REFERENCE FRAME

The Persistence of Ether

Frank Wilczek

Quite undeservedly, the ether has acquired a bad name. There is a myth, repeated in many popular presentations and textbooks, that Albert Einstein swept it into the dustbin of history. The real story is more complicated and interesting. I argue here that the truth is more nearly the opposite: Einstein first purified, and then enthroned, the ether concept. As the 20th century has progressed, its role in fundamental physics has only expanded. At present, renamed and thinly disguised, it dominates the accepted laws of physics. And yet, there is serious reason to suspect it may not be the last word.

As with most general ideas, the germs of the ether philosophy, and its main competitor, can be discerned in debates among the ancient Greeks. Aristotle taught that "Nature abhors a vacuum," while Democritus postulated "Atoms and the void." The modern history begins with the contest between the world system of René Descartes, who proposed to explain the motion of planets as caused by vortices that sweep them through in a universal medium, and the austere theory of Isaac Newton, who specified precise mathematical equations for the forces and motions, but "framed no hypotheses." Newton himself believed in a continuous medium filling all space and, in Query 21 of his *Optics*, speculated on how it could be responsible for a tremendous variety of physical phenomena. But his equations did not require any such medium, and his successors rapidly became more Newtonian than Newton. By the early 19th century the generally accepted ideal for fundamental physical theory was to discover mathematical equations for forces between indestructible atoms moving through empty space. In particular, it was in this form that leading mathematical physicists, including such giants as André Marie Ampère, Karl Friedrich Gauss, and Bernhard Riemann, tried to formulate the emerging laws of electrodynamics.

It was Michael Faraday, a self-taught and mathematically naive experimenter, who revived the idea that space was filled with a medium having physical effects in itself. His intuition led him to devise experiments looking for physical effects of magnetic flux lines in "empty" space, and of course, in his law of induction, he found them. To summarize Faraday's results, James Clerk Maxwell adapted and developed the mathematics used to describe fluids and elastic solids. To orient himself, and to understand Faraday's conceptions in terms of more familiar things, Maxwell postulated an elaborate mechanical model of electric and magnetic fields. In the end, though, his equations could stand by themselves.

The first sentence of Einstein's original paper on special relativity refers to "an asymmetry in the formulation of electrodynamics, which does not appear to inhere in the phenomena." His paper's achievement was to highlight and interpret the hidden symmetry of Maxwell's equations, not to change them. The Faraday–Maxwell concept of electric and magnetic fields, as media or ethers filling all space, was retained. What had to be sacrificed was only the false intuition that motion at a constant velocity would necessarily modify the equations of an ether.

Indeed, the argument can be turned around. One of the most basic results of special relativity, that the speed of light is a limiting velocity for the propagation of any physical influence, makes the field concept almost inevitable. For it implies that the influence of particle A on particle B depends not on the present position of A, but rather on where it was some time ago. This makes it very awkward to build up dynamical equations in terms of the position of particles.

Though it required major conceptual readjustments, the mathematics required to bring the equations of mechanics—that is, the motion of particles in response to given forces—into a form consistent with special relativity, is not hard. Einstein developed it swiftly and painlessly. The remaining foundational piece of classical physics, the theory of gravity, posed a greater challenge. Although Newton's extremely economical, and extensively battle-tested, formulations deployed forces depending on the present distance between particles, special relativity taught that observers moving relative to one another would have different notions of distance, and that the speed of light bounded the transmission of all possible influences. Henri Poincaré formulated what is in retrospect the most straightforward response to these defects, modeling gravity as what we would now call a massless scalar field. (Of course, it was very far from straightforward in the contemporary state of the art!) But Einstein, influenced by the experimental results of Roland, Baron Eötvös of Vásárosnamény and inspired by his own famous elevator thought-experiment, sought a formulation in which the equality of inertial and gravitational mass, and the universality of gravitational response, were rigorous and organic features. As we know, he achieved this goal by identifying the gravitational interaction as the bending of spacetime by matter.

Thus in 1917, following Einstein's revelations, the electromagnetic field remained essentially in the form bequeathed by Maxwell, satisfying his "ethereal" equations. Moreover spacetime itself had become a dynamical medium—an ether, if ever there was one. For example, a major consequence of general relativity is that distortions of spacetime can themselves produce further distortions, initiating gravitational waves.

To account for physical phenomena, one needs—apparently—more than the gravitational and electromagnetic fields. Electrons, for instance. By 1917, J. J. Thomson had discovered them, Hendrik Lorentz had made impressive progress in understanding many properties of matter from a theory in which they are prime players and Niels Bohr had used them to make

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his brilliantly successful atomic model. In all these applications, the electrons were modeled as point particles. As such, they constituted an element of reality quite separate and distinct from any continuous ether.

Einstein was not satisfied with this dualism. He wanted to regard the fields, or ethers, as primary. In his later work, he tried to find a unified field theory, in which electrons (and of course protons, and all other particles) would emerge as solutions in which energy was especially concentrated, perhaps as singularities. But his efforts in this direction did not lead to any tangible success.

The development of quantum theory changed the terms of the discussion. Paul Dirac showed that photons—Einstein's particles of light—emerged as a logical consequence of applying the rules of quantum mechanics to Maxwell's electromagnetic ether. This connection was soon generalized: Particles of any sort could be represented as the small-amplitude excitations of quantum fields. Electrons, for example, can be regarded as excitations of an electron field.

This formulation, which at first hearing might sound extravagant, had a lot going for it right from the start. First, it answers one of the most basic and profound riddles about the physical world, which is otherwise quite mysterious: Why do electrons anywhere in the universe have precisely the same properties—the same mass, charge, magnetic moment? Because they are all surface manifestations of a single more basic entity, the electron field, an ether that pervades all space and time uniformly.

Classic atomism sought to account for the world in terms of irreducible building blocks that could be rearranged, but neither created nor destroyed. This notion is incompatible with democratic treatment of the photon as a particle among others, since radiation and absorption of light are commonplace. In beta decay, a neutron is destroyed, and a proton, together with two particles of quite a different character, an electron and an antineutrino, are created. Evidently, neither protons nor neutrons nor electrons nor photons can be considered as abiding building materials. Instead, Enrico Fermi built a successful theory of beta decay in terms of excitation and de-excitation of the relevant fields. Particles come and go, but the ethers abide.

As hinted above, it is very much easier to incorporate the principles of locality and propagation of influence at finite speed when one deals with fields. Our current—extremely successful—theories of the strong, electromagnetic, and weak forces are formulated as relativistic quantum field theories, with local interactions. In fact, having told you that, I need only add a few more detailed specifications to sum up pretty much everything reliable we know about the nongravitational fundamental interactions. The most ethereal of all theories, Einstein's general relativity, does the same for gravity.

Once I was fortunate enough to catch Richard Feynman alone and a little tired after a day of bravura performances. When I gently provoked him, he displayed a subdued, wistful side I never saw before, or again. He told me that he had been very disappointed when he realized that his theory of photons and electrons, the method of calculating amplitudes by using Feynman graphs, was mathematically equivalent to the usual quantum electrodynamics. He had hoped that, by formulating his theory directly in terms of paths of particles in spacetime, he would be avoiding the field concept, and constructing something essentially new and different.

Uniquely (as far as I know) among physicists of high stature, Feynman had hoped to remove the field–particle dualism by getting rid of the fields. For pure quantum electrodynamics, he came close. In retrospect, though, it is clear he was swimming against the tide for understanding the other interactions. Even in electrodynamics, his rules for dealing with virtual particles appear rather *ad hoc*, except when they are derived from standard quantum field theory. It gets much worse both in modern electroweak theory, which works smoothly only if we allow for a uniform excitation of the so-called Higgs field to fill spacetime, and in quantum chromodynamics, where we operate with quark and gluon fields whose corresponding particles do not, properly speaking, exist at all.

How did I provoke Feynman? I asked him, "Doesn't it bother you that gravity seems to ignore all we have learned about the complications of the vacuum?" To which he immediately responded: "I once thought I had solved that one. I had a slogan: 'The vacuum is empty.' " It was then he got wistful.

I was deeply impressed to realize that Feynman had been wrestling with the problem of the cosmological term already in the 1940s, long before it became a widespread obsession, and frustration. You have to admit that his slogan is catchy. So just maybe, despite everything I've said up to this point, eventually we really may have to do without ether. ■