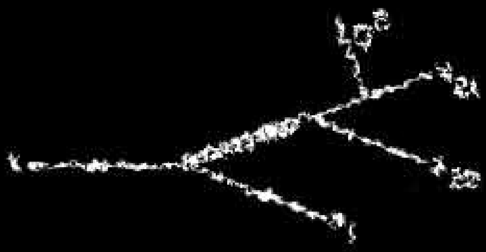
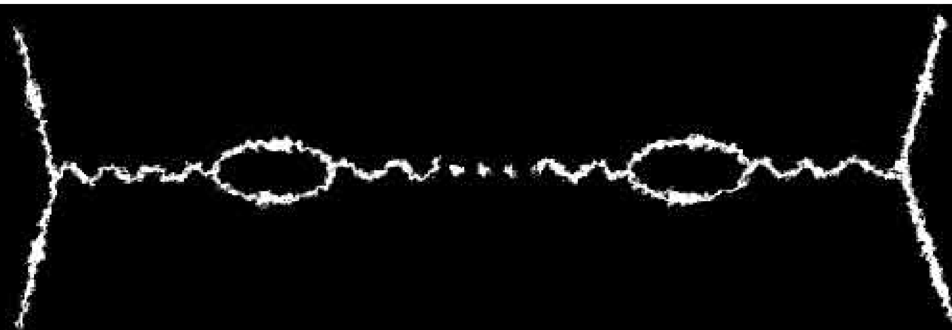
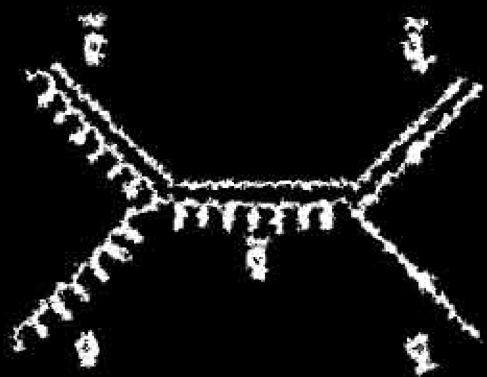
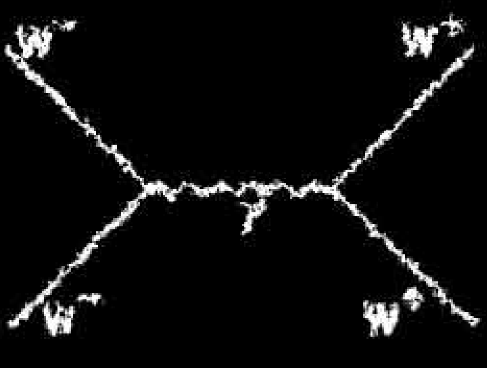


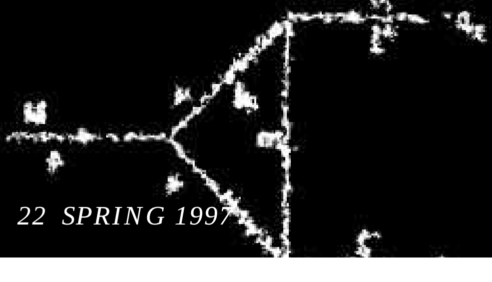


Elementary Particles: Yesterday, Today, and Tomorrow

by CHRIS QUIGG



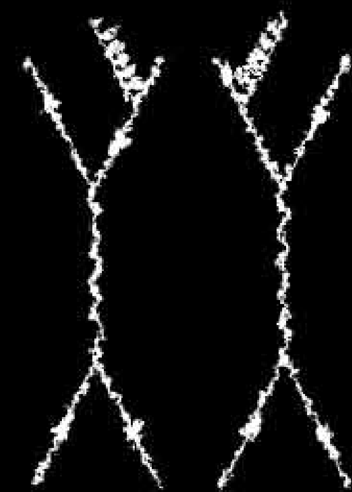




WITHIN THE LIFETIME of my grandparents, there lived distinguished scientists who did not believe in atoms. Within the lifetime of my children, there lived distinguished scientists who did not believe in quarks. Although we can trace the notion of fundamental constituents of matter—minimal parts—to the ancients, the experimental reality of the atom is a profoundly modern achievement. The experimental reality of the quark is more modern still.

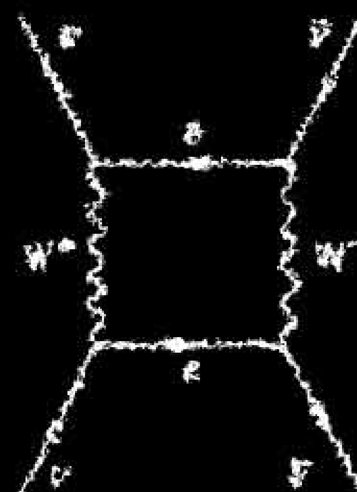
Through the end of the nineteenth century, controversy seethed over whether atoms were real material bodies or merely convenient computational fictions. The law of multiple proportions, the indivisibility of the elements, and the kinetic theory of gases supported the notion of real atoms, but it was possible to resist because no one had ever seen an atom. One of the founders of physical chemistry, Wilhelm Ostwald, wrote influential chemistry textbooks that made no use of atoms. The physicist, philosopher, and psychologist Ernst Mach likened "artificial and hypothetical atoms and molecules" to algebraic symbols, tokens devoid of physical reality that could be manipulated to answer questions about nature.

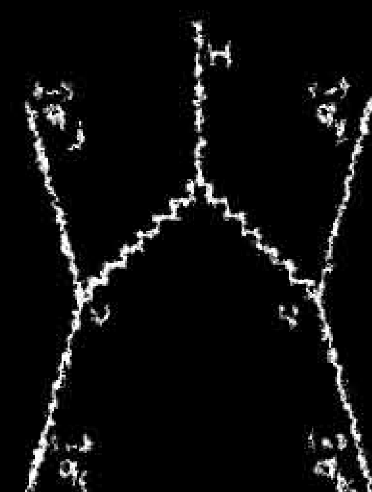
Atoms became irresistibly real when they began to come apart, with the discovery of the electron that we celebrate in



this special anniversary issue. In the end the atomists won not because they could see atoms—atoms are far too small to see—but because they learned to determine the size and weight of a single atom. In 1908 Jean-Baptiste Perrin established that the erratic "Brownian" movement of microscopic particles suspended in liquid was caused by collisions with molecules of the surrounding medium. This demonstration of the mechanical effects of tiny atoms and molecules effectively ended skepticism about their physical reality. Ostwald announced his conversion in 1909, the year he won the Nobel Prize. Mach went to his grave in 1916, still fighting a futile rear-guard action.

It is tempting to date the vanishing of resistance to the quark model to the discovery of the J/ψ particle in November 1974, but a look at the theoretical papers in the famous January 6, 1975, issue of *Physical Review Letters* will remind us that the epiphany wasn't quite universal. The observation of the ψ',





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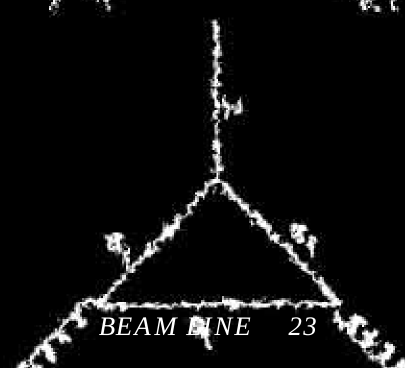

Proceedings of the XIIIth International Conference on High-Energy Physics, Berkeley, California
August 31–September 7, 1966

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a second new particle that was obviously related to the J/ψ, made the notion of quarks as mechanical objects irresistible to all but an obdurate few. The holdouts were either converted or consigned to a just irrelevance by the discovery of charm eighteen months later.

MEETING THE QUARK

My first contact with quarks came during the summer of 1966, as I was about to begin graduate school in Berkeley. Before I had set foot in a classroom, the Thirteenth International Conference on High Energy Physics took place on campus, a gathering of about four hundred scientists from around the world. Though attendance was by invitation, with strict national quotas, I could present myself at the front door of Wheeler Auditorium in the morning and obtain a day pass that allowed me to sit inconspicuously in the back of the room and watch the proceedings. Except for what I had learned that summer working through two little books by Richard Feynman, I knew nothing of the interactions between particles, or even what the particles were like. So there I was, *tabula rasa* among the experts.

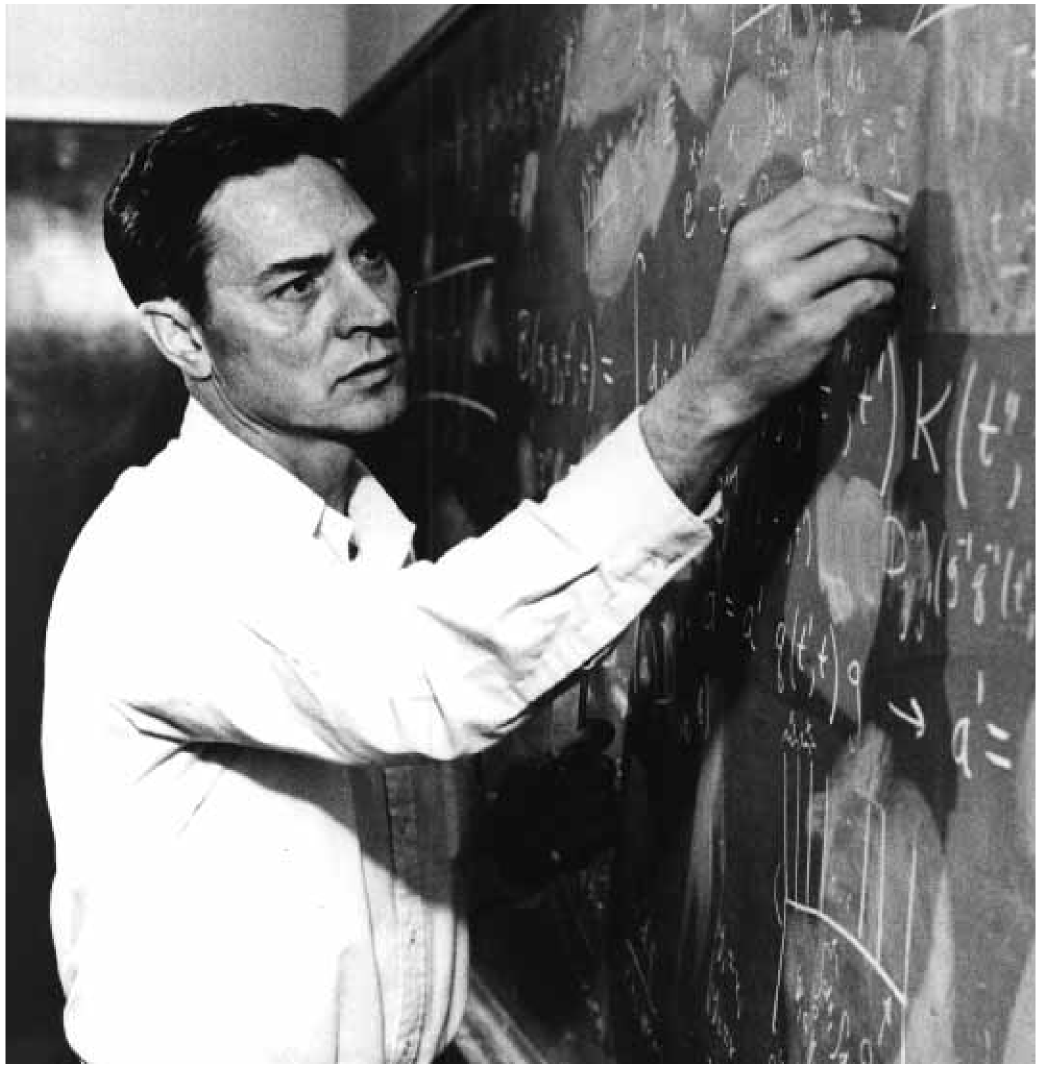
I could understand a little of the opening address by Murray Gell-Mann and a talk on symmetries by Richard Dalitz of Oxford. Both of them talked—rather cautiously, it seemed—about hypothetical objects called quarks as fundamental constituents of the proton and neutron and all the other strongly interacting particles. Although the idea that three quarks made up a proton while a quark and antiquark made up a meson brought order to a lot of information, it was clear that nobody had any idea how this could happen and whether there could be a self-consistent theory. And besides, no one had seen a quark.

Courtesy G.C. Wick and AIP Emilio Segrè Archives

Richard Dalitz in 1961.

Just as the Greek atomists had their opponent in Anaxagoras, who advocated an infinite progression of

Opposite: Physicists attending the 1966 International Conference on High Energy Physics at Berkeley, California. (Courtesy Lawrence Berkeley National Laboratory)



Right: Geoffrey Chew in the 1960s. (Courtesy Lawrence Berkeley National Laboratory and AIP Emilio Segrè Visual Archives)

seeds within seeds—and no minimal parts—the quark advocates had to face the challenge of "nuclear democracy." Berkeley, it turned out, was the hotbed of an opposing point of view: that there were no fundamental constituents, that all the composite "elementary" particles were somehow made out of each other in an intricate interplay called the bootstrap. Gell-Mann deflected this challenge by repeatedly stressing that quarks didn't have to be real to be useful and that if the mesons and baryons were made up of "mathematical quarks," then the quark model might perfectly well be compatible with the bootstrap hypothesis.

Courtesy C. Quigg

The author in 1970, as a fresh Ph.D. and research associate in the Institute for Theoretical Physics at the State University of New York, Stony Brook.

There was also the question of how to deal with interactions, with theorists divided into sects promoting "*S*-matrix theory," or "field theory," or "Lagrangian field theory," or "abstract field theory." Gell-Mann urged the partisans to stop wasting their breath on sectarian quarrels and to pool their energies to campaign for a higher-energy accelerator that would enable us to really learn more about the basic structure of matter. That accelerator sweeps across the prairie outside my office window.

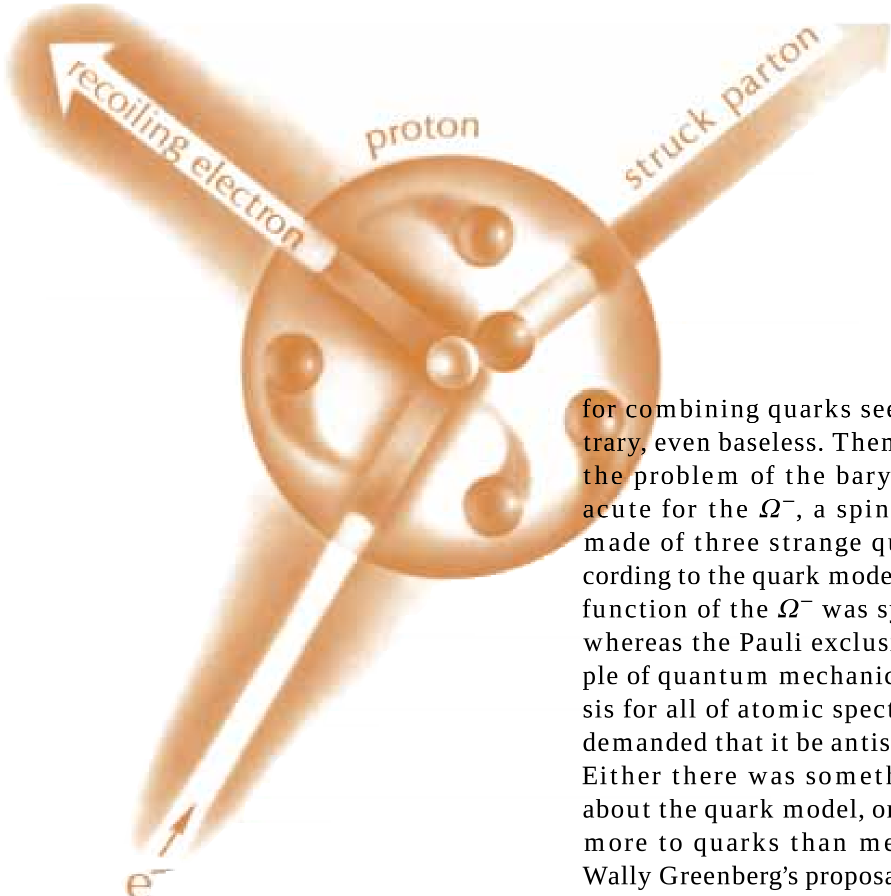
QUARKS IN BERKELEY?

Berkeley was indeed the Mother Church of the *S*-matrix bootstrap denomination. I don't think quarks were ever mentioned in Geoff Chew's course on the dynamics of strong interactions. Even in Dave Jackson's more catholic version of the course, quarks appeared only once, on a list of term-paper topics at the end of the year. But that was only part of the story. Learning about other approaches to particles and interactions was not only encouraged, it was obligatory. Berkeley graduate students were expected to follow two year-long courses in field theory. The Rad Lab was a center of hadron spectroscopy where the quark model was discussed as a classification tool. In the spring of 1968, George Zweig flew up from Caltech every Friday to teach a graduate seminar on the quark model. George was one of the inventors of quarks. He also knew everything about resonance spectra and decays, and he gleefully showed us how much a simple quark model could explain.

Courtesy G. Zweig

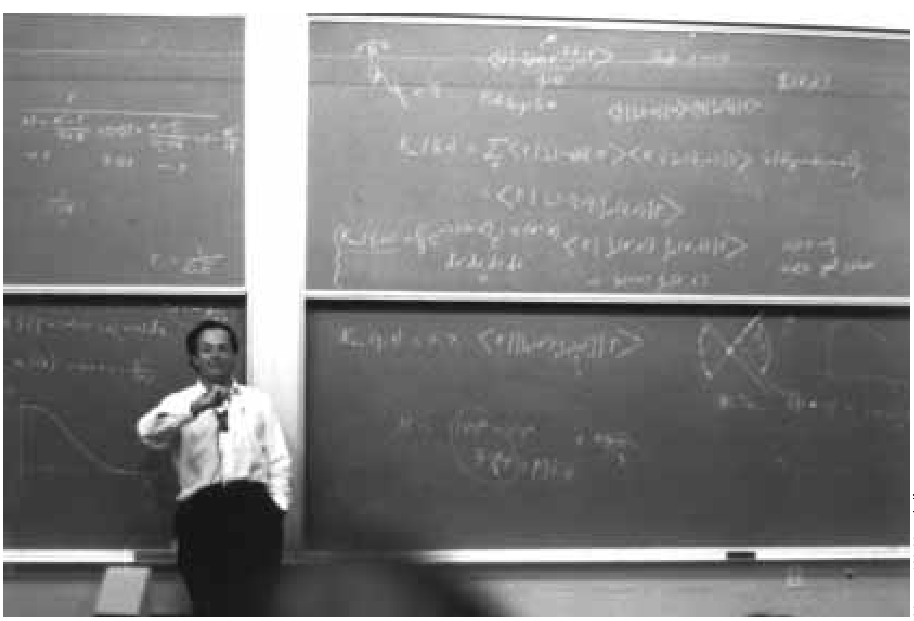
George Zweig in 1965.

What the quark model couldn't explain was itself: "How could this be true?" was the question everyone had to ask. Until the interactions of quarks could be understood, the rules



for combining quarks seemed arbitrary, even baseless. Then there was the problem of the baryons, most acute for the Ω^-, a spin-$\frac{3}{2}$ particle made of three strange quarks. According to the quark model, the wave function of the Ω^- was symmetric, whereas the Pauli exclusion principle of quantum mechanics—the basis for all of atomic spectroscopy—demanded that it be antisymmetric. Either there was something dicey about the quark model, or there was more to quarks than met the eye. Wally Greenberg's proposal that each quark flavor (up, down, and strange) came in three distinguishable "colors," and that antisymmetry in color brought the quark model into conformance with the exclusion principle, seemed to many like invoking the tooth fairy. But in one of those delicious ironies that make research so interesting, when we learned to measure the number of colors of each quark species, it really was three. And color would turn out to be the key to explaining how the quark model could be true.

Richard Feynman lecturing on his parton model at SLAC in October 1968.



Henry W. Kendall

The other evidence that drew attention to quarks arose from the MIT-SLAC experiments in which Jerry Friedman, Henry Kendall, Dick Taylor, and their colleagues studied the structure of the proton. To the prepared mind, the high rate of inelastic collisions they observed showed that there were within the proton tiny charged bodies. No mind was more prepared to take the leap than Feynman's. Feynman presented his interpretation at a SLAC colloquium that occasioned my first pilgrimage across the Bay. The colloquium was then held in the evening after what has been described to me as a vintner's dinner. Whatever the reason, I remember both speaker and audience as extremely exuberant. If an electron scattered from one of the hypothetical tiny charged bodies, not the whole proton, it was easy to understand why the inelastic cross section was so large. Instead of measuring the delicacy of the proton, the MIT and SLAC experimenters were measuring the hardness of the little bits. Feynman wasn't prepared to say what the tiny charged parts of the proton were, so he called them "partons." Everyone in the room must have thought, "Quarks?"

Before long, Bj Bjorken and Manny Paschos had worked out the consequences of the quark-parton model for electron scattering and neutrino scattering. The success of their predictions added to a gathering crisis. If the quark-partons acted as if they were free, independent objects when examined by energetic electrons, why didn't the quarks come out and show themselves? Gell-Mann derided Feynman's picture as the "put-on" model. Many theorists of my generation found great sport in showing that Bjorken's scaling law, which was implied by the parton model, wasn't possible in this or that interacting field theory. Like the quark model of the hadron resonances, the parton model could explain many things, but it couldn't explain itself.

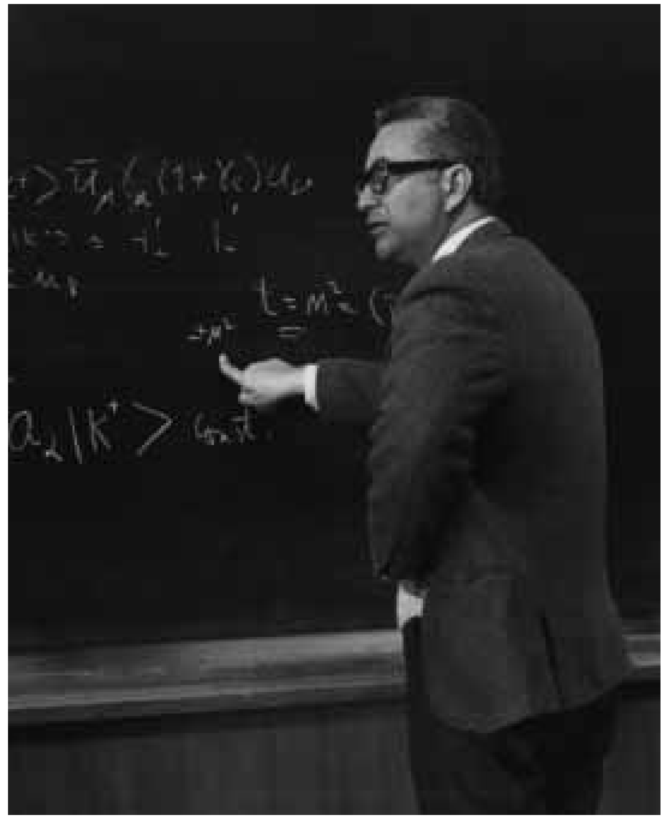
DYNAMICS, DYNAMICS, DYNAMICS!

Some of the reasons why it took so long for the idea of quarks to be accepted have to do with the human frailties of obtuseness, or obstinacy, or preoccupation with other matters. But others, the reasons of real importance, reflect the standards of scientific evidence. The repeated failure to find any free quarks sustained the idea that quarks were computational fictions. The main sticking-point was the absence of any understanding of how quarks behave as free and independent objects in hard collisions, and yet form composites in which they are permanently confined. Without an understanding of dynamics, quarks were a story, not a theory.

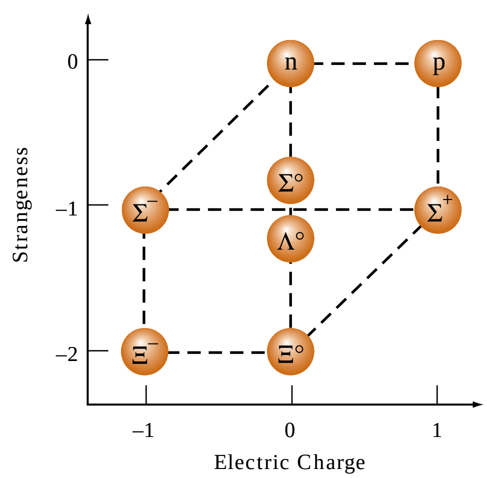
The great illumination came in 1973, when David Gross and Frank Wilczek in Princeton and David Politzer at Harvard found that, alone among field theories, non-Abelian gauge theories could reconcile the permanent confinement of quarks with the relative independence the parton model presumes. In these theories the interaction between two quarks diminishes when they are close together, but becomes an ineluctable pull when the quarks move apart. This "asymptotic freedom" of the strong interaction is just what was needed to understand the MIT-SLAC results—not just in a useful cartoon, but in a real theory.

In what seemed like the blink of an eye, a new theory of the strong interactions was codified. Gell-Mann named it quantum chromodynamics (QCD) to celebrate the central role of color as the strong-interaction charge and perhaps to express the hope that it would become as fertile and robust as quantum electrodynamics, the phenomenally successful theory of electrons and photons. Soon precise predictions emerged for the subtle deviations from Bjorken scaling that QCD predicted.

Even before the scaling violations implied by QCD were established through painstaking experimental effort, asymptotically free gauge theories gave us license to take the quark model and the parton picture seriously. All at once, what we had gingerly called "as-if" models took on new meaning. Now, the J/ψ was such a thunderbolt that it needed no theoretical stage-dressing to help it set the community of particle physicists on its ear. Yet it was the insight of asymptotic freedom that prepared us to read the clues charmonium offered, and change forever the way we think about the structure of matter.



Murray Gell-Mann in 1972. (Courtesy CERN)



The first single-electron event from Gargamelle. The electron's trajectory goes from left to right, beginning at the arrow's tip. The haloed black circles are lights to illuminate the bubble-chamber liquid. (Courtesy CERN)

QUARKS, LEPTONS, GAUGE FIELDS

Today's elementary particles, the leptons (ν_e, e), (ν_μ, μ), (ν_τ, τ), and the quarks (u,d), (c,s), (t,b), form one of the pillars of our understanding of matter and energy. To the limits of our resolution, they are all spin-$\frac{1}{2}$ particles with no internal structure. The quarks are color triplets that experience the strong interactions. The leptons, which have no color charge, do not.

The top quark has so far been seen in such small numbers that we haven't yet examined it as closely as the others. If top is as ephemeral as we think, with a lifetime less than a trillionth of a trillionth of a second, it is the purest quark—the only one that does not form mesons or baryons. We know a great deal about the tau neutrino from the study of τ and Z decays, but it would still be satisfying to execute a "three-neutrino experiment," in which a beam of tau neutrinos interacts with a target to produce tau leptons that live for a millimeter or two before they decay. The DONUT (Direct Observation of NU-Tau) experiment being commissioned at Fermilab should observe about 150 examples of the $\nu_\tau \to \tau$ transition.

The other essential foundation for our current understanding is the notion that symmetries—gauge symmetries—determine the character of the fundamental interactions. Like QCD, the electroweak theory fashioned by Sheldon Glashow, Steven Weinberg, and Abdus Salam is a non-Abelian gauge theory. The electroweak theory got its own boost in the summer of 1973 when André Lagarrigue and his colleagues in the Gargamelle bubble-chamber experiment at CERN announced the first observation of weak neutral-current interactions. Although it would take the discovery of the weak-force particles W and Z and many years of study, culminating in the contributions of the Z factories at CERN and SLAC, to show how successful a creation the electroweak theory is, it was clear very soon that the gauge-field-theory approach to the interactions of quarks and leptons was the right path.

The electroweak theory supplies a clue of profound significance: our world must have both quarks and leptons. Unless each pair of leptons (like the electron and its neutrino) is accompanied by a pair of quarks (like up and down), quantum corrections will clash with the symmetries from which the electroweak theory is derived, leaving it inconsistent. I take this constraint as powerful encouragement for a family relationship joining quarks and leptons, and for a unified theory of the strong, weak, and electromagnetic interactions.

Have we found all the quarks and leptons? We do not really know. Precision measurements of the width of the Z resonance assure us that there are no more normal generations with very light neutrinos. But there could well be new families of quarks and leptons in which all the members are too massive to be produced in Z decays. We don't know yet whether the neutrinos have any mass. If they do, we need to learn whether each neutrino is its own antiparticle.

Even if we have already met all the quarks and leptons, we have good reason to be open to the possibility of new kinds of matter. The astrophysical case for dark matter in the galaxy is persuasive, and the evidence that most of the matter in the Universe is both nonluminous and unlike the stuff we know is highly suggestive. Supersymmetry, which is for the moment the most popular candidate to extend the electroweak theory, implies a greatly expanded list of elementary particles, including spin-zero partners of the quarks and leptons.

If we take as our goal not merely describing the world as we find it, but understanding why the Universe is the way it is, the array of elementary particles presents us with many challenges. What makes a top quark a top quark, or an electron an electron? Can we calculate the masses of the quarks and leptons and the relative strengths of the weak transitions between quark flavors? Why are there three generations?

ANOTHER LAYER OF STRUCTURE?

No experimental evidence except the history of molecules and atoms and protons suggests that quarks and leptons are composite. However, there is an undeniable aesthetic allure to the notion that a complex world may arise out of the combinatoria of a few simple parts. If today's elementary particles are composite, we might be able to compute their masses, understand the trebling of generations, and decipher the relationship of quarks to leptons.

Some specific currents in theoretical research also lead toward composite quarks and leptons. In dynamical theories of electroweak symmetry breaking such as technicolor,

> *The idea that elementary constituents of matter interact according to the dictates of gauge symmetries has become the organizing principle of particle physics, as important to our field as evolution is to biology.*

the longitudinal components of the weak gauge bosons are composite. Why not the quarks and leptons, too? And a new approach to supersymmetric model-building, in which strong gauge interactions break the supersymmetry, suggests that some of the quarks may be composite.

Composite models of quarks and leptons must differ in a crucial way from familiar dynamical pictures. In QCD the pions are the lightest—nearly massless—particles, while the proton mass is set by the scale of binding energy. A theory of quark and lepton compositeness must deliver fermions much lighter than the (several TeV, at least) binding energy of the constituents. Without a specific composite model, we have no theoretical clue for the scale on which we might resolve structure in our elementary particles. Nevertheless, we can characterize the experimental signatures that composite quarks and leptons would leave.

At energies approaching such a compositeness scale, quarks and leptons that have size will interact at such short distances that they interpenetrate and rearrange, or even exchange, their constituents. In quark-quark scattering, the conventional gluon exchange of QCD would be supplemented by a contact interaction whose strength is determined by the size of the quarks. In $\bar{p}p$ collisions, this new contribution would lead to an excess of hadron jets at large values of the transverse energy, where quark-antiquark scattering is the dominant reaction. Typically, the angular distribution of the jets will differ from the shape QCD predicts. If quarks and leptons have common constituents, a similar excess will be seen in dilepton production from the elementary process $\bar{q}q \to \ell^+\ell^-$. At still higher energies, we would expect to see the effects of excited quarks and leptons. Finally, at energies well above this compositeness scale, quarks and leptons would begin to manifest form factors characteristic of their size.

Since I first met the quark, charm, beauty, top, and the rest have become my friends and teachers—in fact, they have taken over my life. The idea that elementary constituents of matter interact according to the dictates of gauge symmetries has become the organizing principle of particle physics, as important to our field as evolution is to biology. I don't know how far the revolution of quarks and leptons and gauge bosons will carry us, but I have a wish for the decade ahead: that we will learn the true nature of electroweak symmetry breaking and begin to understand the individuality of the quarks and leptons. And I hope we will look back with pleasure and satisfaction at how passionate and optimistic—and naïve—we were in 1997.