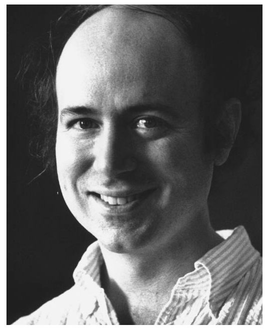
Mass without Mass II: The Medium is the Mass-age

Frank Wilczek



In the November issue (page 11), I discussed how most of the mass of ordinary matter arises from the energy associated with quark motion and color gluon fields. That mass can be computed with good accuracy using the theory I call QCD Lite—a simplified form of quantum chromodynamics (QCD), in which the masses of the up and down quarks are set to zero, and the other quarks are omitted. In QCD Lite, protons and neutrons are assembled entirely from massless building-blocks. For the bulk of ordinary matter, we thereby realize John Wheeler's goal of deducing mass as a secondary property, without having to introduce mass as a primary property. In Wheeler's phrase, we've achieved "mass without mass."

The elimination of mass as a primary property of matter is a delightful and important approximate consequence of QCD. However, in QCD this feature is a luxury, not a necessity. If the up and down quarks had larger masses, QCD Lite would be a poor approximation, and the masses of protons and neutrons would arise mostly from the masses of the quarks that made them, but QCD itself would remain a perfectly consistent theory. Indeed, many of its central results—for example, its predictions for the probabilities of jet production in high-energy collisions—would not be significantly different.

By contrast, in the other part of the Standard Model of particle physics, the electroweak sector, mass without mass is indispensable. The modern theory of electroweak interactions couldn't work without it. For the core principle of this theory is chiral gauge symmetry, and chiral gauge symmetry abhors mass. This tight knot of jargon entangles some profound and far-reaching ideas, which I'll now try to untangle.

First, *chiral*. As used in this context, it refers to an intrinsic distinction between right and left. In 1956-57, the physics world was rocked by the discovery that the weak interaction makes such a distinction. All previous experience in atomic and nuclear physics was consistent with fundamental symmetry between left and right. Theorists had elevated this observation into a principle: parity. The weak interactions flout parity. The electrons emitted in beta decay, for example, are almost always left-handed: if you point your left thumb in the direction of such an electron's motion, usually you'll find that it's spinning in the same direction as your fingers curl. The same is true for electrons, or for muons, emitted in other weak decays, whereas positrons and antimuons are almost always right-handed. Detailed study revealed that the weak interactions violate parity between left and right systematically, and in a very big way. Theorists attempted to make the best of this situation by proposing a new principle: maximal parity noninvariance (for the weak interaction only).

The ideal, straightforward statement of maximal parity noninvariance would be single-handedness, or chirality. The statement would read: Only left-handed particles and only right-handed antiparticles participate in the weak interaction. This formulation, however, is inconsistent with the principle of relativity. Indeed, what appears as a left-handed electron to a stationary observer will look right-handed to an observer moving in the electron's direction, but faster—the direction of motion appears reversed, but the direction of spin remains the same. If electrons were massless, this inconsistency would not arise, for then they would move at the speed of light, and no observer could overtake them. The nonzero mass of electrons, and other particles, greatly complicates the task of converting maximal parity noninvariance from a rough rule of thumb into a precise principle. Chirality's natural habitat is a massless world.

Second, *gauge symmetry*. Gauge symmetry was first discovered as a property of quantum electrodynamics (QED). We learn in freshman physics that electromagnetic waves are purely transverse: that the fields in such waves are excited only in directions perpendicular to the direction of wave propagation. When we come to quantize the electromagnetic field, it turns out to be quite difficult to ensure this behavior. Quantum fluctuations will explore all possible field configurations, including longitudinal waves. To correctly reproduce freshman physics, one must make sure that these longitudinal waves do not represent any physical effect. So adding or subtracting longitudinal waves must leave the equations of QED unchanged. This property implies a very large symmetry, which is what we call gauge symmetry.

Subtle but persuasive theoretical arguments make it appear that gauge symmetry is a necessary property of consistent quantum field theories containing vector (spin-1) particles. This is required because the longitudinal waves have very unpleasant properties (negative probabilities!), and must be avoided. Consistent with this idea, not only QED but also QCD (which is mediated by vector particles, the color gluons) is based on equations with gauge symmetry. Gauge symmetry requires that the vector particles be massless. The reason is similar to that given above in connection with chirality. If an observer could catch up with an electromagnetic wave so that it appeared stationary, there would be no distinction between longitudinal

Frank Wilczek *is the J. Robert Oppenheimer Professor in the School of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey.*

and transverse excitations. To prevent this ambiguity, electromagnetic waves had better move at the limiting velocity—not coincidentally, the speed of light!

The weak interaction is mediated by vector particles, the W and Z bosons. Unfortunately, they're massive. Oops.

From two independent perspectives, therefore, we see that the theory of the weak interaction would much prefer a world built from massless particles. Ours is not such a world. There is a happy resolution, however.

Amazingly enough the phenomenon of superconductivity, which seems a world away from these problems, points the way. The limitation of magnetic fields to a thin layer—the Meissner effect—is the essence of superconductivity. The microscopic theory of superconductivity ascribes this effect to a pervasive condensate of Cooper pairs in the superconducting material. When electromagnetic fields attempt to invade the superconductor, they disturb the condensate it houses. This perturbation costs energy, and the condensate does its best to expel the fields. Thus photons no longer come cheap, and the fields associated with them are short ranged. Within a superconductor, in a word, photons have become massive.

The modern theory of the weak interaction postulates a condensate that plays, for W and Z bosons in empty space, the same role played by Cooper pairs in a superconductor. This condensate can serve double duty, also gumming up the propagation of leptons and quarks. According to this conception, the basic equations of electroweak theory apply to a (nonexistent) external world of massless particles, within which we happily inhabit a weird superconductor.

At present, there is no independent or direct evidence for the required condensate. Its existence is simply a hypothesis that allows the known facts to snap into place, while introducing no contradictions. No known form of matter has the right properties to produce the required condensate. Something new must be added—the so-called Higgs field. What we call empty space, or vacuum, is filled with a condensate spawned by that field.

Fortunately, this fantasy has observable consequences. By agitating the Higgs field, we should be able to produce its quanta—Higgs particles. The spin of the Higgs particle (namely 0—it's a chip off the vacuum), and its couplings to matter are unambiguously predicted. Indeed, if the Higgs field is doing the job we hired it for—that is, generating masses of quarks, leptons, and W and Z bosons— the coupling strength of the Higgs particle to each of the other particles ought to be proportional to their own mass. These properties are quite distinctive, so we'll certainly be able to recognize the Higgs particle, if and when it's found.

Ironically the one property of the Higgs particle that's not predicted precisely is its mass. There are excellent reasons, however, to think that the mass is such as to render the particle accessible to near-future accelerators—the Large Hadron Collider (LHC), if not the Large Electron–Positron (LEP) collider or the Tevatron. It will be very satisfying—and a great triumph for theoretical physics—if experimentalists find a particle with the predicted properties. Failure to find it could be still more instructive (but I don't expect that to occur).

Let me summarize. We've come a long way toward dethroning mass as a primary, irreducible property of matter. Most of the mass of ordinary matter, for sure, is the pure energy of moving quarks and gluons. The remainder, a quantitatively small but qualitatively crucial remainder—it includes the mass of electrons—is all ascribed to the confounding influence of a pervasive medium, the Higgs field condensate. There is already much indirect evidence for this concept, and crucial direct tests are in the offing.

So much for mass, in the Standard Model. Physics as a whole offers additional mass parameters that still await comparable assimilation. Perhaps the most profound is the Planck mass, which characterizes quantum gravity. Another is the recently discovered nonzero neutrino mass. They are, respectively, much larger (factor $\sim 10^{17}$) and much smaller (factor $\sim 10^{-13}$) than the Higgs mass. A major objective for a unified theory of fundamental physics must be to give a convincing account of these extraordinary ratios. At present, one can venture important connections, but they're too loose for comfort, and tenuous to boot.

Astronomy may jazz the chord. Indeed, notoriously, the source of most of the gravitational mass in the universe is yet to be identified. "Mass without matter"? As we realize past dreams, we awaken to new realities. ■