If a hydrogen atom were Earth-sized, the proton that is its nucleus would fit comfortably in the Rose Bowl, and a quark would be smaller than a softball.

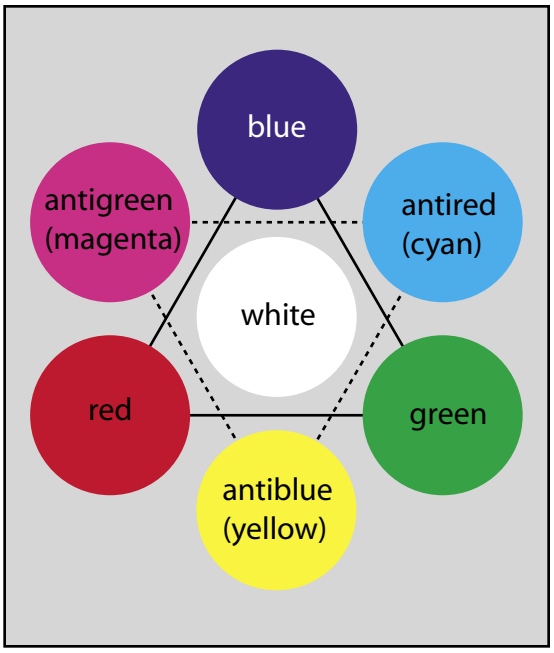
Quark Tale

by Douglas L. Smith

Professor of physics David Politzer is Caltech's newest Nobel laureate.

In our world, forces get stronger as the objects that feel them get closer together. Drop a bowling ball off the Empire State Building, and it accelerates as it falls to Earth. Hold two powerful, opposing magnets at arm's length and slowly bring them towards each other, and at some point they'll leap out of your grip and clang together. This is quite reasonable, logical, and natural. But deep within the atom, the strong nuclear force that holds quarks together to make protons and neutrons behaves just the opposite: it increases as the quarks are pulled apart, as if the proton were wrapped in a stout rubber band. The harder you pull, the harder they snap back. But if the quarks are rubbing up against one another, as it were, the band goes slack. On October 5, H. David Politzer, professor of theoretical physics, shared the Nobel Prize in physics with David Gross at UC Santa Barbara, and Frank Wilczek at MIT, for explaining why this is so—a property known as asymptotic freedom.

To follow the trail leading to this discovery, we need to back up a bit. By 1964 the number of "fundamental" particles being discovered had gotten entirely out of hand. So Caltech's Murray Gell-Mann, and George Zweig of CERN, the European Organization for Nuclear Research, independently proposed that protons, neutrons, and an entire bestiary of other particles collectively known as hadrons were themselves made up of smaller, really truly fundamental particles that Gell-Mann dubbed quarks. (Of course, if superstring theory pans out, it will show that quarks aren't fundamental after all, but superstrings are. Honest, they are.) Gell-Mann postulated that a proton is made up of two up quarks (each with an electric charge of $+\frac{2}{3}$) and one down quark carrying a charge of $-\frac{1}{3}$. These bizarre fractional charges were needed to give the proton its +1 charge and the neutron, which consists of two downs and one up, its zero charge. A third "flavor" of quark was needed for the class of "strange" particles that Gell-Mann had described earlier, so this he of course called the strange quark.



The quark color wheel. A color plus its anticolor make a colorless, or white, entity. One blue, one green, and one red quark also add up to white, as do one of each of the three anticolors.

Since then, as accelerators have reached higher and higher energies, more and more particles have been found. The quark inventory is now up to six, with the addition of the charm, bottom, and top quarks. (The latter two are also sometimes known as beauty and truth.) But that's OK. The way the theory is structured, it can accommodate up to 16 flavors—enough for a respectable ice-cream parlor. Gell-Mann won the physics Nobel in 1969, although not for quark theory.

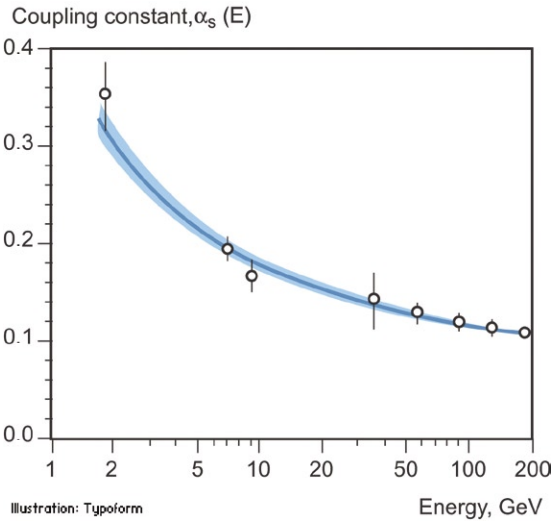
Just as electrons interact by exchanging photons—the carrier of the electromagnetic force—quarks interact by exchanging gluons, the carrier of the strong nuclear force. (Or strong interaction, as they like to call it nowadays.) Constant gluon swapping makes quarks stick together to form protons, neutrons, and whatnot, and even overcomes the mutual repulsion of positively charged protons to bind them with neutrons into atoms. Which gets us to why it's called the strong force. The electromagnetic force that keeps the proton and the electron together in a hydrogen atom is 10^{41} times stronger than gravity at that range. At the boundary of the proton, the strong nuclear force is stronger still—roughly 100 times stronger.

And now things start to get messy. There are only two magnetic poles, north and south, and two forms of electric charge, positive and negative. But the strong force comes in three forms of charge, called colors: blue, green, and red. These aren't real colors visible to the eye, of course, but they do exhibit a similar bit of behavior—one blue, one green, and one red quark add up to be colorless, just as equal parts of blue, green, and red light add up to white light. All observable particles—your protons, neutrons, pions, kaons, and what have you—are color-neutral. And just as all particles, including quarks, have antiparticles, colors have anticolors: antiblue (yellow), antigreen (magenta), and antired (cyan). A bound pair of a color and its anticolor is also color-neutral. To make things really interesting, every gluon carries two units of color charge—a color and a (generally different) anticolor—and when quarks trade gluons, they usually change color as well. By analogy with quantum electrodynamics, which explains electromagnetism on a quantum level, Gell-Mann christened this *Trading Spaces* nightmare quantum chromodynamics, or QCD.

Quantum electrodynamics, or QED, had been independently proposed in the late 1940s by Sin-Itiro Tomonaga of the University of Tokyo, Julian Schwinger of Harvard, and Richard Feynman, who was then at Cornell but left for Caltech almost immediately afterward. The three would share the Nobel for QED in 1965. QED solved a stubborn problem in quantum field theory, which had been invented at the dawn of the quantum age to deal with electromagnetism. Unfortunately, the mathematics that was so spectacularly successful in calculating electromagnetic interactions proved completely useless for the strong force. In a

Below: A few members of the hadron zoo. Hadrons are made up of pairs or triplets of quarks and antiquarks; some are quantum superpositions of quark pairs. Here "u" is the up quark, "d" stands for down, and "s" is for strange. Antiquarks are marked by horizontal bars. The "rest mass," given in millions of electron-volts, is the amount of energy needed to create the particle with zero momentum. The particle's mean life is 1.44 times its half-life.

PARTICLE	QUARKS	CHARGE	REST MASS (MeV)	MEAN LIFETIME (seconds)
proton (p)	uud	+1	938.280	stable
neutron (n)	udd	0	939.573	898
Λ	uds	0	1116	3.8×10^{-9}
π^+	$u\bar{d}$	+1	140	2.6×10^{-8}
π^-	$\bar{u}d$	−1	140	2.6×10^{-8}
π^0	$u\bar{u} - d\bar{d}$	0	135	8.7×10^{-17}
K^+	$u\bar{s}$	+1	494	1.24×10^{-8}
K^0 long	$d\bar{s} - \bar{d}s$	0	498	5×10^{-8}
K^0 short	$d\bar{s} + \bar{d}s$	0	498	8.6×10^{-11}



The coupling constant, or strength with which force-carrying particles interact, depends on the amount of energy they have. The values predicted by QCD are shown in blue, and the actual measured values are shown as open circles, plus or minus the vertical error bars. GeV stands for billion electron-volts. The line slopes downward, which is the hallmark of a negative beta function.

nutshell, QED calculations assumed that the larger the number of particles involved in some event, the less likely it was to happen. The law of diminishing returns sets in pretty rapidly, so you could make the calculation as accurate as you pleased by deciding where to draw the line. This worked for QED because photons have no electric charge, so they don't "feel" other photons. But gluons do have a color charge, so they create new gluons to trade among themselves. As quarks get pulled apart, they barrage one another with gluons in a frantic effort to stick together. Each gluon begets more gluons, and quantum field theory goes straight down the drain.

Efforts to apply a QED-type field theory to the strong force was quickly abandoned, but not everyone gave up on it completely. In May 1964 Gell-Mann wrote, "We [may] construct a mathematical theory of the strongly interacting particles, which may or may not have anything to do with reality, find suitable algebraic relations. . . and then throw away the model. We may compare this process to a method sometimes employed in French cuisine: a piece of pheasant meat is cooked between two slices of veal, which are then discarded." However, since experimentalists were unable to observe free quarks directly, there was very little evidence that they were anything more than a handy bookkeeping device.

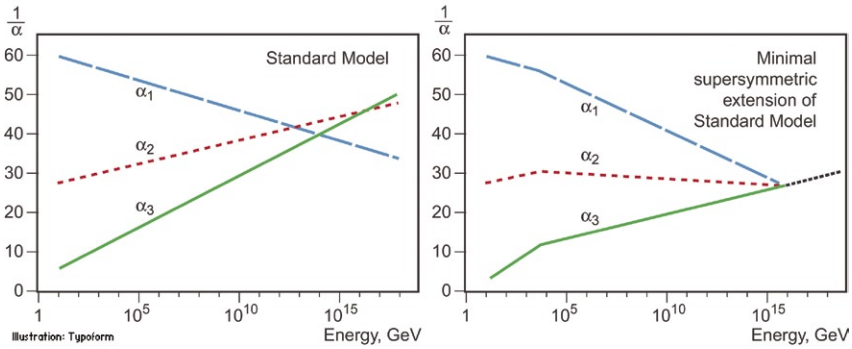
That is, until 1969, when researchers at the Stanford Linear Accelerator who were hurling electrons into protons at a significant fraction of the speed of light got some very odd results. This behavior could best be explained by Feynman's suggestion that, at the very high energies equivalent to very short distances, the proton acted as if it were made up of freely moving, point-like particles—although Feynman, being Feynman, called them "partons" instead of quarks. (If a hydrogen atom were Earth-sized, the proton that is its nucleus would fit comfortably in the Rose Bowl, and a quark would be smaller than a softball.) In other words, you could liberate quarks by squeezing them together. Freedom in confinement is a very Zen notion, whose mathematical equivalent is something called a negative beta function. In a negative beta function the coupling constant, or the strength with which objects interact, increases with distance—or decreases with energy, as it takes more and more energy to force particles closer and closer. When you get close enough, the coupling constant essentially vanishes. Alas, several people had already "proved" that a negative beta function was physically impossible.

In the spring of 1973, David Politzer, then a graduate student of Sidney Coleman at Harvard, was attempting to caculate the beta function for something called Yang-Mills theory, a forbidding and little-explored realm at the time. Coleman, meanwhile, was visiting Princeton for the semester, where Politzer's co-winners, David Gross and his graduate student, Frank Wilczek, were working on the same calculation. The approaches were different, but the results, compared via Coleman, were the same, and back-to-back papers describing what is now called asymptotic freedom appeared in the June 25 issue of *Physical Review Letters*—in Politzer's case, his first-ever publication. An asymptote is a mathematical term for a line bounding a curve that the curve approaches but never quite meets.

The mathematical picture led to a physical one. Explains John Preskill, the MacArthur Professor of Theoretical Physics, "The crucial difference between the two theories is that while the photons of QED carry no charge of their own, the gluons of QCD are themselves colored particles. A quark is surrounded by a sea of 'virtual' gluons that arise due to quantum fluctuations, and the color of the virtual gluons enhances the quark's own color. A probe coming closer and closer to the quark is influenced less and less by the virtual gluons, so that the effective color charge of the quark seems to weaken; this is asymptotic freedom."

And because the coupling constant increases as you separate the quarks, it soon becomes insurmountable. The rubber band snaps, but instead of spilling forth the quarks it restrained, two new rubber bands form, each binding up a new particle. The fresh quarks needed to round out the new doublets or triplets are conjured out of the energy imparted to them—$E=mc^2$ and all that.

Armed with the proper beta function, the interactions resulting from the strong nuclear force suddenly became calculable in full detail. As Gross wrote in *Twenty-Five Years of Asymptotic Freedom* in 1998, "During a very short period, a transition occurred from experimental discovery and theoretical confusion to theoretical triumph and experimental confirmation." Perhaps the most spectacular confirmation came from the DESY (Deutsche Elektronen-SYnchrotron) particle accelerator in Hamburg, Germany, in the late 1970s. Experimenters studying the annihilation of the electron by its antiparticle, the positron, found that this



If you use the Standard Model (right) to plot the energy dependence of the coupling constants of the strong nuclear force (green), the weak nuclear force (red) and the electromagnetic force (blue), the three lines cross but do not meet at a common point. But supersymmetry (far right) bends the lines, causing them to meet at a point where all three forces have equal strength. At that point, the forces become unified, and one equation will describe all three.

sometimes created a quark, an antiquark, and a gluon, each of which became the source of a shower of stuff that could be traced backward to identify the three original particles. QCD now stands with QED as two of the three pillars of the so-called Standard Model of physics that also describes the weak nuclear force, which is responsible for some forms of radioactivity and is carried by the W and Z particles.

What are the implications? Well, as Mark Wise, the McCone Professor of High Energy Physics and a collaborator of Politzer's, said at Caltech's press conference about the Nobel—which Politzer did not attend—"I don't think that we're going to have a QCD car in the near future, despite the high price of oil." However, the mathematics of QCD and QED are quite similar, and QED and the weak nuclear force have been unified into an "electroweak" theory that has itself produced a clutch of Nobels. So theorists have been floating schemes to unify the strong and electroweak forces—into the "streak" force, presumably—as the last stop en route to the hypothesized Grand Unified Theory, which would incorporate a quantum treatment of gravity as well. These petit unified theories note that if you plot the dependence of each component theory's coupling constant versus energy, all three lines almost cross at one point—in an energy range just out of reach of today's accelerators. And if you invoke something called "supersymmetry," which we won't go into, you can bend the lines until they meet. At the point where the lines cross, the three forces have equal strength, and this equivalence means very interesting things should occur. A whole spate of brand-new particles should appear, and their characteristics will tell the theorists which, if any, of their unified models is correct. The Large Hadron Collider, currently under construction at CERN, is designed to reach these energies. It is slated to begin operating in 2007.

And, as Gross said at *his* press conference at UC Santa Barbara, "Another application of these ideas is tracing the history of the universe back to the Big Bang. . . . We know from observation that the universe is expanding, so early on it was very dense and hot. And without a theory like QCD, we wouldn't be able to say anything about how matter behaves under those circumstances. . . . With asymptotic freedom, with QCD, we can say what happened. In fact, what happens is remarkable. Protons—these bags of quarks which are held together by this strong force—dissolve, and the quarks and gluons get liberated and form a kind of plasma in the earliest moments of the universe."

As Caltech president and fellow Nobel laureate David Baltimore said at the press conference, Politzer "has now been recognized as one of the seminal figures in the history of physics by this prize." Added Wise, "He did a very difficult calculation—at the time it was very difficult; now graduate students can do it. In fact, I'll assign it to my students this year. . . . The smart money was on this [prize]. You could have looked at the Nobel futures market."

Politzer himself, meanwhile, continues to enjoy his prerogative to decline interview requests. □