What does particle physics tell us about the nature of matter?

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The Lightness of Being: Mass, Ether, and the Unification of Forces by Frank Wilczek. Published by Basic Books in the USA, 2008 and by Allen Lane, Penguin in the UK, 2009.

Frank Wilczek's book can be recommended as an attempt to explain to a layperson the implications of more than 50 years of particle physics. Wilczek is a Nobel Prize-winning theoretical physicist.

As a graduate student in the 1970s, he worked on the problem of asymptotic freedom of quarks, part of the developing theory of Quantum Chromodynamics (QCD), with his supervisor David Gross at Princeton. Gross and Wilczek were awarded the Nobel Prize in Physics for this work in 2004, jointly with H. David Politzer, who had discovered the same phenomenon independently. The three discovered that the closer quarks are to one another, the weaker the nuclear force is between them, so that they behave like free particles. According to QCD, the force increases as the quarks move apart, explaining the phenomenon of quark confinement—the impossibility of quarks existing by themselves.

Wilczek's book is written in an approachable style, but is a thoughtful reflection on the philosophical implications of what the science tells us. Wilczek takes an historical approach to the subject.

The publication of *The Lightness of Being* was intended to coincide with the coming on line of the Large Hadron Collider (LHC) at CERN near Geneva. The LHC, the most powerful scientific experiment ever conducted, involves the collision of particle beams that have been accelerated around a ring buried in a 27-kilometre-long tunnel. Costing some $8 billion and involving the work of up to 8,000 scientists of 80 nationalities, the LHC replaced a previous particle accelerator, the Large Electron-Positron Collider (LEP), at the beginning of the twenty-first century.

Particle beams are directed in the LHC by massive super-cooled magnets that are kept just above absolute zero by liquid helium. A problem with these magnets, causing helium to leak into the tunnel, meant the LHC could not start up in 2008 as planned. Only in November of last year were the LHC's particle beams successfully circulated around the tunnel, and in December the first collisions recorded in all four of the main experimental detectors (see picture).

It is expected that the LHC will be ramped up to its full energy level of 7 Tev in each of its colliding proton beams over the next 12 months, giving it seven times more energy than the highest energy currently obtained at the Tevatron collider at Fermilab outside Chicago in the United States.

A key aspect of the LHC is its computing facility, the Worldwide LHC Computing Grid, which will churn out enormous amounts of data to 70 computing centres in 34 countries. Some 300 gigabytes of data per second are emitted from the LHC's detectors. This has to be filtered to find collisions that are expected to give significantly new discoveries over the next year or two.

Much of the publicity surrounding the LHC has focused on the hope that it will provide confirmation of what is known as the Standard Model of particle physics, by finding the only particle which that theory predicts that has so far remained undiscovered—the Higgs boson. But it is also hoped that discoveries will be made concerning possible extensions to current physics. These could include so-called supersymmetry (SUSY), which gives a greater degree of unification and predicts a further range of particles that pair up with current known ones. It may be that dark matter will turn out to consist of supersymmetric particles. Observations in astronomy indicate that ordinary matter makes up only about 4 percent of the total material world. Some 26 percent of the total is dark matter and 70 percent dark is energy.

Much of Wilczek's book is devoted to explaining the Standard Model or the "Core," as he calls it, and exploring its implications. Only in the final sections does he suggest possible extensions and generalisations that might in future emerge from this theory.

"Standard Model is a grotesquely modest name for one of humankind's greatest achievements. The standard model summarises, in remarkably compact form, almost everything that we know about the fundamental laws of physics" (p. 165).

The Standard Model has been vindicated over and over again in experiments in particle accelerators and has proved to be an immensely successful theory. But it is not compatible with Einstein's General Theory of Relativity because it does not incorporate gravity. From the 1980s, physicists hoped that the Standard Model would be demonstrated to be an approximation to a deeper theory—SuperString Theory—that would replace and include Einstein's theory as well. So far this hope has not been realised. But almost every recent popular book on fundamental physics has been concerned with String Theory or the search for "a theory of everything." Wilczek's book is unusual in being a study of the Standard Model.

Wilczek wants to draw our attention to the fact that massively powerful computers have now made it possible to predict the results of particle collisions based on the Standard Model with extraordinary accuracy. Most importantly, the results of these experiments give us confidence in a conception of matter at this fundamental level that is quite revolutionary. From a Marxist standpoint, one can also say that Wilczek's approach supports a materialist outlook, based on the dialectical conception of self-moving matter.

Our commonsense view of matter and the Newtonian physics that dominated science from the seventeenth century to the end of the nineteenth sharply distinguish inert "matter"—meaning corpuscular matter that has mass and is made up of atoms—from light. Light, or more generally electromagnetic radiation such as radio waves, infrared, ultraviolet, etc., is conceived of as something that is freely switched on and off, is without boundaries, and has no mass. Sometimes, scientists have detached electromagnetic radiation from matter altogether and regarded it as pure "energy."

"Matter and light served—and still do serve—as powerful metaphors for other contrasting aspects of reality:" Wilczek writes, "flesh and spirit, being and becoming, earthy and celestial" (p. 9). Light continued to be contrasted to the particles of the atom even with the development of Quantum Mechanics in the 1920s. Bohr, Heisenberg and others studied the cloud of electrons surrounding the nucleus of the atom. Their work explained the basis of chemistry and accounted for many other phenomena, providing the theory on which the transistor and modern electronics, including the computer, was developed. Yet electromagnetic radiation continued to be understood as something distinct from the atom.

In the nineteenth century, light and other forms of electromagnetic radiation came to be understood as the wave-like motion of something that was spread throughout space known as a plenum or field. The English physicist Paul Dirac and others extended Quantum Mechanics to include Einstein's Special Theory of Relativity in the late 1920s and 1930s in an attempt to develop a Quantum Theory of Fields that would incorporate electromagnetism.

Richard Feynman and other US scientists overcame many of the difficulties in this theory after the Second World War when they developed Quantum Electrodynamics (QED), as it became known. QED meant that light and other electromagnetic fields could be combined in the same theory as electrons.

Electrons and protons are still described as "particles," and in ordinary parlance this field of physics is referred to as dealing with "elementary particles." But, in fact, the theory posits electron fields, proton fields, etc., as the basic entities. Particles become clumps or ripples in a field, technically known as field "quanta." The interaction between particles was (and as a simple approximation still is) viewed as due to "forces" between the particles. But in QED this is no longer the case.

The electromagnetic force between charged particles, for example, is considered in terms of an interaction between fields, of which the particles are quanta. "Force" is shown in field theory terms to be produced by the exchange of "virtual" photons of light. Photons are the "particle" or quanta of the electromagnetic field produced by the fields of the charged particles. They are "virtual" because they are not directly observed and do not exist apart from the interacting fields.

Extending the Quantum Theory of Fields to interactions involving the nucleus—of two kinds, weak and strong—proved to be very difficult. The weak interactions were only added to QED in a unified electroweak theory after developments made in the late 1960s by Steven Weinberg, Abdus Salam and Sheldon Glashow.

It was realised that the constituents of the nucleus of the atom, protons and neutrons, were made up of more basic units. These became known as quarks. Explaining the very strange properties of quarks and gluons (which account for strong nuclear interactions between the quarks) and hence the nucleus of the atom, was the great contribution that the 21-year-old Wilczek made in 1973. The property of quarks, which is analogous to the electric charge in QED, is called "color." There are three of these colors from the theory that takes the name of Quantum Chromodynamics (QCD).

Quantum Field Theory now includes QED, which has been extended to include weak interactions, and QCD. Together they make up the Standard Model. It is the culmination of more than 50 years of research. We get some impression in reading Wilczek of the thinking of one of the leading figures involved in this work, which now underlies the experiments that are being carried out at the LHC.

It has been understood since Einstein's work a century ago that mass is equivalent to energy. Wilczek takes time in his opening chapters to stress what this means. For Isaac Newton and for the science of the 200 years after him, matter took the form of inert lumps with fixed mass. Wilczek calls this Newton's Zeroth Law. This conception has been overthrown, and inert mass is now known to be the result of motion, expressed quantitatively as energy in Einstein's famous formula. It would have delighted Frederick Engels to see the confirmation of his famous riposte to Herr Eugen Dühring: "Motion is the mode of existence of matter."

With the advent of QCD a much more detailed explanation of where our everyday mass comes from becomes possible. This is the subject of much of Wilczek's book. More than 99.9 percent of the mass of the atom is contained in the protons and neutrons of the nucleus, which is roughly one hundred thousandth the atom's size. Wilczek attempts to explain how the strange dynamics of the quarks and gluons that make up the proton can now be understood and how the mass of the proton can be explained from the motion of the massless quarks and gluons.

Wilczek is well aware that the processes of QCD are far removed from everyday commonsense logic.

"The success of quantum theory in describing reality transcends and in a sense unseats classical logic, which depends on one thing being 'true,' and its contraries 'false'…. On the one hand, the interior of a proton is a dynamic place, with things changing and moving around. On the other hand, all protons everywhere and everywhen behave in exactly the same way. If a proton at one time is not the same as itself at a different time, how can all protons be identical?… Every individual possibility A for the proton's interior evolves in time to a new and different possibility, say B. But meanwhile, some other possibility C evolves into A. So A is still there; the new copy replaces the old. And more generally, even though each individual possibility evolves, the complete distribution of possibilities remains the same. It is like a smoothly flowing river, which always looks the same even though every drop of it is in flux."

Wilczek is at his most intriguing when he expounds the way in which physics has, over the last few decades, transformed conceptions of space. Einstein overthrew the old mechanical conception of an "ether" that permeated space and gave rise to electromagnetic fields. He later recanted his opposition to ethers in his General Theory. He conceived of gravity as inseparable from space and hence gravitational fields are a type of ether. But he was, in Wilczek's view, not convinced of the primacy of fields in our understanding of matter. Feynman too hoped he had gone beyond Quantum Field Theory. Wilczek recalls fascinating conversations with the great scientist. Feynman was very disappointed when he learned that his famous "Feynman Diagrams" turned out to be equivalent to the theory that Dirac and others had initiated and was not an essentially new departure.

Wilczek, on the contrary, is convinced that fields, or rather their quantum theory version, are fundamental, and he insists that space is full of material ethers that are a consequence of the "Core." According to QED, space, or what is confusingly called the "vacuum," is full of activity. Virtual particle pairs—electrons and positrons—are constantly being created and interact with the electromagnetic field in what is called vacuum polarisation, an effect that can be measured experimentally. But, Wilczek explains, the Standard Model is now known to have further implications.

"Besides the fluctuating activity of quantum fields, space is filled with several layers of more permanent, substantial stuff. These are ethers in something closer to the original spirit of Aristotle and Descartes—they are materials that fill space."

Such ethers are known to physicists as "condensates" and in the case of one such predicted by QCD, so-called quark-antiquark pairs, is well on the way to being established not just in computer models but in the results of accelerator experiments. It is hoped that the LHC will provide evidence of another of these "condensates" that is a result of the electroweak theory. This is the "Higgs condensate."

In the final chapters of the book, Wilczek expresses his confidence that the LHC will provide evidence for the "condensate" view of space that is implied by the "Core" Standard Model, as well as the extension and further unification of the theory that supersymmetry can provide.

“Looking down on the valley of everyday reality, we perceive much more than before. Beneath the familiar, sober appearances of enduring matter in empty space, our minds envision the dance of intricate patterns within a pervasive, ever-present, effervescent medium. We perceive that mass, the very quality that renders matter sluggish and controllable, derives from the energy of quarks and gluons ever moving at the speed of light, compelled to huddle together to shield one another from the buffeting of that medium.”