15

What Should Philosophers of Science Learn from the History of the Electron?

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We have now celebrated the centenary of J. J. Thomson's famous paper (1897) on the electron and have examined 100 years of the history of the first fundamental particle. What should philosophers of science learn from this history? To some, the fundamental moral is already suggested by the rapid pace of this history. Thomson's concern in 1897 was to demonstrate that cathode rays are electrified particles and not aetherial vibrations, the latter being the "almost unanimous opinion of German physicists" (293). But were these German physicists so easily vanquished? De Broglie proposed in 1923 that electrons are a wave phenomenon after all, and his proposal was soon multiply vindicated, even by the detection of the diffraction of the electron waves. Should we not learn from such a reversal? Should we not dispense with the simple-minded idea that Thomson discovered our first fundamental particle and admit that the very notion of discovery might be ill-suited to science?

The purpose of this paper is to argue at length that this sort of skepticism is hasty and wholly unwarranted. Nevertheless, a more detailed examination of the history of the electron can give further encouragement to these skeptical smolderings. The transition from classical corpuscle to quantum wave was just the most prominent of the many transformations of theories of the electron over the last century. Thomson's electron of 1897 was a charged, massive corpuscle—an electrified particle—obeying Newtonian dynamics. It was briefly replaced by one in the electromagnetic world picture whose mass arose as an artifact of its electromagnetic field. Einstein's electron of 1905 once again sustained an intrinsic mass but now obeyed a relativistic dynamics. The electron of Bohr's old quantum theory of the 1910s and early 1920s displayed a precarious and ever-growing mix of classical and discrete properties. Pauli's electron of 1925 obeyed a bizarre, nonclassical "exclusion principle" under which no two electrons could occupy the same energy state in an atom. The electron of the new quantum theory of the mid- to late-1920s could be portrayed apparently equally well by Heisenberg's matrices, Schrödinger's waves, and Dirac's q-numbers.[1]

At least in this new theory, the electron maintained some measure of identity as an independent physical system. But even this was lost as the electron continued to mutate into forms ever more remote from Thomson's corpuscles. In Jordan and Wigner's (1928) theory, under second quantization of the single-particle electron wave function, the electron became a mere excitation of a fermionic field. Wigner's (1939) analysis of group properties of elementary particles relegated the electron to a spin-1/2 irreducible representation of the Poincaré group. In the 1967–68 Glashow-Salam-Weinberg theory of electroweak interactions, the electron was an even stranger beast: it had massless left-handed and right-handed parts that united to form a massive particle through interactions with a scalar Higgs field. Finally, in the current standard model of fundamental interactions, the electron is a member of the first of three generations of similar leptonic particles that are related in a nontrivial way to three generations of hadronic quarks. With its public persona displaying more aliases than a master confidence trickster, one may well doubt that we have or ever will unmask the identity of the real electron in our theorizing. Is the lesson of history, then, that we should stop taking our theories of the electron as credible reports of physical reality?

Such concerns have long been a subject of analysis in philosophy of science. They have been given precise form in the "pessimistic metainduction":

> Every theory we can name in the history of science is, in retrospect, erroneous in some respect. The Newtonian theory of gravitation is incorrect, as is the classical theory of electromagnetism, Dalton's atomic theory, classical physical optics, the special theory of relativity, the Bohr theory of the atom, and so on. The errors of these theories may not matter for most practical purposes, but from a contemporary point of view they are all, strictly, false theories. Since all theories in history have been false, . . . we should conclude that all the methods of science do not generate true theories; hence our present scientific theories, which were obtained by the same methods, are false as well. (Glymour 1992, 125–126)[2]

The purpose here is to explain why we believe that the history of electron provides no support for the pessimistic metainduction. In brief, we shall argue that the history of the electron shows that there is something right and that there is something wrong about the pessimistic metainduction. What is right is that the history shows how even the best theories are corrigible. If the history of the electron is typical , then we should expect none of our current theories to be the final theory. But what is wrong is the sad portrait of the sequence of theories in the electron's history as nothing more than a sequence of magnificent failures. Although there proved to be something erroneous in each theory of the sequence, there is also a clear sense in which each accumulates results from earlier members of the sequence and provides an everimproving account of the nature of the electron. Our case for this claim resides in two theses, which are elaborated in the following sections:

- Thomson, Bohr, Dirac, and the other electron theorists all had good evidence for at least some of the novel properties they announced for the electron and these historically stable properties endure through subsequent theory changes.
- This accumulated stock of enduring properties can be collected into what we shall call the structure of electron theory. At any stage in the sequence of theories, one can specify our best candidate for this structure. It gives that theory's representation of the electron and accounts for the successes of earlier theories of the electron.

Thus we shall argue that the gloss of the history of the electron as just a sequence of false theories is seriously misleading. A closer look at the history reveals a sequence of theories in which an evergrowing, historically stable core of properties of the electron is discerned and in which the deficiencies of earlier theories are identified and corrected as our accounts of the electron are brought into ever closer agreement with the minutiae of experiment.

HISTORICALLY STABLE PROPERTIES

As we follow the sequence of theories of the electron starting with Thomson, we find each theory contributing stable properties of the electron that are then retained in the later theories. There are many of these. We catalog just a few of the more prominent and easily describable ones.

Whatever we may now think of Thomson's (1897) theory of the electron as a classical, electrified particle, he did succeed in using it to recover from his experiments on cathode-ray deflection values of the mass-to-charge ratio (m/e) of the electron that agree with the modern value on which the electron literature rapidly settled. He recovered values in the range 0.32×10^{-7} to 1.0×10^{-7} (306) from the theoretical analysis of experiments involving deflection by a magnet and values of 1.1×10^{-7} to 1.5×10^{-7} (309) from the theoretical analysis of experiments involving deflection by an electrostatic field (measured as gram/electromagnetic units of charge). This conforms well with the modern value of m/e of 0.57×10^{-7} in the same system of units—the value used with equal comfort and success in classical electrodynamics and quantum field theory.

Correspondingly, Millikan (1917), using essentially the same classical framework, proclaimed the atomicity of the charge of the electron. He found (238) that electrons all carry the same unit of charge of 4.774×10^{-10} esu.

Once again, this compares favorably with the modern value of 4.803×10^{-10} esu. This value proved stable to within a few percent through the development of the theory of the electron. Indeed it had already arisen in Planck's (1900) famous analysis of heat radiation, which is now taken to mark the birth of quantum theory. Planck concluded by showing that his analysis yielded new values for certain fundamental constants of physics, including the charge of the electron, which he reported as 4.69×10^{-10} esu.

Bohr's (1913) celebrated analysis of bound electrons in atoms and their spectra depended on his conclusion that an electron bound into orbit around the positive charge of the nucleus of an atom did admit stationary states, contrary to the classical theory. Moreover, these states were determined by the condition that the angular momentum of the electron due to its orbital motion was a whole multiple of $h/2\pi$, where h is Planck's constant. While the electron has been embedded in ever more sophisticated theories of emission and absorption spectra, the basis of spectrographic analysis retains these two notions as its foundation, with Bohr's angular momentum quantum number now supplemented by further quantum numbers.[3]

In a communication of October 1925, essentially within the aegis of the soon to be superseded "old quantum theory," Uhlenbeck and Goudsmit (1925) introduced electron spin. They inferred from the splitting of spectral lines in the anomalous Zeeman effect that the electron possesses an intrinsic angular momentum of $h/4\pi$ that had been hitherto neglected and was responsible for a fourth quantum number in the theory of line spectra. The equivalent characterization of the electron as a spin-1/2 particle persists in all later, mainstream theories of the electron.

In 1925, Pauli suggested that atomic electrons obey an "exclusion principle" that prohibits more than two electrons from occupying the same atomic energy level. A year later, Pauli's phenomenological rule was formalized by Fermi (1926), and independently by Dirac (1926), as a new type of nonclassical statistics that govern ensembles of particles obeying the rule. Particles, such as the electron, governed by these statistics came to be known as "fermions." Fermi-Dirac statistics entered into quantum field theory in the form of anticommutators in Jordan and Wigner's (1928) extension of second-quantization techniques to fermions. In 1940, the fermionic character of electrons became even more firmly entrenched into electron theory when Pauli proved the spin/statistics theorem. He demonstrated that particles with half-integer spin must obey Fermi-Dirac statistics on pain of violations of causality. Hence, if the electron has spin 1/2, it must obey Fermi-Dirac statistics if it is to be described by a causal theory of quantum fields.

That these investigations into the properties of the electron produce an evergrowing list of stable properties should come as no surprise. In each case, the property discerned results from careful experiment, theoretical analysis, or both, and in each case the investigator had strong evidence for that property. This is not the place to analyze the strategies used to mount evidential cases for microentities such as electrons. In principle, each instance could be different and the investigator could need to mount evidential cases of qualitatively different character for each property. It turns out, however, that this is not the case. As one of us has argued elsewhere,[4] we can discern methods that are used repeatedly to mount the evidential case. One method requires a multiplication of experiments that massively overdetermine some fundamental numerical property of the electron. For example, one evaluates the mass-to-charge ratio revealed by many different manifestations of the electron—such as the deflection of cathode rays in different experimental arrangements or the normal Zeeman effect. That one recovers essentially the same value in all these circumstances is strong evidence that each is a manifestation of the same particle, the electron, and that electrons do carry inertial mass and charge and in the ratio recovered. A second strategy applied to the electron is known in the philosophy of science literature by many names, including eliminative induction or demonstrative induction. In it, one maps out as large a class of candidate theories as possible and then shows that some item of evidence, usually experimental, forces selection of just one theory from that class as the only one that is compatible with this item of evidence. The force of this method is that it not only gives strong evidence for the theory selected, but it also gives direct evidence against the theory's competitors.

Both methods are instances of inductive inference and thus can and did sometimes fail. But should their occasional failure make us complete skeptics about the results of all such investigation and the possibility that we can detect and correct the failures? It should not, just as a few successes should not delude us into the belief that we are infallible.

STRUCTURE

How is it possible for the sequence of theories of the history of the electron to display this growing list of historically stable properties? One of us has argued elsewhere that this can be explained by urging that the theories of the sequence have a common feature.[5] This common feature, the structure, is preserved through the changes of theory and is, in retrospect, that for which the investigators of the electron do have strong evidence. It is by no means assured that a sequence of theories will admit such a common feature. For a sequence of theories with historically stable properties, however, such as the theories of the electron, this view predicts that we will be able to identify a common feature of nontrivial content sufficient to support these properties.

Ideally we would like to be able to set out in simple terms the structure that holds together the sequence of theories of the electron. But that would be impudent and impossible, for it would require us to say what the final, incorrigible theory of the electron must be. But the history of the electron shows us that our theories are always corrigible. Although we cannot display the structure, we can certainly display our best candidate for that structure, recognizing that its form and content are likely to change as understanding grows. At any one time in the development of theories of the electron, we can read our best candidate from the latest theory. It is simply the smallest part of the latest theory that is able to explain the successes of earlier theories. We have followed this prescription and, in the remainder of this section, we will list the best candidates that result for the last 100 years of theories of the electron. We identify these best candidates in the Hamiltonian or Lagrangian for the electron in the corresponding theory.

There is an uncanny stability in this string of best candidates. Except for one brief period in the late 1920s, the structure stays remarkably constant. Changes are not so much changes in the mathematical description of the electron but rather in the framework in which that description sits, or (in the later period) in additions to the vehicles through which the electron interacts with other elements of the physics ontology. Prior to the 1920s, the classical electron Hamiltonian remains unchanged excepting adjustments for relativity theory. After the 1920s, once the Dirac Hamiltonian/Lagrangian is fixed, its form remains unchanged in all subsequent descriptions of the electron. What changes is the list of interactions the electron experiences. And each type of interaction is itself given by a separately definable structural feature.

The basic sequence of developments involves six modifications:

First, virtually all the properties of the electron discovered at the advent of wave/matrix mechanics prior to the incorporation of spin can be recovered from the Hamiltonian of an electron in an electromagnetic field:

$$H = (\mathbf{p} - e\mathbf{A})^2/2m + e\phi, \tag{1}$$

where $\mathbf{p}$ is the momentum, e is the charge and m is the mass of the electron. $\mathbf{A}$ and ϕ are the vector and scalar electromagnetic potentials.

Embedding this Hamiltonian into a classical (nonquantum, nonrelativistic) dynamics yields the electrostatic interactions Millikan needed for his oil drop experiment and those that Thomson called upon to explain the deflection of cathode rays by electric and magnetic fields. In the old quantum theory, the same Hamiltonian describes the interaction of the electron with the electric field of the atomic nucleus. It does so in sufficient measure to give us the stationary electron states from which the atomic spectra are recovered.

It also accounts for the effects of external electric and magnetic fields on these states, which are in turn associated in the spectra with the Stark and normal Zeeman effects. If, following Schrödinger (1926), this Hamiltonian is inserted into the time-independent Schrödinger equation for a spinless, massive particle using the identification $\mathbf{p} \rightarrow -i\hbar\nabla$, we once again recover stationary states capable of returning much of the known atomic spectra. We are, in addition, freed from the old quantum theory's puzzle of how such stationary states are possible.

Second, the classical relativistic Hamiltonian for a particle with mass m and charge e in the presence of an electromagnetic field is

$$H = [(\mathbf{p} - e\mathbf{A}/c)^2 c^2 + m^2 c^4]^{1/2} + e\phi. \tag{2}$$

The change from (1) does not reflect the discovery of some new property peculiar to the electron but does accommodate the relativistic behavior of energy and momentum in all its forms.[6] The adjusted Hamiltonian (2) allowed a more precise accounting of atomic spectra. Most famously, following the approach of Sommerfeld (1915, 1916) in the old quantum theory, the relativistic corrections introduced a precessional motion in the electron's elliptical orbit, eradicated a degeneracy in the energy levels of the Bohr atom, and allowed explanation of the fine structure of the hydrogen emission spectrum. Correspondingly, a relativistic Hamiltonian could be employed in Schrödinger's (1926) wave mechanics. One could recover results in gross agreement with the experimental hydrogen spectrum from a wave equation obtained by substituting the identifications $\mathbf{p} \rightarrow -i\hbar\nabla$ and $H \rightarrow i\hbar\partial/\partial t$ into (2), for an electron described by a wave equation $\psi(\mathbf{x}, t) = \psi(x)e^{-iEt/\hbar}$ in a coulomb potential, $\mathbf{A} = 0$, $\phi = e/4\pi r$ (i.e., an electron in a hydrogen atom). The Hamiltonian (2) fails, however, to account for the line splitting of the anomalous Zeeman effect. Uhlenbeck and Goudsmit (1925) accounted for this splitting by positing the internal spin of the electron. While the other shifts in electron theory responded to a deeper understanding of the theoretical context in which electrons were set, intrinsic spin was the first new property peculiar to the electron discovered since Thomson.

Third, spin could be accommodated to varying degrees of satisfaction by adding spin coupling terms to (2); but these terms are incomplete as long as they only reflect the two degrees of freedom associated with the angular momentum Hilbert space of a spin-1/2 particle. The simplest and fullest modification of (2) that accommodates spin was accomplished by Dirac (1928) using Dirac spinors with four degrees of freedom.[7] In modern notation (in units where $\hbar$ and c are set equal to 1 and with spacetime signature $(1, -1, -1, -1)$), the Dirac equation is

$$(i\gamma^{\mu}\partial_{\mu} - m)\psi(x) = 0 \text{ for } \mu = 0, 1, 2, 3, \tag{3}$$

and the Lagrangian density for which (3) is the Euler-Lagrange equation is

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}\,(i\gamma^{\mu}\partial_{\mu} - m)\psi. \tag{4}$$

Here ψ is a 4-component Dirac spinor, γ^{μ} are 4×4 anticommuting matrices, and $\bar{\psi} = \gamma^{0}\psi^{\dagger}$. The modification of (3) to account for classical electromagnetic interactions follows the prescription $\partial_{\mu} \rightarrow D_{\mu} \equiv \partial_{\mu} + ieA_{\mu}$ (in analogy with the classical case). In this modified form, the nonrelativistic limit of (3) yields the magnetic moment estimated by Uhlenbeck and Goudsmit due to internal spin as well as the fine-structure spectrum of hydrogen unaccounted for by Schrödinger. The new properties that (3) adds to the electron are spatiotemporal in nature. The electron of (3) is now characterized by a new type of spatiotemporal transformation property that the electron of (2) does not possess. The electron of (2) transforms under Poincaré transformations as a scalar; that of (3) as a 4-component spinor. The electron of (1), in contrast, transforms under Galilean transformations as a scalar.

Fourth, in Dirac's original (1928) theory, $\psi(x)$ is considered a wave function for a single-particle electron. To explain the negative-energy solutions allowed by (3), Dirac (1930) suggested that the vacuum state consists of a negative-energy electron sea. This introduces two conceptual changes into the description of the electron. First, the single-particle Dirac theory must now be considered a many-particle theory. Second, the creation and annihilation of electrons is now possible. The transition of a positive-energy electron to the state occupied by a hole in the sea appears as the annihilation of an electron-hole pair. If a negative-energy electron in the sea absorbs enough energy that its total energy becomes positive, it makes the transition to a positive-energy state, leaving behind a hole. This appears as the creation of an electron-hole pair.[8]

The quantized field interpretation of the electron was proposed by Jordan and Wigner (1928) and employed the Lagrangian (4) that had been introduced in the Dirac theory. Dirac (1927) had previously quantized the electromagnetic field by a process that became known as second quantization. He identified the coefficients of the Fourier expansion of the electromagnetic field as photon creation/annihilation operators obeying commutation relations. Jordan and Wigner interpreted solutions $\psi(x)$ to the Dirac equation as fields and then applied the second-quantization method of Dirac to the electron field. They thus introduced electron creation/annihilation operators, which, owing to Fermi-Dirac statistics, obey anticommutation relations. They did not consider an electron interacting with an electromagnetic field.[9]

The first fully consistent quantum field-theoretic account of the electron that incorporates electromagnetic interactions is quantum electrodynamics (QED). Formally, the move to QED does not require alteration of Dirac's Lagrangian (4) but the addition of new terms to it to accommodate interactions with the electromagnetic field. The electromagnetic field is given by a local abelian U(1) gauge field $A_\mu(x)$, which couples to the electron field $\psi(x)$ with a strength given by the electron charge e. There is a standard recipe for describing such gauge field interactions that amounts to adding two new terms to the Lagrangian density under consideration. To the Dirac Lagrangian density, we add a piece due to the electromagnetic field and an interaction piece:

$$\begin{aligned} \mathcal{L}_{\text{QED}} &= \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Maxwell}} + \mathcal{L}_{\text{int}} \\ &= \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - \frac{1}{4}(F_{\mu\upsilon})^2 - e\bar{\psi}\gamma^\mu A_\mu \psi \qquad (5) \\ &= \psi(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}(F_{\mu\upsilon})^2, \end{aligned}$$

where $F_{\mu\upsilon} = \partial_\mu A_\upsilon - \partial_\upsilon A_\mu$ is the electromagnetic field tensor.[10] QED corrects the Dirac theory in predicting the Lamb shift in the hydrogen spectrum and the anomalous magnetic moment of the electron. The gauge field recipe amounts to a new way, consistent with the properties of a Dirac electron, of embedding the electron in an electromagnetic field and thus maintaining electromagnetism in the list of interactions experienced by it.

Fifth, the electron is embedded into an electroweak field by means of a local symmetry-breaking mechanism. Again, there is a standard recipe for describing such interactions. Formally, the modification has the appearance of adding to the QED Lagrangian density an additional term describing the symmetry-breaking mechanism, although the implementation of the mechanism requires that the modification be a bit more subtle than this. With the addition of the weak force, although the structure of the electron itself remains basically unaltered, given by the Dirac Lagrangian, the gauge fields the electron couples to now have peculiar symmetries. A Lagrangian density is constructed in such a way as to (a) account for parity violations of the weak force, (b) account for the massive vector boson mediators of the weak force, and (c) preserve the massless nature of the photon field and produce the QED interaction term.[11] The Lagrangian density that accomplishes this contains four gauge fields (one abelian U(1) and three nonabelian SU(2)), a massless spin-1/2 fermion field representing the electron, and a scalar Higgs field. After symmetry breaking, the gauge fields combine linearly to form three massive gauge fields identified as the weak gauge fields (the two $W^\pm$ boson fields and the Z^0 boson field) and a massless gauge field identified as the photon field. The electron field acquires a mass and couples to the photon field via the required QED interaction term. Formally, the Electroweak Lagrangian density is given by

$$\mathscr{L}_{\text{Electroweak}} = \mathscr{L}_{\text{F}} + \mathscr{L}_{\text{G}} + \mathscr{L}_{\text{int}} + \mathscr{L}_{\text{S}}, \tag{6}$$

where $\mathscr{L}_{\text{F}}$ is the Lagrangian density for a massless spin-1/2 fermion field (having the same form as $\mathscr{L}_{\text{Dirac}}$ in (5) without the mass term), $\mathscr{L}_{\text{G}}$ is the Lagrangian density for an abelian U(1) gauge field and a nonabelian SU(2) gauge field (each having the same general form as $\mathscr{L}_{\text{Maxwell}}$ in (5)), $\mathscr{L}_{\text{int}}$ describes the interaction between the gauge fields and the fermion field (having the same general from as $\mathscr{L}_{\text{int}}$ in (5)), and $\mathscr{L}_{\text{S}}$ is the Lagrangian density for a scalar Higgs field that couples to the fermion field via a Yukawa-type interaction.[12]

Sixth, for the standard model, the Lagrangian density is again modified by adding new terms. In this case, the new terms are for a hadron (quark) sector of the Electroweak Lagrangian density and the three terms of (nonabelian SU(3)) quantum chromodynamics (QCD): one for fermion (quark) fields, one for the gluon gauge fields, and one for the quark/gluon interaction term:

$$\mathscr{L}_{\text{Standard Model}} = \mathscr{L}_{\text{Electroweak-lep}} + \mathscr{L}_{\text{Electroweak-had}} + \mathscr{L}_{\text{QCD}}, \tag{7}$$

where $\mathscr{L}_{\text{Electroweak-lep}}$ and $\mathscr{L}_{\text{Electroweak-had}}$ are of the form (6) and $\mathscr{L}_{\text{QCD}}$ is the Lagrangian density for a nonabelian SU(3) gauge theory (having primarily the same general form as $\mathscr{L}_{\text{QED}}$ in (5)).[13]

To summarize, in terms of properties, the third modification adds a new type of spacetime transformation property to the electron. It consistently describes the electron as a relativistic particle with the property of internal spin (Schrödinger had the relativistic part but not the spin part; Uhlenbeck and Goudsmit had the spin part but not the relativistic part). The fourth modification describes a new way, consistent with the third, of adding electromagnetism to the list of interactions experienced by the electron. In addition, the move from the third to the fourth constitutes a conceptual change in describing the electron, from a purely single-particle description to a field-theoretic/many-particle description.[14] This move adds interactions in which electrons are created and destroyed to the list. The fifth adds the weak force to this list. (It also indicates some of the properties the electron possesses at high energies; namely, at such energies, it decouples from the Higgs field and becomes a massless fermion field.) The sixth adds the property of membership in one of three generations of leptons that have a symmetrical relationship with three generations of quarks.[15]

Again, we emphasize that the development of the first through the sixth involves primarily a preservation and augmentation of structure as given by the Hamiltonian/Lagrangian of the electron. In much of the development the structure is preserved while changes are due to alteration in the theoretical context within which the structure is set: the transition from classical to relativistic space-times and from classical physics through the various forms of quantum theory. The augmentation involves addition: the novel property of spin and an expansion of the list of interactions sustained by the electron.

CONCLUSION

What, then, should philosophers of science learn from the parade of theories that is a century of the history of the electron? The mere fact that the century has seen a succession of different theories is not, by itself, grounds for pessimism or optimism. What would properly raise our suspicions is the opposite: a vigorous program of investigation into nature in which later researchers find no occasion to correct their predecessors. Our optimism or pessimism should rely on our examination of the details of the changes in electron theories. If these theories were to form a sequence of disconnected portraits, each merely answering to the transient expedients of the moment and each eradicating the content and successes of the earlier theories, then we could be excused for suspecting that we have just replaced one error with another as we pass from one theory to the next. But we do not have such a sequence. We have good reason to see our sequence of theories as correcting errors of former members while preserving their successes and providing richer and improved representations. We have shown that we can discern a growing core of historically stable properties of the electron in the sequence of theories and that this core is supported by a stable evidential base. Whatever we may now think of the details of Millikan's picture of the electron, for example, his experiments on the discreteness and magnitude of electron charge are reliable. Moreover, we have shown that this growing stock of properties can be integrated into a structure that, at each stage of theorizing, captures the essential properties of the electron then known and explains the successes of the earlier theories.

If we are licensed to fit any induction to the history of the electron, then it should not be the pessimistic induction. It should be an "optimistic induction": Physicists are fallible and their evidential base never complete, so that we cannot expect any theory to be error-free or final.[16] We have seen a sequence of theories each of which identifies and corrects errors of its predecessor while preserving a growing core of stable properties. Thus we should expect that errors remaining in our present theories will be identified and corrected by theories to come as we continue to improve our understanding of the electron.

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NOTES

1. Such is the received view. Muller (1997) has recently argued that Heisenberg, Jordan, and Dirac's 1925 matrix mechanics and Schrödinger's 1926 wave mechanics were not equivalent until the completion of von Neumann's 1932 work.

2. See Putnam (1978, 24–25) for the original statement. The current proponent of the argument is Laudan (1984, 1981). Some responses to Laudan are given in Kitcher (1993, 136) and Psillos (1996, 1994). For critiques of these positions, see Bain (manuscript).

3. They are, primarily, a principal quantum number n (energy), an orbital magnetic quantum number m (angular momentum in the z direction), a spin quantum number s, and a spin magnetic number m_s (spin in the z direction).

4. Norton (2000).

5. Bain (1998).

6. Hamiltonian (1) proceeds from the classical result that the kinetic energy of a particle of momentum p and mass m is $p^2/2m$, whereas (2) proceeds from the relativistic result that the particle's total energy is $[p^2c^2 + m^2c^4]^{1/2}$, where m is now the rest mass.

7. Dirac's original motivation in part was to find a first-order equation for which a positive definite probability density could be identified.

8. Dirac initially identified the holes as protons but later (in 1931) identified them as a new type of particle: positrons.

9. Nor did they address the problem of the interpretation of the negative energy solutions to the Dirac equation. This had to wait for the papers of Fock (1933) and Furry and Oppenheimer (1934). These authors continue the work of Jordan and Wigner, interpreting solutions to the Dirac equation as fields and quantizing these via the second quantization method. They introduce creation/annihilation operators for positron fields, however, in addition to those for electron fields. The resulting charge-symmetric field theory is then equivalent to Dirac's many-particle Hole theory, accounting for negative energy states without recourse to the negative-energy electron sea.

10. The general gauge field description of interactions (abelian and nonabelian cases) was given first in 1954 by Yang and Mills and became theoretically respectable after it was shown by 'tHooft in the early 1970s to be renormalizable. Nevertheless, the simple abelian case of QED was well established already in the papers of Tomonaga, Schwinger, Feynman, and Dyson in the 1940s.

11. Briefly, to address (a), the two charged weak gauge fields $W^{\pm}$ should couple only to the left-handed component or the right-handed component of the electron (these are already well-defined in Dirac's (1928) theory). The Electroweak theory assigns the left-

handed component to an SU(2) doublet (the other component of which is a left-handed electron-neutrino) and the right-handed component to an SU(2) singlet. To address (b), this SU(2) symmetry must be spontaneously broken via a Higgs scalar field (this is the only way to obtain massive gauge bosons in a Yang-Mills theory: in standard Yang-Mills theory, mass terms for the gauge fields would ruin the gauge invariance of the Lagrangian). Since SU(2) doublets and singlets cannot be coupled, there can be no mass term for the electron field in the initial Lagrangian. The Higgs field is thus coupled not only to the gauge fields, but also to the left- and right-handed massless components of the electron to produce an electron mass term after symmetry breaking. Finally, to address (c), a U(1) symmetry is introduced that does not get broken by the Higgs.

12. In particular,

$$\mathcal{L}_F = i\overline{\psi}_R\gamma^\mu\partial_\mu\psi_R + i\overline{\psi}_{\mathcal{L}}\gamma^\mu\partial_\mu\psi_{\mathcal{L}},$$

where ψ_R and $\psi_{\mathcal{L}}$ are the right- and left-handed components of the massless spin-1/2 fermion field;

$$\mathcal{L}_G = -\frac{1}{4}(\partial_\mu A^a_\upsilon - \partial_\upsilon A^a_\mu + gf^{abc}A^b_\mu A^c_\upsilon)^2 - \frac{1}{4}(\partial_\mu B_\upsilon - \partial_\upsilon B_\mu)^2,$$

where B_μ and A^a_μ ($a = 1, 2, 3$) are the U(1) and SU(2) gauge fields, g is the coupling constant associated with the gauge fields A^a_μ and f^{abc} are SU(2) structure constants;

$$\mathcal{L}_{int} = -g'\overline{\psi}_R\gamma^\mu B_\mu\psi_R - \overline{\psi}_{\mathcal{L}}\gamma^\mu\left(\frac{1}{2}g'B_\mu + \frac{1}{2}gA^a_\mu\sigma^a\right)\psi_{\mathcal{L}},$$

where g' is the coupling constant associated with the gauge field B_μ and σ^a are the Pauli matrices; and

$$\mathcal{L}_S = D_\mu\phi^\dagger D^\mu\phi - \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 - G_e(\overline{\psi}_{\mathcal{L}}\phi\psi_R + \overline{\psi}_R\phi^\dagger\psi_{\mathcal{L}}),$$

where ϕ is the scalar Higgs field with mass μ and self-coupling constant λ. $\mathcal{L}_S$ couples to the fermion field by means of a Yukawa-type interaction with coupling constant G_e. The derivative operator D_μ couples the gauge fields B_μ and A^α_μ to the Higgs field according to

$$D_\mu\phi = \left(\partial_\mu - \frac{i}{2}g'B_\mu \frac{i}{2}gA^a_\mu\sigma^a\right)\phi.$$

After symmetry breaking, the electron charge is recovered as $e = gg'(g^2 + g'^2)^{-1/2}$ and the electron mass is recovered as $m_e = G_e\mu(2\lambda)^{-1/2}$.

13. In particular,

$$\mathcal{L}_{QCD} = \overline{\psi}^a_i(i\gamma^\mu D_\mu - m)^{ab}\psi^b_i - \frac{1}{4}(\partial_\mu A^\alpha_\mu - \partial_\upsilon A^\alpha_\mu + gf^{\alpha\beta\gamma}A^\beta_\mu A^\alpha_\upsilon)^2.$$

Here the fermionic quark fields ψ^a_i are SU(3) triplets with $a, b = 1, 2, 3$ labeling the local SU(3) "color" symmetry. The index $i = 1, \ldots, 6$ labels the global "flavor" symmetry (up, down, strange charm, top, bottom). A^α_μ ($\alpha = 1, \ldots, 8$) are the SU(3) gluon gauge fields.

14. The sense in which the field-theoretic description in interacting QFT is "dual" to the particle description is a topic of some contention. If by duality is meant "to every field there corresponds a particle and vice versa," the duality thesis is simply incorrect. But demoting duality should not tempt us into fundamentalism of either the field or the particle kind.

15. This membership property is nontrivial insofar as the addition of hadron-electroweak couplings serves to cancel potential divergences arising from certain lepton-electroweak couplings (namely what are known as axial vector current anomalies).

16. In speaking of the fallibility of physicists and errors in their theory, we do not have in mind outright blunders. We refer to a more serious problem. While Lorentz developed a most reasonable classical model for the electron as a charged sphere, it was, by later lights, erroneous, since it failed to accommodate quantum properties. The error occurred because physics is an enterprise that makes inductions from experience; physicists must therefore routinely take inductive risks. Lorentz's is one that did not work out. We are arguing, in effect, that the continuing growth of historically stable properties is evidence that such risks are not always in vain.

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