar indicates film requires somewhat less total energy when delivered over 1000 seconds than for one second. Typical values but not specifications.

Kodak spectroscopic film, type 103a-F, may not be as widely stocked as the others, but let those who really need it note that at 1000 seconds it is even "faster" than at one second! For guidance in obtaining it and for information on Kodak spectroscopic plates, type IIIa, which permit further improvement in low-intensity speed by baking in nitrogen or hydrogen atmosphere (they are now extending the vision of the big optical telescopes to make them in effect very much bigger than when they were built), get in touch with E. J. Hahn, Scientific and Technical Photography, Kodak, Rochester, New York 14650.

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77
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