



The Eightfold Way, by Helaman Ferguson, is a tetrahedral sculpture at the Mathematical Sciences Research Institute in Berkeley, California. Murray Gell-Mann applied the term eightfold way to the organization of subatomic hadrons. (Photo by Ivars Peterson.)

Constructing the theory of the standard model

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It took decades to discover the quarks, leptons, and gauge and scalar bosons that make up our current picture of particle physics.

We begin with quantum electrodynamics (QED), which successfully combines classical electrodynamics, quantum mechanics, and special relativity. QED inherits the gauge-transformation symmetry—called $U(1)$ in group-theoretical language—that classical electromagnetism possesses. QED is also renormalizable; that is, it is well defined mathematically: Infinities that appear at intermediate stages disappear when the theory is expressed in terms of a finite number of measured quantities, such as mass and charge.

The first theory of weak interactions was Enrico Fermi's postulate in 1933 that nuclear decay arises from the coupling of the neutron to the proton, electron, and neutrino at a single point in space and time. The Fermi theory successfully described weak interactions at low energies, but it couldn't be fundamental; unlike QED, the Fermi theory is not renormalizable. Some, but not all, of the infinities are removed by replacing the coupling at a point with the exchange of heavy, electrically charged W^+ and W^- bosons.

That inability to remove all infinities in the calculations was one problem with the theory. Another was the strong suppression of certain processes that did not conserve "strangeness."

Asymptotic freedom

Unlike electrons, neutrinos, and other leptons, hadrons are particles that interact via the strong nuclear force. The structure of the hadron spectrum suggested that the interaction was invariant under an eight-dimensional generalization of the rotation group called $SU(3)$. The structure also led to the proposal in 1964 that hadrons are each composed of three fractionally charged, spin- $\frac{1}{2}$ quarks. The up and down quarks make up the nucleons and other nonstrange matter, whereas the strange quark is among the constituents of strange hadrons.

You might think that the Δ^{++} , a hadron with charge +2, would be made of three up quarks, and experiment

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REVIEWS OF
MODERN
PHYSICS

90
YEARS

shows that indeed it is. But each quark has spin $\frac{1}{2}$, so how can three coexist in the ground state? Fermi statistics, which prevents the three constituents of a nucleon from occupying a totally symmetric state, necessitated the introduction of a new quantum number called color. Each quark of a given “flavor”—the species of an elementary particle—had to come in one of three “colors”: red, green, or blue. (See the article by O. W. “Wally” Greenberg, *PHYSICS TODAY*, January 2015, page 33.)

The color, electric charge, and spin of the quarks were confirmed in lepton–nucleon scattering and electron–positron annihilation experiments. Meanwhile, low-energy pion physics established that strong interactions are mediated by vector bosons. The experiments revealed that strong interactions grow weaker with increasing energy; they are said to be asymptotically free. And yet at low energies, interactions become very strong and confine the quarks inside hadrons. (See *PHYSICS TODAY*, December 2004, page 21.)

In 1954 Chen Ning Yang and Robert Mills extended $SU(2)$ isospin symmetry, which interchanges protons and neutrons, to a local form analogous to the $U(1)$ of QED. The extension implied the existence of three self-interacting vector bosons, which perhaps could partially mediate the strong interactions. That idea never worked out because there was no satisfactory way to generate vector boson masses, but the mathematics of gauge invariance was later reapplied and became the basis of our understanding of the weak and strong interactions.

Spontaneous symmetry breaking

In particle physics, spontaneous symmetry breaking refers to the symmetry loss in solutions to the equations of motion in a system’s lowest energy state. However, hopes that such symmetry breaking could lead to new realizations of strong-interaction symmetries were largely eliminated by the Nambu–Goldstone (NG) theorem: Spontaneous symmetry breaking would lead to the existence of massless, spin-0 NG bosons.

Of course, no massless, spin-0 particles exist. In the 1960s several physicists realized that there is a loophole to the theorem; the twin problems of unwanted NG bosons and the nominal masslessness of the Yang–Mills gauge bosons would “cure” each other. The NG bosons become modes of the now-massive gauge particles. (See *PHYSICS TODAY*, December 2008, page 16.) Simple versions of that Brout–Englert–Higgs (BEH) mechanism also implied the existence of a massive, spin-0 Higgs boson. (See *PHYSICS TODAY*, December 2013, page 10.) But little attention was initially given to such ideas, because researchers were thinking in terms of strong interactions, where the BEH mechanism did not appear to be relevant.

The ultimately successful application of Yang and Mills’s work to the electroweak interactions combines the $U(1)$ symmetry of QED with a local weak interaction version of an $SU(2)$

symmetry. When the combined symmetry is broken by the BEH mechanism, the force-carrying vector bosons are manifest as a massless photon and the massive W^+ , W^- , and Z particles.

The problem of an overlarge prediction for strangeness-violating processes still remained. That conundrum was resolved by postulating a fourth quark, called charm, whose interactions would provide the destructive interference needed to cancel out strangeness-changing interactions.

Concurrent with the experimental confirmation of charmed hadrons¹ was the discovery of a new charged lepton, called τ . It led to the prediction of new quarks called bottom b and top t . The new generation of quarks and leptons introduced just enough extra complexity into the weak interactions to allow for violation of CP (combined charge conjugation and parity) symmetry in the weak interactions.

A major breakthrough was the proof that Yang–Mills theories, like QED, are renormalizable, a property that holds even when the gauge symmetry is spontaneously broken. The proof put the electroweak theory,² with charm included, on firm footing.

Quantum chromodynamics was developed³ in the early 1970s, soon after the electroweak theory. The interactions between quarks are mediated by eight spin-1 gluons, the analogues of the photon and W and Z particles of the electroweak theory. Whereas the photon does not have an electric charge, the gluons carry color charges and interact with each other, which leads to asymptotic freedom and color confinement.

The original standard model assumed that the neutrinos are massless. But later observations of neutrino oscillations and flavor conversions implied the existence of tiny but nonzero masses.⁴

The standard model is undoubtedly correct to an excellent approximation,⁵ but it leaves many questions unanswered. Those include the origin of neutrino masses, the values of the fermion masses, and the explanation for apparent fine-tunings, such as the extremely small ratio of the weak-interaction and gravity energy scales. Similarly, the standard model does not include a quantum theory of gravity or explanations for the excess of matter over antimatter and for the nature of the dark matter and energy in the universe. Promising ideas have been proposed to account for all those shortcomings, but clearly much remains to be discovered.

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