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> *"There is one thing I would be glad to ask you. When a mathematician engaged in investigating physical actions and results has arrived at his conclusions, may they not be expressed in common language as fully, clearly, and definitely as in mathematical formulae? If so, would it not be a great boon to such as I to express them so?—translating them out of their hieroglyphics, that we might also work upon them by experiment."*

From a letter of Faraday to Maxwell, 1857, quoted by Sir Lawrence Bragg, *Nature* **169**, 684 (1952).

QUANTUM

By ***F. J. Dyson***

HISTORICAL PARALLELS are never exact. Each development in science is something new and different from any which preceded it. Still it may be illuminating to discuss the progress that has recently been made in quantum electrodynamics, using the historical development of classical electrodynamics as a standard of comparison. So may we see our present knowledge and our present difficulties in their proper perspective. If Faraday's appeal quoted above had been more effectively answered in his day, might not electromagnetic waves have been discovered less than thirty years later? We cannot answer such a hypothetical question. But every theoretical physicist who reads Faraday's words will be uncomfortably aware that similar appeals are still being made and are still not being answered. This article attempts to express in simple words the results of our recent thinking in quantum electrodynamics, not fully, but clearly and definitely so far as that is possible.

First the meaning and scope of quantum electrodynamics must be defined. In our present state of ignorance we find it necessary to separate our ideas about the physical world into three compartments. In the first compartment we put our knowledge of nuclear structure, protons, neutrons, mesons, neutrinos, and the interactions of these particles with one another. In the second compartment we put theories of the large-scale structure and geometry of the universe, including Einstein's general theory of gravitation. In the third compartment we put our knowledge of all other phenomena, everything intermediate in scale between an atomic nucleus and a massive star. The third compartment includes the whole of classical mechanics, optics and electrodynamics, special relativity and extra-nuclear atomic physics. The convenience of these compartments is that they enable us to isolate the areas of our ignorance. The first two compartments are full of undigested experimental information, empirical rules, and mutually contradictory assumptions. These fields are only beginning to be explored and organized. On the other hand, the third compartment is unified by a logically consistent theory. We possess a set of mathematical equations which agree quantitatively, so far as is known, with all the wealth of accurate experimental data in this field. The equations consist of laws of motion for electrons, positrons, photons, and electromagnetic fields, incorporating the principles of quantum mechanics and of special relativity. This theory of the third compartment is what we mean by quantum electrodynamics.

QUANTUM ELECTRODYNAMICS occupies a unique position in contemporary physics. It is the only part of our science which has been completely reduced to a set of precise equations. It is the only field in which we can choose a hypothetical experiment and predict the result to five places of decimals, confident that the theory takes into account all the factors that are involved. Quantum electrodynamics gives us a complete description of what an electron does; therefore in a certain sense it gives us an understanding of what an electron is. It is only in quantum electrodynamics that our knowledge is so exact that we can feel we have some grasp of the nature of an elementary particle. That is the reason why theoretical physicists for the last thirty years have concen-

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trated their efforts so persistently on the electron. We must expect that the concepts, to which we have been led in our study of the electron, will later find their natural place in a more extended theory of elementary particles. Without these concepts and their mathematical expression in quantum electrodynamics, speculations concerning the nature of elementary particles would be mere guess-work.

The basic equations of quantum electrodynamics were formulated by Heisenberg, Pauli, and Dirac during the period from 1927 to 1929. Historically, they were the Maxwells of the new science. Just as Maxwell's equations in the thirty years after their discovery were triumphantly verified in experiment after experiment, so the equations of Heisenberg-Pauli-Dirac were tested during the 1930s and were found to give a correct account of all phenomena at that time accessible to exact measurement. In particular, all the complicated details of atomic spectra, and also the spectacular process of cascade multiplication of electrons and positrons observed in high-energy cosmic-ray showers, were shown to be in agreement with the theory.

Without stretching our analogies unduly, the historical parallelism between the development of classical and quantum electrodynamics can be pushed a great deal further, so as to include the events of the present day. After its initial successes, the Maxwell theory was found to have a perplexing feature. It predicted that the results of experiments should depend on the absolute velocity of the measuring instruments through space, the space being filled with an ether which provided an absolute frame of reference. It was one of the central features of Newtonian mechanics, on which Newton himself laid much stress, that no such observable effects of absolute velocities could exist. Thus the Maxwell theory, while not inconsistent with Newtonian mechanics, implied the abandonment of one of Newton's most cherished principles. Fortunately for Maxwell, the predicted effects of absolute velocity on measurable quantities were always of the order of the square of the ratio of the velocity to the velocity of light, and therefore too small to be detectable during his lifetime. So long as this was the case, it was possible to hold either of two opinions concerning these effects; either the effects would in time be discovered and the Newtonian principle would be disproved, or the effects would be shown to be absent and Maxwell's theory would have to be modified. Meanwhile, until the decision became experimentally possible, physicists could continue happily to believe in both Maxwell's and Newton's principles.

A STRANGELY SIMILAR evolution of ideas took place in quantum electrodynamics in the 1930s. It was early realized that the electromagnetic field around an electron carried with it energy, and that this energy possessed mass and inertia by virtue of Einstein's law of equivalence of mass and energy. The motion of an electron should thus be affected by some kind of dragging force resulting from the inertia of its own field. The effect of such a force[1] on the electron's motion

1. Strictly speaking, a reaction force is produced both by the field which the electron radiates away into space and by the field which the electron carries around and does not radiate. We use the words "field reaction" here to mean only the second of these two forces.

was called the "field reaction." As the theory was developed, two things gradually became clear. On the one hand, if calculations were made consistently ignoring the field reaction wherever it appeared, the results agreed perfectly with the experiments. On the other hand, when calculations including the field reaction were attempted, the results were always meaningless; the inertia of the electron's self-field turned out to be infinite and therefore the electron was predicted to behave like a particle of infinite mass. The physicists of that period were simply baffled by the situation. They had a theory which by every experimental test was shown to be correct. Yet its success depended on excluding from consideration the field reaction force, and excluding this force came close to denying the validity of Newton's law of the equality of action and reaction. If the electron can set up stresses in the electromagnetic field around it, how can these stresses be prevented from reacting back upon the motion of the electron?

Physicists were agreed upon one point. The experiments showed that the field reaction, if it existed, was too small to be detected by the techniques of that period. Trying to understand this fact, physicists split into two main opinions. One group held that the basic equations of the theory were correct, and that only the method of making calculations needed to be changed, so that the infinite reaction forces would be automatically omitted. The other group held that the basic equations of the theory should be modified in various ways so as to make the reaction forces finite. According to the first group the measured reaction force should be strictly zero; according to the second group it should be not zero but small. Neither group succeeded in making their arguments convincing; neither group had any physical model by which to justify their recommended procedures. Lacking an experimental test of these hypotheses, the majority of physicists continued to believe both in the general correctness of quantum electrodynamics and in the law of action and reaction. This unsatisfactory state of affairs persisted until the summer of 1947.

Both for the Maxwell theory and for quantum electrodynamics, the choice between contradictory alternatives was finally forced on theoretical physicists by a decisive experiment. The Michelson–Morley experiment of 1887 showed that Maxwell's predicted effects of the absolute velocity of measuring apparatus on the results of observations were nonexistent. The Lamb–Retherford experiment of 1947, a precise measurement of the fine-structure of the atomic hydrogen spectrum using the new technique of radio-frequency spectroscopy, showed that the field reaction force on an electron existed and produced a finite measurable displacement of the spectral lines. The physicists of the 1890s were thus faced with the necessity of reformulating the Maxwell theory, and those of the 1940s with the problem of reformulating quantum electrodynamics. In both cases, it was the experimental knowledge of what the results of the new theory ought to be which stimulated the efforts of the theorists and made a successful outcome possible.

It was Lorentz who created the new classical electrodynamics. The new theory was in fact not a departure from the Maxwell theory. It was a reinterpretation of the Maxwell theory, taking into account the fact that the electrical and mechanical properties of measuring instruments are not experimentally separable. In particular, the length of a solid object such as a measuring rod is determined by electrical forces between its constituent atoms, and other mechanical properties are in a similar way mixed up with electromagnetic effects. Lorentz observed that in any experiment in which the electrical effects of absolute motion through the ether should be detectable, there would also be effects of the same order of magnitude arising from effects of the motion on the mechanical properties of the apparatus. These mechanical effects would have to be included in any complete theory of the Michelson–Morley experiment. In particular, the effect of an "ether-wind" blowing lengthwise through the atoms of a measuring rod would be to diminish the length of the rod by a definite factor depending on the velocity. This special effect is called the "FitzGerald contraction" in honor of the man who first suggested it in 1893. Lorentz found that when all these effects of absolute velocity, electrical and mechanical, were taken correctly into account, they cancelled each other out exactly. The result of any measurement in any possible experiment would be independent of the absolute velocity, in agreement with the experience of Michelson and Morley. By reinterpreting the Maxwell theory in this way, Lorentz preserved the Newtonian principle of the unobservability of absolute velocities. This principle appeared in his theory as something of a miracle; the theory started with a real ether having a definite velocity relative to the measuring instruments; only at the end after long calculations it turned out that the ether velocity had no effect on the instruments' readings. Lorentz however was satisfied with his theory. It was ingenious and it gave the right answers to practical questions. What more could one want?

APPROPRIATELY the new quantum electrodynamics of 1947 originated with an idea proposed by Kramers, whose recent death is such a heavy loss to physics, and who happened to be the successor of Lorentz at Leiden. The mathematical formalism was later developed by Schwinger, Bethe, Tomonaga, and others. Kramers' idea was a simple one, and similar to that of Lorentz fifty years earlier. Kramers observed that the problematical inertial force on an electron due to the field reaction could under no circumstances be experimentally separated from the effects of the electron's ordinary mechanical inertia. The only observable inertia is the total inertia, the sum of the mechanical and the electrical effects. The physicists of the 1930s made the mistake of confusing the unobservable mechanical mass of an electron (let us call it m_0) with the observed mass of a free electron (let us call it m). For example, they calculated the field reaction inertia of an electron bound in a hydrogen atom, finding the result which we will call δm, an infinite quantity. They concluded that the total inertia of the bound electron should be ($m + \delta m$), which is infinite since m is finite. This would be an infinite value for an observable quantity and would necessarily imply that the theory is wrong. However, as Kramers pointed out, the total inertia of the bound electron is not ($m + \delta m$) but

$$m_0 + \delta m = m + \delta m - (m - m_0).$$

The quantity ($m - m_0$) is by definition just the field inertia or the δm calculated for a free electron. For the observable total inertia to be finite, it is not necessary for δm to be finite. It is only necessary that the difference between the δm calculated for the bound electron and for a free electron be finite. Kramers suggested, and Schwinger afterwards verified, that this difference is in fact finite. This difference then represents the difference between the total inertia of a bound and a free electron, which is the quantity which is directly measured in the Lamb–Retherford experiment. After long and delicate calculations, it has recently been shown that the theoretical and experimental values of the difference agree to a phenomenally high degree of accuracy (at present about one part in a thousand, in an effect which was ten years ago beyond the limit of detection!).

The new quantum electrodynamics is, like the Lorentz electrodynamics, only a reinterpretation and not a departure from the older theory. It differs from the old theory only in this, that we now take consistently into account the effects of field reaction not only on the measured quantities but also on the standard mass m with which the measured quantities are compared. We can prove quite generally that when observable quantities are calculated and the results expressed in terms of the mass m instead of the unobservable m_0, the infinite expressions always cancel out and the results are finite. Further, the finite results have always turned out to agree with the experiments. A similar argument is also applied to the electronic charge. The measured charge on an electron, which we call e, is different from the quantity e_0 which appears in the starting equations of the theory, as a result of field reactions. If e is calculated in terms of e_0, the result involves infinities. But e_0 is an unobservable quantity, and measured quantities when expressed in terms of e are always finite. Therefore we have in the end a completely precise and workable theory. The starting equations contain the quantities m_0 and e_0 which are unobservable. When we make calculations of observable effects, we obtain expressions involving m_0 and e_0 together with infinite quantities, divergent integrals, and so forth. We have not to be afraid of the infinite quantities. We treat them as if they were ordinary numbers, and then at the end of the calculation, when everything is expressed in terms of the observed mass m and charge e, all the infinities drop out and the result is finite.

We are proud of our new quantum electrodynamics. Like the Lorentz theory, it is a triumph of ingenuity, and it succeeds in reconciling all the contradictions of the older theory without abandoning anything of value. It also shares with the Lorentz theory one other most striking feature. Namely, the whole success of the theory is based on an unexplained miracle. In the starting equations of the Lorentz theory there is a stationary ether. In quantum electrodynamics the starting equations involve the unobservable and mathematically meaningless symbols e_0 and m_0. In both cases there is a complicated mathematical cancellation, so that in calculations of observable quantities the final results are independent of either the ether velocity or of the meaningless symbols. Why these miraculous cancellations occur, the theories do not explain.

WE HAVE NOW brought our historical parallel down to the present moment. Can we extend it further still? The subsequent history of the Lorentz theory at least is well known. After Lorentz had worked for many years creating and perfecting his theory, Einstein appeared with the explanation of the miracle. He showed that all the consequences of the Lorentz theory could be deduced from a much simpler theory involving a new physical principle, the principle of special relativity. In the new theory there was no ether, no absolute velocities. Thus the absence of experimental effects of absolute velocities was assured from the beginning. The impossibility of detecting absolute motion in space was for Einstein the starting point, and everything else was derived from it. Einstein's theory did not substantially depart from the Lorentz theory in its predictions. Einstein simply turned the Lorentz theory upside down, so that the endpoint became the starting point and vice versa. After this inversion, all the satisfactory features of the Lorentz theory remained, and only the unobservable complications, the ether and the absolute velocities, vanished. Einstein's formulation of classical electrodynamics is so simple and complete that it still stands substantially as it did in 1905.

Can we hope for a similar revolution in quantum electrodynamics? It is my firm belief that we can. What we require is again to turn the theory upside down, so that its consequences remain unchanged while its principles are clarified. We need to find a way of starting the theory, so that the unobservable quantities e_0 and m_0 do not appear at all in the equations. That is, we need to describe an electron from the beginning, not as a mechanical particle plus an electromagnetic field, but as a unified whole. The new description should be based on a physical principle, similar to the principle of relativity, expressing just the impossibility of making an experimental separation of an electron into its mechanical and electrical parts. Only when we have such a description shall we understand the real reasons for the success of our present theory. To me it seems that this argument leads to a positive conclusion, that the unexplained success of the present theory is in itself a guarantee that a new and simpler description is waiting to be discovered. How long shall we have to wait for the discovery? This no one can guess. We must only be patient, and remember that the time scale of fundamental understanding is always slow. From Maxwell to Einstein was forty years, from Dirac to the present only twenty-five. PT