What is an electron?

A century after Bohr conceived of the electron as the proton's satellite, our perception of it continues to evolve and expand, says Frank Wilczek.

What is an electron? That question was central to the development of quantum theory early in the twentieth century and remains at the frontier of physics today. There are several inconsistent answers, each correct.

Danish physicist Niels Bohr's answer, in 1927, epitomized his beloved concept of complementarity: in some circumstances electrons are best described as particles, with definite positions; in others as waves, with definite momenta [1]. Either description is valid and useful, yet according to Heisenberg's uncertainty principle they are mutually exclusive, as positions and momenta cannot be known accurately at the same time. Each depiction captures an aspect of the electron's nature, but neither exhausts it.

Modern quantum theory reinforces Bohr's conclusion that what you see depends on how you choose to look. Electrons are both ideally simple,

and unimaginably complex. Electrons are understood with precision, and at the same time utterly mysterious. Electrons are stable bedrock in our world-picture, and playthings we are learning to fragment and transform.

Simple, and Complex

For most practical purposes, an electron is a structure-less particle that possesses an intrinsic angular momentum, or spin. Just two numbers, the electron's mass and electric charge, fuel the equations that describe its behavior in full. From this 'practical electron' model, physicists constructed microelectronics from the ground up. It is also the working foundation for chemistry, including biochemistry.

But to a high-energy positron (anti-electron), an electron is a cornucopia. Collisions of electrons with positrons, as carried out at the Large Electron-Positron collider (LEP) at CERN, produce streams of quarks, gluons, muons, tau leptons, photons and neutrinos. To understand the complexity of an electron, all the esoteric resources of modern physics must be brought to bear. To understand the electron is to understand the world.

There is tension between these two observations, that the electron is a simple point-particle, and that it contains the world. They can be reconciled through a concept I call quantum censorship, whereby properties of electrons vary according to the energy with which they are probed. Quantum censorship was implicit in Bohr's atomic model and, in a more general form, remains a central pillar of modern quantum theory.

In his 1913 model of the hydrogen atom [2] Bohr pictured an electron orbiting the proton like a planet in a miniature solar system. As he knew, and James Clerk Maxwell had emphasized before him, mechanical models of the atom have severe problems. They predict a variety of hydrogen atoms, with different orbit shapes and sizes – whereas in reality each is identical. They predict that atoms are unstable, since moving electrons should radiate energy and spiral into the central proton, which clearly it does not.

With his concept of stationary states, Bohr boldly assumed those difficulties away. He restricted electrons to a set of discrete - quantized – states within an atom, to avoid instability. And he recognized that the level with the lowest energy, or ground state, has a finite size, keeping the electron and proton apart.

Today we trace Bohr's rules to the fact that the proper quantum mechanical description of electrons involves wave functions, whose oscillation patterns are standing waves. The equations that govern electrons in atoms are similar to those for vibrations in musical instruments, which produce scales of discrete tones.

The same ideas apply to complex, bound systems, such as atoms made of many electrons and larger nuclei. A system in its ground state tends to remain there, if little energy is input, betraying no evidence of its internal structure. Only when we excite it into a higher state, do complexities emerge. This is the essence of Quantum Censorship. Thus, below an energy threshold, atoms appear to be the "hard, massy, impenetrable" units Isaac Newton inferred. Above it, their components can be torn out.

Similarly electrons themselves, despite the fecundity they showed at LEP, betray nothing of their inner workings at low energies. When one supplies enough energy -- at least 1 MeV, corresponding to the unearthly temperature 10^{10} K -- to unleash electron-positron pairs, the electron's structure is revealed.

The practical electron is not an *approximation* to reality, in the usual sense of fuzziness; rather, it is a *precise* description that applies under limited (but quite generous!) conditions.

Having recognized its power, let us celebrate the practical electron's intellectual beauty. Each of its properties is intimately connected to profound symmetries of physical law. Mass, a real-valued parameter, and spin, a discrete one, uniquely classify all possible realizations of special relativity by particles. (For experts: mass and spin occur as the Casimir operators for the inhomogeneous Lorentz group.) Electric charge, a conserved quantity, classifies realizations of the gauge symmetry of electromagnetism. Once you specify how the practical electron responds to those symmetry transformations, you have determined its physical behavior. In that sharp and concrete sense, the electron is an *embodiment* of symmetry: Its physical properties inhere in its mathematical form.

Precisely Known, and Deeply Mysterious

The spin of the electron provides an axis, with which dipole fields can be associated. Both magnetic and electric fields are allowed, in

principle. Their status could hardly be more different, however. While the strength of the electron's magnetic field provides perhaps the most stringent, and brilliantly successful, comparison of theory and experiment in all of physical science, the value of the electric field has never been measured, and is a mystery even to theory.

Establishing the strength of the electron's magnetic field – in terms of a gyromagnetic ratio or "g factor" – was a major focal point for twentieth-century physics. An early triumph of Paul Dirac's 1928 relativistic wave equation for the electron [3] was its suggestion that g = 2, then nicely consistent with atomic spectroscopy.

Postwar developments in precision spectroscopy, using atomic beams, revealed that g deviated from that value by one part in a thousand [4]. Theorists matched it when they mastered the mathematical difficulties of quantum field theory sufficiently to calculate corrections to the Dirac equation due to quantum fluctuations (whose energy releases virtual photons) [5].

Creative dialogue between experiment and theory continues today, with improved accuracy on each side allowing ever more rigorous comparisons.

The experimental frontier has moved to beautiful investigations of single electrons in electric and magnetic traps [6]. Theoretical calculations have become intricate, now including fluctuations in fluctuations in fluctuations [7]. The value of g is known to a dozen significant digits [8].

A crude but appealing 'explanation' of the origin of the electron's magnetic field is that quantum uncertainty in position smears the electron's charge over a volume, which rotates on account of the electron's spin. The electron is effectively a spinning ball of charge, which electromagnetism tells us, generates a dipole magnetic field. The size of that ball can be estimated to be roughly 2.4×10^{-12} meters. Attempts to pin down an electron's position more accurately than this require, according to the uncertainty principle, injecting so much energy into the electron that additional electrons and anti-electrons get produced, confusing the issue.

An electric dipole, should it exist, would generate broadly similar corrections. But no such field has been detected. Great efforts have gone into the experimental search, using all the tricks and traps that revealed the magnetic moment. But so far there is only an upper bound for the electric

dipole moment [9]. This is an extraordinary 17 orders of magnitude smaller than one might expect, naively, give the electron's effective size.

Why is it so hard for spin to align electric charge? One explanation involves time-reversal symmetry. If we run time backwards, the laws of physics stay the same. But for a spinning electron, the north and south poles would interchange. Thus an electric dipole accumulating charge at one pole violates time-reversal symmetry.

On the other hand, nature does not always respect time-reversal symmetry, as we know from observations of K and B mesons [10]. So a non-zero electric dipole moment for electrons is a theoretical possibility. Indeed, it is tantalizing that values of the electric field just below the present bound are expected in many theories of physics beyond the Standard Model, including supersymmetry [11]. Ingenious experiments using solid-state physics [12] and molecular spectroscopy [13] have been proposed to search more sensitively for the existence tiny electric fields generated by re-orienting spins. This 'other' dipole moment might prove a major focus for twenty-first century physics.

Rigid, and Protean

Electrons follow Pauli's Exclusion Principle, which states that no two electrons can be in the same quantum state at the same time. (This is the defining characteristic of fermions, a class of particles that includes protons and neutrons as well as electrons.) As a result, electrons cannot be crushed, and defend their integrity stoutly.

Nature's most imposing macro-electronic creation is the white dwarf star. Our Sun will become one 4·5 billion years from now, when its nuclear fuel exhausts causing the collapse of the star roughly the size of Earth but a million times denser. Such ancient suns rely on the quantum statistics of electrons for their support. Squeezing electrons together promotes some into higher-energy states, exerting a force or 'degeneracy pressure' that balances gravity and halts further collapse.

Subtle collective action can, however, achieve what raw pressure does not.
Fragmentation of electrons has been extensively studied in fractional quantum Hall effect liquids [14]. These states occur in thin (effectively two-dimensional) electron-rich semiconductor interfaces that are extremely pure, cold and subjected to strong magnetic fields. Shot noise for

electric currents flowing in these states reveals particles whose charge is a fraction of an electron's charge [15, 16, 17]. Such electron fragments should, theory predicts, no longer behave as fermions but as 'anyons' [18], whose dynamics are more intricate than Pauli exclusion or bosonic attraction.

By combining fragmentation with superconductivity, we can get half-electrons that are their own antiparticles [19]. Such `Majorana modes', a special kind of anyon, have recently been observed experimentally [20], and promise to have very exotic properties.   Notably, their quantum is not uniquely specified by their positions and spins, but retains memory of how they were created and where they have been.

Manipulating electron fragments opens up rich new possibilities for micro-electronics which are only beginning to be explored. Circuits involving anyons can support much more complex quantum behavior than ordinary circuits [21], and have been used to thought-engineer quantum computers [22].

Conclusion: No Conclusion

So, what is an electron? An electron is a particle, and a wave; it is ideally simple, and unimaginably complex; it is precisely understood, and utterly mysterious; it is rigid, and subject to creative disassembly. No single answer does justice to reality.

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