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H. A. Lorentz and the Electromagnetic View of Nature

*By Russell McCormmach**

> It is a kind of new America where one breathes easily, which stirs all one's energies, which can instruct the Old World in many things.
> —PAUL LANGEVIN, IN 1904, ON THE PROMISE OF THE ELECTRON THEORY.[1]

AN ELECTROMAGNETIC VIEW OF NATURE was announced at the beginning of the twentieth century. It drew influential followers from among younger physicists, those in Germany especially, and for a time it was widely regarded as the most promising projection of the future of physical theory. It was advocated as a replacement for the mechanical view of nature that had ably guided physical research for more than two centuries. The mechanical view asserted that the ultimate constituents of physical reality are discrete or, sometimes, continuous inertial masses, and that they move according to the laws of mechanics under the influence of distance or contact forces. The electromagnetic view of nature asserted that the only physical realities are the electromagnetic ether and electric particles and that all laws of nature are reducible to properties of the ether, properties which are defined by the electromagnetic field equations. The simplest version of the electromagnetic view held that electric particles are merely structures in the ether and that therefore the ether is the sole reality.

The Lorentz electron theory together with the empirical confirmation of the electron and the evolution of techniques for directly testing electron dynamics led to the anticipation of a purely electromagnetic understanding of physical reality. The electromagnetic view expressed a programmatic intent in physics: it called for a concentration of effort on problems whose solution promised to secure a universal physics based solely on electromagnetic laws and concepts. The feasibility of the program depended critically on the successful reduction of mechanical concepts and laws to electromagnetic analogues. Problems concerning the stability and deformability of the electron and its dynamic relation to the electromagnetic field acquired an enhanced importance and priority by being intimately related to the larger reduction problem.

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[1] Paul Langevin's report to the 1904 St. Louis congress, "La physique des électrons," *Revue générales des sciences*, 1905, *16*:257–276; quotation on p. 257.

In this essay I have analyzed Lorentz's successive formulations of the electron theory, tracing the consolidation of a new dynamics through the solution of specific problems connected with the earth's absolute motion. I have shown how others responded to the problem areas Lorentz's theory made central to physics and how they modified the theory to exclude all nonelectromagnetic elements and then extrapolated it into a vision of the future universal physics. I have shown how others, responding to the same problems, laid the foundations of the quantum and relativity theories, new theoretical programs that made the electromagnetic view of nature as peripheral as the mechanical one it had supplanted. Finally, I have indicated how the objective of the original electromagnetic view was transmuted into a broader field-theoretical ideal for all of physics.

I. INTRODUCTION OF LORENTZ'S ELECTRON THEORY

Lorentz's electron theory was part of a widespread response to Maxwell's theory following Heinrich Hertz's empirical proof of electromagnetic waves in the late 1880s. The intense interest in Maxwell's theory together with the common assent to molecular foundations stimulated several electrodynamics workers to seek a synthesizing theory of particle and field. Their search connected with a long tradition extending from O. F. Mossotti and Michael Faraday through Wilhelm Weber and J. C. F. Zöllner, basing universalist expectations on electrical understanding.

In Germany the electromagnetic view of nature was adumbrated by Emil Wiechert in 1894.[2] He suggested that the electromagnetic ether might be the only reality, that electric particles might be excitations in the ether, and that all matter might be built up from aggregates of electric particles. He raised the enticing prospect that the most characteristic property of matter—its mass—might be explained as an apparent electromagnetic mass arising from self-reaction. From 1896 on,[3] and independently of Lorentz, he began developing an electron theory. He based it on a stationary ether, and his theory generally bore large areas of resemblance to Lorentz's, a fact that Wiechert soon acknowledged.[4]

Beginning in 1893 Joseph Larmor,[5] in England, developed a comprehensive electron theory based on a stationary ether and entailing an entire view of nature. He regarded matter as composed solely of positive and negative particles, which in turn were centers of rotational strain in the ether. Although his ether was not an ordinary body, its only defining properties—inertia and elasticity—were mechanical. He was drawn to his conception of the ether by the recent elastic gyrostatic ether model of William Thomson, the leading British exponent of the mechanical worldview. Oliver Lodge, J. J. Thomson, and other British physicists of the post-Maxwell generation confidently spoke of the ether as the ultimate physical reality. Lines of force, electric particles, molecules, and in general all physical concepts were thought to be reducible in principle to vortices and strains in the ether. The British usually did not hold an

[2] E. Wiechert, "Bedeutung des Weltäthers," *Physikalisch-ökonomische Gesellschaft zu Königsberg*, 1894, *35*:4–11.

[3] E. Wiechert, "Über die Grundlagen der Elektrodynamik," *Annalen der Physik*, 1896, *59*:283–323.

[4] E. Wiechert, "Hypothesen für eine Theorie der elektrischen und magnetischen Erscheinungen," *Nachrichten von der Königl. Gesellschaft der Wissenschaften zu Göttingen*, 1898, pp. 87–106.

[5] J. Larmor, "A Dynamical Theory of the Electric and Luminiferous Medium," *Philosophical Transactions of the Royal Society*, 1894, *185*:719–822; 1895, *186*:695–743; 1897, *190*: 205–300.

electromagnetic view of nature in the European sense. They endowed the ether with the mechanical concept of mass conceived of as an elementary property rather than deriving it as a secondary phenomenon from a totally nonmechanical, electromagnetic ether. Their intention in this regard differed fundamentally from that of their European colleagues, who wished to eliminate all mechanical concepts and laws in favor of electromagnetic ones.

Writing in 1888[6] Henri Poincaré identified the fundamental idea of Maxwell's theory as the proof of the possibility, in general, of a mechanical representation of electromagnetic processes. There was much effort in Europe, as in Britain, following Hertz's experiments to expose and develop Maxwell's theory through particular mechanical representations. In 1892, the year Lorentz first published on the electron theory, Ludwig Boltzmann,[7] Arnold Sommerfeld,[8] and Georg Helm[9] developed mechanical representations of the ether, as did R. Reiff, W. Voigt, L. Graetz, and others in the years immediately following. At the same time a reaction was beginning to set in against the use of mechanical hypotheses and analogies. The view was gaining that the present object of electromagnetic theory should not be to penetrate the mechanism, but to find the simplest equations for describing the phenomena. The formulation of Maxwell's theory by E. Cohn[10] in 1890 reflected this attitude. An extreme contemporary reaction against mechanical reasoning in electrodynamics was represented by Pierre Duhem's thermodynamic treatment of electricity and magnetism in 1892.[11]

Lorentz's approach to theory construction in electrodynamics did not derive from any of these routes, not from mechanical analogy, nor from phenomenology, nor from thermodynamics. His unique approach was conditioned by insights accumulated over a considerable time. In his thesis in 1875 Lorentz applied Maxwell's electromagnetic theory to the problem of the reflection and refraction of light.[12] He approached the subject through Hermann von Helmholtz's more general, action-at-a-distance equations rather than Maxwell's contiguous-action ones. At the end of his thesis[13] he detailed the enormously fruitful consequences he anticipated from the introduction of material molecules into electromagnetic theory. Maxwell's original unification of light and electromagnetism was only the start; from the pervasive presence of electricity in nature, he argued, the union of electromagnetic theory and molecular theory promised to go far toward completing a synthesis of all branches of physical science. By 1878 Lorentz had arrived at an understanding close to that upon which his later electron theory was founded: charged harmonic oscillators exist

[6] H. Poincaré, *Électricité et optique* (Paris: Gauthier-Villars, 1954), p. viii.

[7] L. Boltzmann, "Über ein Medium, dessen mechanische Eigenschaften auf die von Maxwell für den Electromagnetismus aufgestellten Gleichungen führen," *Ann. Phys.*, 1893, *48*:78–99.

[8] A. Sommerfeld, "Mechanische Darstellung der electromagnetischen Erscheinungen in ruhenden Körpern," *Ann. Phys.*, 1892, *46*:139–151.

[9] G. Helm, "Die Fortpflanzung der Energie durch den Aether," *Ann. Phys.*, 1892, *47*:743–751.

[10] E. Cohn, "Zur Systematik der Electricitätslehre," *Ann. Phys.*, 1890, *40*:625–639.

[11] P. Duhem, *Leçons sur l'électricité et le magnétisme* (Paris: Gauthier-Villars, 1892), Vol. III.

[12] H. A. Lorentz, "Sur la théorie de la réflexion et de la réfraction de la lumière" (1875), in *Collected Papers*, Vol. I, pp. 193–383.

[13] *Ibid.*, pp. 382–383.

within ponderable molecules, and the ether in intermolecular spaces retains the same properties as it has in a vacuum.[14]

Through the 1880s Lorentz continued to be concerned with molecular physics, but chiefly in the context of the mechanical theory of heat. Prompted by Hertz's critique of Maxwell's theory as applied to bodies in motion,[15] Lorentz returned to the foundations of electrodynamics in the early 1890s. He had convinced himself of two things since the time of his thesis. In 1886, in an investigation of the aberration of light—the seasonal shift in the positions of stars due to the earth's orbital motion—he concluded that Augustin Fresnel's stationary ether was superior to G. G. Stokes' dragged ether.[16] His second conclusion, first announced in a popular address in 1891,[17] was that Maxwell's contiguous action was preferable to action at a distance. In the following year, 1892, he published his first statement of the electron theory.[18]

For Lorentz the most important idea in Maxwell's theory was that electromagnetic actions propagate through the ether at the speed of light. He believed that what was wrong with the German theories was their adherence to instantaneous action at a distance. He thought that they were perfectly correct in their molecular conception of electricity and needed only to be revised to incorporate the field concept and the electrical nature of light. In his view electrodynamics should return to the theories of Weber and Rudolf Clausius, while at the same time retaining the core of Maxwell's theory—the finite propagation of electrical action. The major problem, then, was to show that the contiguous-action forces required by Maxwell's theory could be reconciled with the

[14] H. A. Lorentz, "Concerning the Relation between the Velocity of Propagation of Light and the Density and Composition of Media," *Verhandelingen der Koninklijke Akademie van Wetenschappen Amsterdam*, 1878, *18*:1; *Collected Papers*, Vol. II, pp. 1–119.

[15] H. Hertz, "On the Fundamental Equations of Electrodynamics for Bodies in Motion" (1890), in H. Hertz, *Electric Waves*, trans. D. E. Jones (New York: Macmillan, 1893), pp. 241–268.

[16] H. A. Lorentz, "De l'influence du mouvement de la terre sur les phénomènes lumineux," *Verslagen. Koninklijke Akademie van Wetenschappen Amsterdam*, 1886, *2*:297; *Collected Papers*, Vol. IV, pp. 153–214.

[17] H. A. Lorentz, "Electriciteit en Ether," *Nederlandsche Natuur- en Geneeskundig Congress, 4 April 1891. Verhandel*, 1891, *3*:40; *Collected Papers*, Vol. IX, pp. 89–101.

[18] H. A. Lorentz, "La théorie électromagnétique de Maxwell et son application aux corps mouvants," *Archives néerlandaises des Sciences exactes et naturelles*, 1892, *25*:363; *Collected Papers*, Vol. II, pp. 164–343.

There have been several historical studies of Lorentz's electron theory. The most penetrating is T. Hirosige, "Origins of Lorentz' Theory of Electrons and the Concept of the Electromagnetic Field," *Historical Studies in the Physical Sciences*, 1969, *1*:151–209. Other relevant writings by the same author are "A Consideration Concerning the Origins of the Theory of Relativity," *Japanese Studies in the History of Science*, 1965, No. 4:117–123; "Electrodynamics Before the Theory of Relativity, 1890–1905," *Jap. Stud. Hist. Sci.*, 1966, No. 5:1–49; "Theory of Relativity and the Ether," *Jap. Stud. Hist. Sci.*, 1968, No. 7:37–53. The last two references contain a discussion of the electromagnetic view of nature. Further useful writings on the Lorentz theory are A. D. Fokker, "The Scientific Work," in *H. A. Lorentz. Impressions of His Life and Work*, ed. G. L. de Haas-Lorentz (Amsterdam: North-Holland, 1957), pp. 48–66; P. Ehrenfest, "Professor H. A. Lorentz as Researcher 1853—July 18—1923," in *Paul Ehrenfest: Collected Scientific Papers*, ed. M. J. Klein (Amsterdam: North-Holland, 1959), pp. 471–477; A. Einstein, "H. A. Lorentz, His Creative Genius and His Personality," in *H. A. Lorentz. Impressions*, pp. 5–9; E. Whittaker, "Classical Theory in the Age of Lorentz," in his *A History of the Theories of Aether and Electricity, 1: The Classical Theories* (New York: Harper, 1960), pp. 386–428; R. Dugas, *A History of Mechanics*, trans. J. R. Maddox (New York: Central Book, 1955), pp. 466–472; G. Holton "On the Origins of the Special Theory of Relativity," *American Journal of Physics*, 1960, *28*: 627–636; K. F. Schaffner, "The Lorentz Electron Theory and Relativity," *Am. J. Phys.*, 1969, *37*:498–513; R. McCormmach, "Einstein, Lorentz, and the Electron Theory," *Hist. Stud. Phys. Sci.*, 1970, *2*.

older atomistic conception of electricity. Beginning with a stationary ether he re-introduced, in a manner consistent with contiguous forces, a modified version of those atomistic electric fluids which Hertz thought must be banished at the same time that distance forces were.

Lorentz, in his publication of 1892, regarded it as equally important to establish electrodynamic laws on mechanical foundations as to promote a certain view of the ether and electricity. His opening sentence refers to one of the "most beautiful chapters" of the *Treatise* where Maxwell elucidates electrodynamics on mechanical principles without having to penetrate the secret of the mechanism. Conceding that there were advantages in beginning with the equations as succinct descriptions of the facts, Lorentz recalled that "one has always tried to return to mechanical explanations."[19] There was in this regard an essential difference between Maxwell and Hertz. Hertz had postulated Maxwell's equations without relating them to mechanical principles, and Lorentz objected to this way of beginning. It happened that the first volume of Boltzmann's lectures on Maxwell's theory had come into Lorentz's hands in time for him to mention it in a note. Lorentz observed that he had been motivated by the same fundamental idea as Boltzmann, which was to continue the mechanical explanation begun by Maxwell.[20]

While Lorentz's 1892 theory had deliberate elements of mechanical construction, it was by no means a purely mechanical theory. His electrical charge and electromagnetic ether were both avowedly nonmechanical entities. He did not probe deeper into the possible nature of these ultimate electromagnetic constituents, an attitude that was rooted in his understanding of the character of physical theories.[21] The object of all research, he believed, was to find simple basic principles from which the phenomena can be deduced mathematically. The charges and the ether of his theory were basic principles, and he did not liken them to anything else. Maxwell, by contrast, spared no effort to avoid admitting into his theory nonmechanical representations of electric charge and the ether. Lorentz disliked the practice of placing undue importance on the visualization of first principles. The principles were the starting point of physical and mathematical thought, and he tended to feel it was vain to hope they could be further explained.

Lorentz introduced his 1892 theory by laying down six hypotheses sufficient for a mechanical derivation of the field equations. The first hypothesis is that charged particles have inertial mass and weight. The charged particles are in part mechanical bodies to which the laws of motion apply; the charges attached to these bodies remain, however, unexplained. All ordinary matter contains these particles—small, spherical, carrying both positive and negative signs. The nature of electricity was once again clearly drawn, one of Lorentz's essential clarifications of Maxwell's theory.

Lorentz explained that ether exists in the space occupied by a charged particle or by an uncharged molecule. The space can contain a dielectric displacement and

[19] Lorentz, "La théorie électromagnétique de Maxwell," p. 168.

[20] *Ibid.* Ludwig Boltzmann exploited Maxwell's concept of mechanical analogy throughout his *Vorlesungen über Maxwells Theorie der Elektricität und des Lichtes. 1. Ableitung der Grundgleichungen für Ruhende, Homogene, Isotrope Körper* (Leipzig: Teubner, 1891). The second volume was published in 1893; its chief purpose was to show the place of the older ideas of Weber, Neumann, Helmholtz, and others in Maxwell's theory.

[21] H. A. Lorentz, "Molecular Theories in Physics" (1878), *Collected Papers*, Vol. IX, pp. 26–49.

magnetic force produced by an exterior cause, just as though the charged particle or molecule were not there. The ether and electric charges alone interact; the sole connection of the ether with matter occurs through the charged particles contained in ponderable molecules. Lorentz offered no detailed picture of the interaction; it was another first principle of the theory and was without deeper explanation. As the properties of the ether are in no way changed by its coextension with electricity or ordinary matter, only two quantities, one electric and one magnetic, are required to characterize the state of the ether. This is so whether matter is present or not, confuting Hertz's grounds for rejecting a stationary ether. Since there is no mechanical linkage or exclusion, ordinary bodies move through the ether without setting it in motion. The ether is not motionless, however; it has internal motions, since it is a dynamical substance, even though it is not analogous in its properties to the mechanical bodies of ordinary experience.

There was little Lorentz cared to say about the local electromagnetic motions beyond specifying their equations and their total independence from the motion of uncharged matter. He anticipated that readers might find his theory colorless and unsatisfying, since it did not unveil the mechanism of the phenomena. It revealed the relation of the electromagnetic motions to the laws of mechanics, which at best left open the hope that the mechanism might one day be uncovered. Lorentz himself did not search for it and in general remained apart from preoccupations with the constitution of the ether and its hidden mechanisms.

The second hypothesis of Lorentz's theory identifies the potential energy of an electromagnetic system with its electric energy, which is, in electromagnetic units, $2\pi\int(f^2+g^2+h^2)\,d\tau$, where f, g, h is the dielectric displacement at each point of the ether. The dielectric displacement satisfies $(\partial f/\partial x)+(\partial g/\partial y)+(\partial h/\partial z)=0$ outside the space of a charged particle, and

$$\frac{\partial f}{\partial x}+\frac{\partial g}{\partial y}+\frac{\partial h}{\partial z}=\rho \tag{1}$$

inside, where ρ is the density of electric charge. The third hypothesis states that charged particles behave like rigid bodies; moreover, each point of a particle preserves the same value of ρ, whatever its motion. The fourth defines the total electric current u, v, w as $u=\rho\xi+(\partial f/\partial t)$, $v=\rho\eta+(\partial g/\partial t)$, $w=\rho\zeta+(\partial h/\partial t)$, where ξ, η, ζ is the velocity of a given point of a charged particle. This hypothesis, together with the first and second, provided Lorentz with a material unification of electrical science: the material contribution to the displacement current in a dielectric is an infinitesimal translation of electric particles; a current in a conductor is a real migration of particles; and a static charge is a preponderance in a body of particles of one or another sign. From this and the previous hypothesis Lorentz deduced that electricity behaves like an incompressible fluid—the distinguishing mark of Maxwell's electromagnetic theory. That Lorentz should derive this characteristic not in Maxwell's way,[22] but from the mechanical properties of charged particles points up the fundamental way in which molecular conceptions enter his theory. He followed the suggestion he made in

[22] Lorentz could easily have derived this property in Maxwell's way had he chosen to. From the next—the fifth—hypothesis, in which the total current is equated to the curl of the magnetic force, the incompressible-fluid character of electricity follows analytically (div curl $\mathbf{H}=0$, from which div $\mathbf{j}=0$, where $\mathbf{H}$ is the magnetic force and $\mathbf{j}$ is the current).

his thesis that once the correct equations for the motion of electricity were settled, they should be deduced directly from molecular considerations.[23]

Lorentz derived the incompressible character of electricity as follows: a charged particle when viewed as a rigid body is capable only of translation and rotation, a characteristic expressed analytically by the vanishing of the divergence of the velocity ξ, η, ζ. And the constancy of ρ at every point of the moving particle is equivalent to the vanishing of its convective derivative. From these two facts it follows that $(\partial u/\partial x) + (\partial v/\partial y) + (\partial w/\partial z) = 0$, which means that electricity behaves like an incompressible substance, or, equivalently, that all currents are closed. Lorentz's mechanical assumptions went somewhat beyond those commonly made in Continental electrodynamics, but not much beyond. Weber[24] had endowed the electric atoms of his theory with inertia and had pointed out that it was essential to imagine them as occupying a finite volume; under electric, as under gravitational, laws, pairs of point-particles acquire infinite energy at infinitely close separations. Lorentz observed that "from atoms of electric fluid to [his] charged corpuscles the distance is not great,"[25] the chief difference being that his were material bodies to which charges were attached rather than special imponderable particles.

The fifth hypothesis identifies the kinetic energy with the magnetic energy, $1/8\pi\int(\alpha^2+\beta^2+\gamma^2)\,d\tau$, where the magnetic force α, β, γ everywhere satisfies

$$\frac{\partial\alpha}{\partial x}+\frac{\partial\beta}{\partial y}+\frac{\partial\gamma}{\partial z}=0 \tag{2}$$

and is determined by the total current according to:

$$\begin{aligned}\frac{\partial\gamma}{\partial y}-\frac{\partial\beta}{\partial z}&=4\pi\left(\rho\xi+\frac{\partial f}{\partial t}\right),\\ \frac{\partial\alpha}{\partial z}-\frac{\partial\gamma}{\partial x}&=4\pi\left(\rho\eta+\frac{\partial g}{\partial t}\right),\\ \frac{\partial\beta}{\partial x}-\frac{\partial\alpha}{\partial y}&=4\pi\left(\rho\zeta+\frac{\partial h}{\partial t}\right).\end{aligned} \tag{3}$$

The sixth and last hypothesis is that the location of each point of the ether participating in the electromagnetic motions of the system is determined by the positions of all of the charged particles and by the values of f, g, h at all points in the ether.

Unlike the position, the motion of each point of the ether is not determined solely by the above hypotheses. Invoking the principles of mechanics in the form of d'Alembert's law, and generalizing Maxwell's mechanical derivation from linear circuits to currents in three dimensions, Lorentz derived the equations of motion of each point of the ether:

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[23] Lorentz, "Sur la théorie de la réflexion et de la réfraction de la lumière," p. 221.

[24] W. Weber, "Electrodynamic Measurements. Sixth Memoir, relating specially to the Principle of the Conservation of Energy," *Philosophical Magazine*, 1872, *43*:1–20, 119–149, esp. p. 149.

[25] Lorentz, "La théorie électromagnétique de Maxwell," p. 229.

$$4\pi V^2\left(\frac{\partial g}{\partial z}-\frac{\partial h}{\partial y}\right)=\frac{\partial \alpha}{\partial t},$$
$$4\pi V^2\left(\frac{\partial h}{\partial x}-\frac{\partial f}{\partial z}\right)=\frac{\partial \beta}{\partial t}, \tag{4}$$
$$4\pi V^2\left(\frac{\partial f}{\partial y}-\frac{\partial g}{\partial x}\right)=\frac{\partial \gamma}{\partial t},$$

where V is the velocity of light.

The force of the ether on charged particles can also be derived by mechanical reasoning from the hypotheses. Lorentz spoke of this force as the "electric force" and as his "fundamental law," and as such it is directly filiated with the electric forces or fundamental laws of Continental electrodynamic theories. It was in the derivation of this force that mechanical principles were most useful. Before, he had only to recover Maxwell's equations; now he was looking for a force that would be characteristic of his, not Maxwell's, theory, and a theoretical guide was helpful in constructing it. True, Maxwell stated the "Lorentz" force, but it was combined with other terms and it did not have the same meaning. From the assumption that the variation in the dielectric displacement of the ether within a particle is proportional to the particle's virtual displacement, he mechanically derived the total force X, Y, Z on a charged particle:

$$X=4\pi V^2\int\rho f\,d\tau+\int\rho(\eta\gamma-\zeta\beta)\,d\tau,$$
$$Y=4\pi V^2\int\rho g\,d\tau+\int\rho(\zeta\alpha-\xi\gamma)\,d\tau, \tag{5}$$
$$Z=4\pi V^2\int\rho h\,d\tau+\int\rho(\xi\beta-\eta\alpha)\,d\tau,$$

where the integrals are taken over the volume of the particle. The first terms on the right represent the electrostatic force, a force actually dependent upon relative motion, but only upon the motion of the other particles producing the dielectric displacement. The second terms define the force on a charged particle moving through the ether. Lorentz's force draws attention to a significant asymmetry which the introduction of particles seems to impose on Maxwell's theory. Lorentz did not write his field equations for free space in terms of the electric and magnetic forces, as Hertz had done, but in terms of the dielectric displacement and the magnetic force. By viewing the electric force as a force accelerating charged particles and the magnetic force as a state of the ether, he departed from the practice of stressing the reciprocal status of the two forces in the formulation of Maxwell's theory; this departure seemed necessary, as the ponderomotive electric force involved contributions from both the magnetic force α, β, γ and the dielectric displacement f, g, h.

The most important formulas of Lorentz's theory are the five numbered equations above. They remained the mathematical basis of his theory after 1892, although he later expressed them more simply in vector notation and in a less cumbersome system of units. After his mechanical derivation of the basic equations he explained that if all he had wanted was a description of the phenomena he could have started with these equations, and he showed how to arrive at them by reasoning that was independent of mechanical considerations. His equations, then, were to be evaluated apart from his readers' predilections for or against mechanical or phenomenological starting points.

With Lorentz's derivation of the fundamental law the presence of both the electrostatic and the electrodynamic components is seen to be necessary. This is a theoretical unification of the two great branches of electrical science, achieved, significantly, by mechanical reasoning. In sum, Lorentz's force gives rise to the electrodynamic action between charged bodies, to the electromotive force displacing charged particles in dielectrics or producing currents in conductors, and to the static attraction of electrified bodies. It embodies precisely the unifying ideal that was central to Continental aspirations in electrodynamic theory.

The most important application of Lorentz's basic equations was his derivation of Fresnel's drag coefficient, the outstanding test of a theory based on a stationary ether. Lorentz showed that his hypotheses were sufficient to explain the apparent dragging of the ether by bodies moving through it, as indicated by Armand Fizeau's 1851 measurement, repeated by A. A. Michelson and E. Morley in 1886, of the influence of moving columns of water on the speed of light. The physical explanation of why a ponderable body impresses on light a definite fraction of its speed is as follows. When a ray strikes the first charged particle of a dielectric, Lorentz's electrical force is called into play at once, displacing the particle from its equilibrium position. Because of its motion, the particle becomes the center of an electromagnetic disturbance which propagates outward at the speed of light, and this new pulse interferes with the already existing state of the ether. This sequence is repeated at the second charged particle and so on; and the resulting superposition of primary and induced vibrations accounts for the slowing and bending of light inside dielectrics.

In short sequel papers in 1892, Lorentz examined the difficulties that the earth's motion through the ether posed for the electron theory, difficulties he had not taken up in his initial paper. The stationary ether naturally raises the objection that bodies moving through it should experience an ether wind. The magnitude that determines the expected optical and electrical effects of the wind is the ratio of the absolute velocity of moving bodies p to the velocity of light V. Although this ratio is small for ponderable bodies such as the earth, the anticipated effects of the wind are within the limits of observation. It was well known, however, that these effects were not observed, and Lorentz needed to explain this in order for his theory to have plausibility. By his equations he showed that a remarkable compensation of actions occurs that annuls the wind effects in first-order approximation (i.e., neglecting small second-order quantities in p/V). The first-order invariance of the equations assured that an observer on earth would not be able to detect his absolute motion by any of the usual optical or electrical tests of ether wind. There was, however, an unusual optical test that Lorentz was familiar with. Michelson's 1881 interferometer experiment and Michelson and Morley's more accurate repetition of it in 1887 were precise enough to detect second-order effects of the ether wind for which compensating actions no longer took place. The experiment had failed to produce evidence of the earth's absolute motion, and Lorentz discussed the failure in one of his later 1892 papers.[26] The experiment is based on the following analysis, accurate to second-order magnitudes. The time that it takes light to travel once each way over a distance l in a direction parallel to the earth's motion should be $2l/V(1 + p^2/V^2)$, where p is the earth's speed.

[26] H. A. Lorentz, "The Relative Motion of the Earth and the Ether," *Versl. Kon. Akad. Wet. Amst.*, 1892, *1*:74; *Collected Papers*, Vol. IV, pp. 219–223.

When light travels at right angles to the earth's motion the time is $2l/V(1 + p^2/2V^2)$. In 1881 Michelson tried to measure the difference between the two times, lp^2/V^3, by passing light along two paths normal to each other and recombining the reflected beams to produce an interference pattern. When the apparatus is rotated by ninety degrees there should be a phase shift in the interference lines equivalent to twice the predicted time difference. Michelson and Morley found no such shift.

This experiment, Lorentz said, had puzzled him for a long time, and the only way he could think of to reconcile it with a stationary ether was to suppose that the interferometer arms contracted in the direction of the earth's motion by a factor α. The idea was audacious, but not unthinkable; the British physicist G. F. FitzGerald had independently conceived of the same explanation of the Michelson-Morley experiment. The different times, Lorentz said, for traversing the two arms are $2l/V(1 + p^2/2V^2)$ and $2l(1 - \alpha)/V\,(1 + p^2/V^2)$; this difference disappears if $\alpha = p^2/2V^2$, neglecting a small term of fourth order in p/V. Lorentz argued that such a contraction is conceivable if the molecular forces determining the size and shape of bodies are propagated through the ether analogously to the electric force. He said that the electric force on moving charged particles produces exactly the right contraction, though he cautioned that this may be mere coincidence, since nothing at all was known about molecular forces. All that was certain was that a change in dimensions is possible, and that the Michelson-Morley experiment cannot decide between a moving and a stationary ether; as Lorentz now saw it, the experiment's significance lay in its implications for molecular forces.This was Lorentz's first tentative inference from the electron theory to far-reaching conclusions about nonelectromagnetic physics, an inference prompted by the need to defend his theory's stationary ether from Michelson's experimental challenge. The notion of finitely propagated molecular forces was foreign to the usual versions of the mechanical view of nature.

In Lorentz's next major theoretical statement—his 1895 treatise on the influence of the earth's motion on electrical and optical phenomena[27]—he abandoned his mechanical derivation, now regarding his basic equations as hypotheses as Hertz had done. He did not elaborate on the reasons for proceeding in this new way. For one thing, he no longer needed a theoretical guide for himself or for others, having already established his basic equations. For another, he, like others, was becoming used to starting with the field equations, not repudiating their relation to mechanics, but not troubling about it either. Yet another possible reason is that he now knew, if he had not before, that his theory violated Newton's third law of motion. He showed this by writing the x-component of the electric force as the sum of two integrals, one taken over the surface σ enclosing a charge and the other over the volume τ contained in that surface: $2\pi V^2\int(2d_x d_n - \alpha \mathbf{d}^2)\,d\sigma + 1/8\pi\int(2H_x H_n - \alpha \mathbf{H}^2)\,d\sigma + d/dt\int(H_y d_z - H_z d_y)\,d\tau$, where α is the x-directional cosine for the surface, n the surface normal, and $\mathbf{d}$ and $\mathbf{H}$ the dielectric displacement and magnetic force respectively. For a stationary state the last integral vanishes, and the force on charged matter is then calculated solely from integrations over an enclosing surface, suggesting the ponderomotive action of stresses. Lorentz explained that he could not accept these stresses as the fifth basic

[27] H. A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (1895); *Collected Papers*, Vol. V, pp. 1–137.

equation of his theory, since they are incompatible with his hypothesis of a stationary ether. The difficulty is easy to see.

In a volume containing no ponderable matter, the electric force vanishes; for the x-component, this means that $2\pi V^2\int(2d_x d_n - \alpha\mathbf{d}^2)\,d\sigma + 1/8\pi\int(2H_x H_n - \alpha\mathbf{H}^2)\,d\sigma = -\,d/dt\int(H_y d_z - H_z d_y)\,d\tau$. The right-hand side is the time rate of change of the x-component of Poynting's energy current, and the left side gives the surface stresses. Wherever Poynting's vector changes in time, the stresses do not vanish and must therefore move the ether as a whole, an observation which Hertz had made in 1890. Lorentz concluded that while the ether is able to exert forces, no forces can act on it; in other words, Newton's law of action and reaction does not hold. All that he could think to say was that there was no reason for elevating Newton's third law to a principle of universal validity.[28] This was Lorentz's first explicit reservation about the scope of the principles of mechanics drawn from consequences of the principles of the electron theory.

Lorentz extended the application of his theory in 1895 to the three known optical effects of the motion of a source or observer. These were the aberration of starlight (change in the direction of light), Fizeau's experiment (change in the speed of light), and the Doppler shift (change in the frequency of light). Lorentz derived the aberration and Doppler phenomena, and he improved upon his 1892 explanation of Fizeau's experiment, refining his formula for the Fresnel drag coefficient by means of a dispersion theory. These three positive influences posed less difficulty for a stationary ether than did the numerous failures in other circumstances to observe an anticipated, positive influence of motion.

In his 1895 *Versuch* Lorentz for the first time systematically reviewed the whole problem of ether-wind effects. He began with the case of the first-order electrical consequences of the earth's motion. For example, a steady current moving with the earth cannot induce a current in another conductor moving with the earth; a charge distribution arises in the conducting circuit exactly cancelling the inductive effect, explaining Theodor Des Coudres' null measurements of the effect of the earth's motion on the induction of closed currents. This sort of calculation was familiar; E. Budde, as Lorentz knew, had come to the same conclusion in 1880 in his examination of Clausius' fundamental law; and, for stationary or slowly changing motions, Lorentz's charged particles act on one another exactly as do Clausius' electric particles.

In another calculation he proved, as Clausius had done, that the earth's motion through the ether should not affect electrostatic phenomena. I will go through his argument, since it clarifies the reasoning he had alluded to in his 1892 note on Michelson's experiment and which he would repeat and elaborate on in an appendix to his 1895 work. In his examination of electrostatics Lorentz considered a collection of charged particles at relative rest in a system S_1 moving with velocity p in the x-direction. Referred to the moving coordinates, the fundamental equation of electrostatics reads

$$\left(1-\frac{p^2}{V^2}\right)\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}+\frac{\partial^2\omega}{\partial z^2}=\rho\,,$$

where ω is the electric potential and ρ is the charge density. To clarify the meaning of this equation Lorentz compared the system S_1 with a second system S_2 at rest in the

[28] *Ibid.*, p. 28.

ether; S_2 arises from S_1 through a dilation of its dimensions in the x-direction in the ratio of $V/\sqrt{(V^2-p^2)}$; the dilation applies both to the dimensions of charged particles and to the distances between particles. Accordingly, the relations between the coordinates x, y, z of a point in S_1 and the coordinates x', y', z' of the corresponding point in S_2 are

$$x=x'\sqrt{1-(p^2/V^2)},\ y=y',\ z=z'.$$

The conservation of charge requires that the charge density ρ be written differently in the two systems, and this in turn leads to different expressions for ω in the two systems. Upon taking the spatial derivatives of the two potentials, the electric forces in the two systems are seen to be related by

$$E_x=E_x',\ E_y=E_y'\sqrt{1-(p^2/V^2)},\ E_z=E_z'\sqrt{1-(p^2/V^2)}.$$

If at a point in S_2, the force $\mathbf{E}'=0$, then, according to these relations $\mathbf{E}=0$ at the corresponding point in S_1; therefore, a collection of charged particles in equilibrium in one system will be in equilibrium in the other if the dimensions of the two systems are related as above. In 1892 Lorentz conjectured, as he would continue to do, that molecular forces vary with motion exactly as $\mathbf{E}$ does; this variation is associated with a contraction of the dimensions of ponderable systems analogous to the contraction of the dimensions of electrostatic systems.

To explain the more difficult null optical results, as well as the positive optical influences of motion, Lorentz introduced a new independent variable, a so-called "local time,"[29] $t'=t-(p_x/V^2)x-(p_y/V^2)y-(p_z/V^2)z$, where t is the true, or absolute, time, V the speed of light, and p_x, p_y, p_z the velocity of the localized point x, y, z of the moving dielectric. He had already used a local time in 1892, but without labelling or emphasizing it. The significance of the new variable is not especially easy to see, and Lorentz was little help (the local time at a point x, y, z is found from the true time by subtracting a factor proportional to the velocity of the point and the time required by light to travel from the origin to the point). Lorentz had in mind only a convenient auxiliary transformation, not at all a revision of the concept of time.

He now applied the kinematic transformations of mechanics to his basic equations, referring them to axes attached to the moving dielectric. To first order in p/V, the equations describing the behavior of light in a moving dielectric in electromagnetic units are:

$$\mathrm{div}'\ \mathbf{D}'=0,$$

$$\mathrm{div}'\ \mathbf{H}'=0,$$

$$\mathrm{rot}'\ \mathbf{H}'=4\pi\frac{\partial\mathbf{D}'}{\partial t'},$$

$$\mathrm{rot}'\ \mathbf{E}=-\frac{\partial\mathbf{H}'}{\partial t'},$$

and $\chi_1 E_x=4\pi V^2 D'_x$, $\chi_2 E_y=4\pi V^2 D'_y$, $\chi_3 E_z=4\pi V^2 D'_z$, where χ_1, χ_2, and χ_3 depend upon the frequency of light and the nature of the dielectric (and *div* and *rot* stand for

[29] *Ibid.*, pp. 49, 81.

the vector operations of divergence and rotation, or curl). The primes on the operators indicate that the differential quotients are taken with respect to x, y, z, t', where the spatial coordinates as well as the local time refer to axes moving with the dielectric. The primed field variables are defined by

$$\mathbf{D}' = \mathbf{D} + \frac{1}{4\pi V^2}\mathbf{p} \times \mathbf{H} \qquad \text{and} \qquad \mathbf{H}' = \mathbf{H} - \frac{1}{V^2}\mathbf{p} \times \mathbf{E},$$

where $\mathbf{D}$ is the dielectric displacement, $\mathbf{H}$ the magnetic force, and $\mathbf{E}$ the electric force in the dielectric at rest. The four equations are identical in form to those describing the behavior of light in a dielectric at rest, provided that t, $\mathbf{D}$, and $\mathbf{H}$ are written in place of t', $\mathbf{D}'$, and $\mathbf{H}'$. To achieve this limited invariance of Maxwell's equations was precisely the point of bringing together the transformations for t, $\mathbf{D}$, and $\mathbf{H}$, which Lorentz had introduced singly in different places in the treatise. While his choice of definition of local time seems to have been guided by abstract considerations (as a mathematical aid in finding the field due to oscillating charged particles in a moving dielectric), his choice of $\mathbf{p} \times \mathbf{H}$ and $\mathbf{p} \times \mathbf{E}$ for the transformations of $\mathbf{D}$ and $\mathbf{H}$ respectively is what one would have expected at the time from the physics of translating systems.

Lorentz's transformations afforded him a simple way of examining the influence of the earth's motion on optical phenomena: if, in general, a state of motion exists in a system of bodies at rest, described by $\mathbf{D}$, $\mathbf{E}$, and $\mathbf{H}$, as functions of x, y, z, t, then a corresponding state of motion can exist in the same system moving with velocity $\mathbf{p}$, described by $\mathbf{D}'$, $\mathbf{E}$, and $\mathbf{H}'$, expressed as identical functions of x, y, z, t' (where the coordinates are assumed to share in the translation). A far-reaching consequence is that if there is darkness, $\mathbf{D} = \mathbf{E} = \mathbf{H} = 0$, anywhere in the system at rest, then there will be darkness, $\mathbf{D}' = \mathbf{E} = \mathbf{H}' = 0$, at the corresponding place in the moving system. Since a ray is defined by the absence of light at its boundaries, the same laws of reflection and refraction must hold in systems at rest and in motion. Further, since any interference pattern involves alternating light and dark areas, the same pattern must occupy corresponding places in stationary and moving systems.

At the end of his treatise[30] Lorentz acknowledged that his corresponding-states theorem could not account for the second-order null effect of the Michelson-Morley experiment. He referred to his calculation earlier in the treatise of the influence of translation on the electric force. If, he argued, the molecular forces are influenced in the same way as the electric force, then a ponderable body, such as the arms of Michelson's interferometer, must contract in the direction of the earth's motion in a ratio of $\sqrt{1 - p^2/V^2}$ ($\sqrt{1 - p^2/V^2} \div 1 - 1/2{\cdot}p^2/V^2$, the approximate factor he wrote in 1892) in order that its molecular configuration remain in equilibrium. However suggestive the familiar parallel between electric and molecular forces might be, Lorentz understandably felt some uneasiness over the status of this explanation of the Michelson-Morley result.

II. THE ELECTROMAGNETIC VIEW OF NATURE

From the middle of the nineteenth century, electrodynamics had stood in uneasy relation to the mechanical view of nature. The relational tension took two

[30] *Ibid.*, pp. 119–124.

forms: a challenge to specific assumptions of the mechanical view, and a thrust to supplant the mechanical view with a universal physics based on electrodynamics. In 1846 Weber introduced a fundamental law of electric force between electric masses.[31] The law involved the relative velocity and acceleration of electric-mass pairs, a radical departure from the prototypic law, the motion-invariant force of gravitation. Weber not only refused to balk at his new type of fundamental force, but he proceeded to extend it to all of nature. In his first memoir he anticipated that the other basic forces might have the same dependence on motion as his electric force. He began in earnest in 1871 to extend the application of his law, recasting the law of gravitation according to his electrical model.[32] Throughout the 1870s he elaborated an electrical view of nature, explaining chemical aggregations, heat, the kinetic theory of gases, and the luminiferous ether as electrical phenomena. He advanced a complete image of nature: the sole constituents of the physical world were electric particles of two signs moving in accordance with one dynamic law. Lorentz, who admired Weber's electrodynamics, was drawn to an analogous, unifying view of nature, but one based on the electromagnetic field as well as on electric particles.

Weber and those following his direction—Clausius, B. Riemann, and Carl Neumann—introduced a number of radical departures from the conventional mechanical viewpoint in working out internal problems of their electrodynamics. These departures included the replacement of the Newtonian instantaneous action by the finite propagation of electric force,[33] the violation of Newton's law of action and reaction by electrodynamic forces,[34] the stipulation of a nature-imposed upper limit on the possible relative velocity of particles,[35] the suggestion of the need for a completely symmetric use of space and time in descriptions of electrodynamic phenomena,[36] the proposal of a new concept of energy conservation suited to electrodynamic rather than mechanical needs,[37] and the recognition, at least in a mathematical sense, of a velocity-dependent apparent mass for electric particles.[38] Ideas like these reappeared in the context of the Maxwellian electrodynamics of moving bodies, where they were viewed as signalling the arrival of an expressly non-Newtonian dynamics. Before this they were fragmentary ideas, not fully explored or coherently ordered, and not yet seen as heralding a post-Newtonian era. It was only when the non-Newtonian concepts were made explicit in the foundations of the electron and relativity theories that a new era was conceded to be firmly consolidated. The novel

[31] W. Weber, "Elektrodynamische Maasbestimmungen über ein allgemeines Grundgesetz der elektrischen Wirkung" (1846), in W. Weber, *Werke*, Vol. III, pp. 25–214.

[32] Weber, "Electrodynamic Measurements. Sixth Memoir."

[33] B. Riemann, "A Contribution to Electrodynamics," *Phil. Mag.*, 1867, *34*:368–372; C. Neumann, "Die Principien der Elektrodynamik" (1868), in *Mathematische Annalen*, 1880, *17*: 400–434.

[34] R. Clausius, "On a New Fundamental Law of Electrodynamics," *Phil. Mag.*, 1876, *1*:69–71; "On the Bearing of the Fundamental Law of Electrodynamics toward the Principle of the Conservation of Energy, and on a further Simplification of the former," *Phil. Mag.*, 1876, *1*: 218–221.

[35] Weber, "Electrodynamic Measurements. Sixth Memoir," p. 121.

[36] Weber, "Elektrodynamische Maasbestimmungen über ein allgemeines Grundgesetz der elektrischen Wirkung," Sec. 20; Neumann, "Die Principien der Elektrodynamik," pp. 433–434.

[37] Weber, "Electrodynamic Measurements. Sixth Memoir," p. 2; "Elektrodynamische Maasbestimmungen inbesondere über die Energie der Wechselwirkung" (1878), in *Werke*, Vol. IV, Pt. 2, pp. 361–412, esp. p. 370.

[38] B. Riemann, *Schwere, Elektricität und Magnetismus*, ed. K. Hattendorff (Hannover, 1875), pp. 313–337.

dynamical concepts were not directly taken over by Lorentz from the prior German electrodynamics, but they were well known, establishing the immediate, exploratory tradition in which he elaborated his electron dynamics.

The development of the electron theory followed closely the historic development of the German molecular-electric theories. Lorentz found that to firm the foundations of his theory he needed increasingly to modify the traditional mechanical foundations of general physics. He took a major step toward the revision of conventional dynamics in 1889,[39] in a paper whose immediate purpose was to relieve his and others' uneasiness over the status of the explanation of the Michelson-Morley experiment.

Lorentz made the contraction hypothesis an integral part of his theory in 1899 by generalizing his corresponding-states theorem to apply to a system composed both of "electrons" (his first use of the term) and ponderable matter. He postulated that molecular forces are influenced by motion exactly as the electric force; accordingly all parts of a system, charged and uncharged, contract equally. He unified his theory in an important respect by bringing together the three separate but equally essential parts of his transformation theory: the local time, employed in his analysis of optical phenomena; the motion-dependent electric force, derived from his study of the invariance of electrostatics; and the motion-dependent molecular forces of his 1892 conjecture on the resemblance of molecular and electrostatic forces. The contraction relations were no longer a special assumption, but a formal "transformation" associated with an extended corresponding-states theorem, one valid for second-order as well as first-order effects.

Lorentz was evidently led to reformulate his theory in 1899 as a result of a publication of A. Liénard the year before. Liénard suggested that the theory should lead to a positive result if the Michelson-Morley experiment employed a solid or liquid dielectric rather than air. Lorentz doubted that it would make any difference, and his new approach showed why: as the nature of the dielectric nowhere enters his new corresponding-states theorem, Liénard's supposition appeared to be baseless.

As usual Lorentz began his analysis by referring his equations to variables x, y, z attached to a dielectric moving with velocity p_x, using the (Galilean) coordinate transformations of mechanics for this purpose. And as before, his next step was to seek another transformation, one proper to electrodynamics, which formally reversed or annulled the changes in the equations brought about by the original transformation. The great difficulty in carrying out this second step was that there was no way of deciding on a unique set of transformations. There were too many things to vary all at once: x, y, z, t, $\mathbf{H}$, $\mathbf{D}$, and the choice of prior approximations in the equations of the moving system. On the surface, the problem seemed to have become more complicated in 1899 by the introduction of coordinate transformations, but in fact it became more controllable. By knowing how the spatial variables had to transform, Lorentz acquired a fixed point from which to begin his search for the remaining transformations. The inclusion of contraction relations in the corresponding-states theorem imposed a redefinition of the transformations of the other variables, including the local time. These transformations had practically the same form as the ones which Lorentz

[39] H. A. Lorentz, "Théorie simplifiée des phénomènes électriques et optiques dans des corps en mouvement," *Versl. Kon. Akad. Wet. Amst.*, 1899, *7*:507; *Collected Papers*, Vol. V, pp. 139–155.

derived in a more general way in his later, better-known article of 1904. I will not write out all his 1899 transformations, only those for space and time:

$$x = \epsilon/kx'', \; y = \varepsilon y'', \; z = \varepsilon z'', \; t' = k\varepsilon t'',$$

where $k = V/\sqrt{V^2 - p_x{}^2}$, and ε stands for an undetermined factor differing from unity by a second-order quantity (allowing for a possible dilation in lateral dimensions compatible with the Michelson-Morley experiment). The double-primed variables refer to the state of motion inside a stationary dielectric. By these transformations Lorentz recovered the equations for a dielectric at rest; their meaning is very simply that they allow a moving system to be deduced from a stationary one and conversely. Lorentz called attention to the fact that his transformations now contain the formulas by which he had explained the Michelson-Morley experiment. Their new, central role in the general problem of establishing the (still limited) invariance of the field equations appeared to him as strong evidence that contraction really does apply to the distribution of all matter and not just to the positions and shapes of electrons as in the earlier form of his theory.

Lorentz said that a principal objective was to bring forward the "theoretical significance"[40] of his new approach, and this is the aspect of his 1899 work I wish to stress. Exposing the profound implications of his transformations for all species of force and matter, he essentially proposed a new dynamics applying—as his corresponding-states theorem did—to ponderable bodies, not just to electrons; a fundamental revision of dynamics was inescapable if his explanation of the Michelson-Morley experiment were adopted. Now, since his transformations apply to molecular as well as to electric forces, the total force in a dielectric must be influenced by motion exactly as is the electric force (for electrons moving in the x-direction the electric force is $1/\varepsilon^2$, $1/k\varepsilon^2$, $1/k\varepsilon^2$ times the force on electrons at rest). Then, by Newton's second law, the same influence must be admitted for the product of mass and acceleration. And since according to the time and coordinate transformations the acceleration in the moving system must be $1/k^3\varepsilon$, $1/k^2\varepsilon$, $1/k^2\varepsilon$ greater than that in the rest system, the mass in the moving system must be k^3/ε, k/ε, k/ε times greater than the rest mass.[41]

The idea that mass can depend on speed and direction was intelligible, at least in the case of electrons, since the effective mass of an electron depends on what happens in the ether, and that in turn depends on the speed and direction of the motion of the electron. Lorentz's conclusion, however, applies to all mass, not just electron mass; and that is extraordinary. By incorporating his explanation of the Michelson-Morley experiment into his overall theory, he was led to suggest that no bodies exist for which Newtonian mechanics holds; when introduced into Lorentz's electromagnetics, mechanics denies in a sense its basic tenet—the constancy of mass. This is a crucial fact, pointing up a tension which always existed in Lorentz's theory. His conception of the electromagnetic world had a dual foundation: the forces were computed with the aid of Maxwell's continuous fields, while the motion of electrons under these forces followed the mass-point laws of Newtonian mechanics. The inherent revolutionary implications of this dual foundation were reflected in the non-Newtonian consequences which issued from Lorentz's particle-field synthesis and, later, from Einstein's critical examination of Lorentz's synthesis.

[40] *Ibid.*, p. 151.

[41] *Ibid.*, p. 154.

It was well known, as Lorentz intimated, that the effective mass of a charged body varies with its motion. J. J. Thomson had first shown this in 1881 by directly applying Maxwell's equations to a moving charged sphere, calculating its self-inductive effects.[42] Oliver Heaviside, G. F. C. Searle, and W. B. Morton had subsequently improved and extended this calculation. Now, by a very different route than the moving electrified sphere studies, Lorentz arrived at a velocity dependence of electron mass and mass in general, an immediate consequence of the incorporation of the contraction hypothesis into the electron theory. More than any other result in the electrodynamics of moving bodies the variation of mass stimulated the search for a new dynamics, which in turn was seen as the cornerstone of an electromagnetic view of nature.

As early as 1898, in a discussion of cathode-ray experiments, Theodor Des Coudres[43] suggested the possibility of empirically deciding whether or not the mass of electrons is only an apparent mass arising through self-induction. In anticipation he pictured an electron as a purely ethereal phenomenon, a convergence of weightless lines of electric force. In 1901 Lorentz investigated this by now much-discussed question of critical significance for an electromagnetic physics.[44] The possibility that electrons have no true, or Newtonian, mass was for Lorentz fundamentally related to the question of the dynamics of electrons and to the larger, deeper one of the connection of ponderable matter with electricity and the ether. He regarded the mass problem as one of first priority and urged that experiments be made to determine the exact form of the electron's velocity dependence; by deflecting electrons in electric and magnetic fields, he thought that the question of the true and apparent mass might be settled.

Experiments of this sort were made possible by the discovery of the empirical electron. Shortly before 1900 it had been established that cathode rays are negative particles and are the same regardless of their source or the way they are produced. This is just what Lorentz had hypothesized about the nature of electricity, and he confidently identified the cathode-ray particles with the negative charged particles of his theory. Applying his theory to explain Pieter Zeeman's measurements of the separation of the components of the D line when a sodium flame is placed between the poles of a magnet, he predicted the ratio of charge to mass of the negative particles in sodium atoms.[45] His value for the ratio was in agreement with the subsequent estimates by J. J. Thomson, Walter Kaufmann, and others—obtained by deflecting cathode particles in electric and magnetic fields—dramatically confirming the general correctness of his theory.

That there existed means for experimenting directly on electrons had immense significance for Lorentz, and he immediately cast his theory differently, partly in response to this. From 1899 on, he usually worked with equations for individual electrons, whereas before he had constructed equations for macroscopic bodies by averaging his field variables over the contributions of many electrons. Now he would point to the empirical knowledge of the nature of charged particles as a basic advance of

[42] J. J. Thomson, "On the Electric and Magnetic Effects produced by the Motion of Electrified Bodies," *Phil. Mag.*, 1881, *11*:229–249.

[43] T. Des Coudres, "Ein neuer Versuch mit Lenard'schen Strahlen," *Verhandlungen der Physikalischen Gesellschaft zu Berlin*, 1898, *17*:17–20.

[44] H. A. Lorentz, "Über die scheinbare Masse der Ionen," *Physikalische Zeitschrift*, 1901, *2*:78; *Collected Papers*, Vol. III, pp. 113–116.

[45] H. A. Lorentz, "Optical Phenomena Connected with the Charge and Mass of the Ions I, II," *Versl. Kon. Akad. Wet. Amst.*, 1898, *6*:506, 555; *Collected Papers*, Vol. II, pp. 17–29, 30–39.

the modern electron theory over Weber's. Most important of all, it was possible to experimentally study the behavior of electrons and to learn their true dynamical laws; this meant especially that the theoretical velocity dependence of the electron mass might be accurately tested. The expected dependence was of second order, a quantity which was sensible only for electrons moving at speeds close to that of light. Another opportune discovery—radioactivity—offered precisely the means for obtaining sufficient speeds. In 1901 Kaufmann began reporting his experiments on the magnetic and electric deflections of Becquerel rays, or rays of very fast electrons emitted by radium salts. His results indicated a certain dependency of the electron mass on velocity, convincing him and others, including Lorentz, that the mass is entirely electromagnetic in origin.

The possibility of a completely electromagnetic physics was much in Lorentz's thought at this time. In an address at Leyden in 1900 he chose to speak about the extent to which all physical phenomena promised to be subsumed under the electron theory,[46] re-covering in detail much of the molecular-electrical image of the world that Weber and his disciple Zöllner had evolved a quarter century before. Admitting that he had no good idea of the mechanism producing the more complex magnetic splitting of spectral lines, he explained that the real challenge anyway was to predict the primary spectral frequencies, not merely the splittings. The ultimate goal was to understand the structure of atoms. After the Zeeman phenomenon, especially, atomic theory became in Lorentz's eyes another potential province of electron theory. Turning to other branches of physical science, Lorentz supposed that chemical forces had an electronic origin, an insight, he noted, which he shared with Weber and other earlier electrical theorists. And if it were premature to indentify molecular forces with electric and magnetic ones, his explanation of Michelson's experiment showed that these forces are at least propagated similarly through the ether. Of the great forces in nature, only gravitation seemed to remain outside the reach of electron theory; but, because electric charges are inseparable from ponderable matter, he was confident that gravity could not be unrelated to electromagnetism. The difficulty was that, as Laplace had argued, astronomical facts seemed to demand a velocity for gravitational actions much greater than that for electromagnetic ones. In that same year, 1900, Lorentz published a possible solution to the velocity question from the viewpoint of electron theory, demonstrating at least one way of annexing gravitation to an electromagnetic physics.[47]

Lorentz's approach was inspired by Mossotti's gravitational theory of 1836, which had been recently revived by Weber and Zöllner.[48] Mossotti had assumed that a ponderable particle is a composite of two opposite electric atoms and that the attraction between two such ponderable particles is greater than their repulsion. Lorentz, as usual, substituted electrons for the older electric atoms and states of the ether for

[46] H. A. Lorentz, "Elektromagnetische Theorien physikalischer Erscheinungen," *Phys. Z.*, 1900, *1*:498, 514; *Collected Papers*, Vol. VIII, pp. 333–352.

[47] H. A. Lorentz, "Considérations sur la pesanteur," *Versl. Kon. Akad. Wet. Amst.*, 1900, *8*:603; *Collected Papers*, Vol. V, pp. 198–215.

[48] W. Weber, "Elektrodynamische Maasbestimmungen inbesondere über den Zusammenhang des elektrischen Grundgesetzes mit dem Gravitationsgesetze," first published in 1894 in Weber, *Werke*, Vol. IV, pp. 479–525. J. C. F. Zöllner, *Principien einer Elektrodynamischen Theorie der Materie. I. Abhandlungen zur Atomistischen Theorie der Elektrodynamik von Wilhelm Weber* (Leipzig, 1876).

distance forces. Denoting the field of a positive electron e by $\mathbf{d}$ and $\mathbf{H}$, and that of a negative electron e' by $\mathbf{d}'$ and $\mathbf{H}'$, he expressed the forces exerted by other positive and negative electrons on e as $k_1 = \alpha(4\pi V^2\mathbf{d} + \mathbf{v} \times \mathbf{H})e$ and $k_2 = \beta(4\pi V^2\mathbf{d}' + \mathbf{v} \times \mathbf{H}')e$. The corresponding forces on e' are $k_3 = \beta(4\pi V^2\mathbf{d} + \mathbf{v}' \times \mathbf{H})e'$ and $k_4 = \alpha(4\pi V^2\mathbf{d}' + \mathbf{v}' \times \mathbf{H}')e'$. The constants α and β are assumed to be different. Upon the further assumptions that the charges are equal and that they interpenetrate, and that opposite electrons move together in coupled pairs, the formulas simplify: the electrons e and e' are acted on by the same force $k_1(1 - \beta/\alpha)$ in the same direction, which means that the force cannot be due to an electric field since that would move the charges oppositely. The force, Lorentz concluded, must then be gravitational. He remarked that his theory could be freed from the assumption that ponderable matter consists of positive and negative electrons. It would only be necessary to admit that gravitation propagates through the ether analogously to electromagnetic forces. Then gravitation would be characterized by its own proper set, $\mathbf{d}$, $\mathbf{H}$, satisfying the same field equations as the corresponding vectors of electron theory. Here Lorentz followed the pattern set by Weber of imagining alternative possibilities: either gravitation was to be reduced to electrical forces—the goal of a comprehensive electrical physics—or gravitational theory was to be reformed after the model of electrical theory—a weaker objective. In either case the new law is identical with Newton's when there is no motion; but when two bodies are moving, their attraction involves velocity-dependent terms as well, and these latter, Lorentz noted, are analogous to terms appearing in the laws of Weber, Riemann, and Clausius. Applying his force to the secular motion of Mercury, he found that it did not fit nearly as well as Weber's. But he was not especially troubled, as his chief purpose had been to show that gravitation could be understood as an action that propagates through the ether with a speed no greater than that of light. Convinced that the properties of the ether, as revealed in electromagnetic investigations, set conditions on all theories, he supposed that the ether does not allow the communication of any action—gravitational, molecular, or electromagnetic—at speeds greater than that of light, an idea uncommon to the mechanical tradition.

Lorentz's theory of gravitation prompted Wilhelm Wien that same year, 1900, to publish similar, though more thoroughgoingly electromagnetic, thoughts of his own. In the first formal pronouncement of the electromagnetic view of nature[49] he assumed that all mass is electromagnetic in origin and that all ponderable matter is composed of positive and negative charges; the latter assumption, he claimed, with some little exaggeration, had come to be granted by all physicists. There is a detail in Wien's paper that nicely illustrates the appeal an electromagnetic view might have for one concerned with basic questions. Two years before, Wien had remarked that acceleration is probably related to gravitation, a possibility having great significance for theoretical physics.[50] The grounds for his conjecture were that the two phenomena provide independent measures of mass which are in total agreement. If, however, inertia and gravitation are not first principles but phenomena deducible from Maxwell's equations, the solution of this ancient conundrum is at hand: the masses defined

[49] W. Wien, "Ueber die Möglichkeit einer elektromagnetischen Begründung der Mechanik," *Arch. néerl. Sci.*, 1900, *5*:96–104.

[50] W. Wien, "Ueber die Fragen, welche die translatorische Bewegung des Lichtäthers betreffen," *Verhandlungen der Gesellschaft Deutscher Naturforscher und Ärzte*, 1898, Pt. 2, 49–56.

by acceleration and gravitation, as he pointed out in his 1900 paper, should be proportional, since both are proportional to the number of charges present. To show that Maxwell's principles apply to gravitation, Wien in 1900 derived an approximate equation of motion for an ellipsoidal mass moving around a second, fixed mass. He observed that except for an insignificant discrepancy in a numerical coefficient, his result was identical with Weber's, a gratifying coincidence, since he believed that Weber's law successfully explained Mercury's perturbations.

Wien's central interest was not, however, gravitation, but something more basic. It concerned what was in his opinion a first task of physics: to bring together the now completely isolated subjects of mechanics and electromagnetism and to deduce the basic differential equations of each from a common foundation. He conceded that the natural way was to derive the electromagnetic laws from a mechanical foundation. W. Thomson, Maxwell, Boltzmann, and Hertz had approached the problem that way and had succeeded to a degree. All the same, Wien was unconvinced by their complicated mechanical models and fixed mechanical constraints; and, in general, he saw mechanics as unfitted for representing electromagnetic phenomena. Accordingly he adopted a tack diametrically opposed to theirs. His goal in 1900 was to assimilate mechanics to electromagnetism, and his approach was to show that Newton's laws of motion are a special case of the more general, exact laws of electromagnetism. He showed that the first law falls out exactly; it is the law of conservation of electromagnetic energy. Newton's second law too is preserved as long as it is taken to mean that the work done by a force is precisely balanced by a change in electromagnetic energy. The third law, however, applies only to forces acting between charges at rest in the ether, failing for moving charges, as Lorentz had shown. Newton's mechanics, like his law of gravitation, was, in Wien's opinion, only approximately true. The lesson was that the physicist should turn to electron theory for the exact foundations of his science. Wien, like Lorentz, explicitly refrained from identifying molecular forces with electric ones; otherwise his position seems to have been that of a fully electromagnetic view of nature.

Wien had earlier stressed the high theoretical significance of the failure of Lorentz's theory to preserve Newton's third law.[51] In one of his rare speculations on the internal motions of the ether, Lorentz had replied that a local portion of the ether when set in motion might move a neighboring portion in such a way as to preserve the third law, even though the latter motion might be imperceptible if the portion were massive enough.[52] This was only a surmise, and Lorentz did not follow it up, although he was deeply troubled by the unclear relation of his theory to Newton's principle. Poincaré was even less sanguine than Lorentz over the conflict, referring to it in 1900 as a grave fault of the theory.[53] Later that year, however, Poincaré published a paper[54] in which he removed his objection; there he pointed to a curious paradox in Lorentz's theory.

[51] *Ibid.*, p. 52.

[52] *Ibid.*, p. 56 ; *Collected Papers*, Vol. VII, pp. 101–115.

[53] H. Poincaré, "Relations entre la physique expérimentale et la physique mathématique," *Rapports présentés au congrès international de physique* (Paris: Gauthier-Villars, 1900), Vol. I, pp. 1–29, esp. p. 24.

[54] H. Poincaré, "La théorie de Lorentz et le principe de reaction," *Arch. néerl. Sci.*, 1900, 5:252–278.

In ordinary mechanics the principle of action and reaction can be deduced jointly from the conservation of energy and the principle of relative motion (the latter taken to mean that force, or potential, is a function of the relative positions of bodies). No violation of energy conservation had been observed, and the relativity principle appeared to be verified by all experiments on the motion of the earth through the ether. Yet, in Lorentz's theory, energy is conserved while the principle of action and reaction does not hold for the forces between bodies. Poincaré resolved this seeming contradiction by noting that in Lorentz's theory the relativity principle is not a premise but a result of complex compensations. The problem of reconciling the theory with Newton's principle, as Poincaré saw it, was to show how the stationary ether can be regarded as containing an exactly compensating momentum. He noticed that according to Lorentz the amount of energy sent out by a radiator does not appear the same in moving and stationary reference frames. If J is the rate of radiation of electromagnetic energy in a rest frame, it is only $J(1 - v/V)$ in a frame moving with velocity v, where V is the velocity of light. The force of recoil on a radiator in the rest frame is J/V, and the corresponding recoil in the moving frame is $J/V(1 - v/V)$. Therefore a system consisting of the ether and a moving material radiator gives rise to an apparent force on the radiator of $-Jv/V^2$, which in turn means that the forces acting on matter are not independent of the motion of the observer. Neither the principle of relative motion nor the principle of action and reaction applies to matter alone, and there is an intimate, necessary connection between these two facts. The apparent force is a necessary consequence of the recoil of the radiator, and the reaction corresponding to this recoil has its seat in the ether; it is represented pictorially by the momentum of a fictitious fluid and quantitatively by Poynting's energy-flux vector. All theories are condemned, Poincaré concluded, which retain Newton's third law without taking into consideration what happens in the ether.

The idea of an electromagnetic momentum had a profound impact on physics. While many forms of energy were known, only one kind of momentum, mechanical momentum, was recognized prior to Poincaré's work.[55] Poincaré's momentum could of course always be interpreted mechanically, but it does not seem that there was much interest then in attempting this. (Maxwell, and especially J. J. Thomson, had previously attributed momentum to the electromagnetic field; theirs was a conventional mechanical momentum.) In 1902 Max Abraham,[56] emerging as a principal spokesman for the electromagnetic view of nature, seized upon Poincaré's concept of a localized electromagnetic momentum in the ether as a means for calculating the "transverse" mass of an electron, that is, the inertia opposing an acceleration normal to the direction of motion. The electromagnetic momentum was essential for this purpose, as the energy alone determines only the "longitudinal" mass, that is, the inertia opposing an acceleration in the direction of motion. It was necessary to know the transverse mass to properly analyze Kaufmann's deflection experiments. The calculations of J. J. Thomson, Heaviside, Searle, and Morton were based solely on the electromagnetic energy of electrons and so could not provide the information.

[55] The anomalous nature of electromagnetic momentum was stressed by Max Planck in "Bermerkungen zum Prinzip der Aktion und Reaktion in der allgemeinen Dynamik" (1908), in *Physikalische Abhandlungen und Vorträge*, Vol. II, pp. 215–219.

[56] M. Abraham, "Dynamik des Electrons," *Nachr. Ges. Wiss. Göttingen*, 1902, Pt. I, pp. 20–41.

Abraham found that the longitudinal and transverse masses have different values, as Lorentz had already recognized in 1899; and, as a result of this difference, the acceleration of an electron is not, in general, in the direction of the force, as it is in ordinary mechanics.

In the following year, 1903, Abraham again made use of Poincaré's momentum to construct a complete dynamics of electrons, deriving basic equations for translational and rotational motion.[57] The linear and angular electromagnetic momenta entering these equations are not linearly proportional to their corresponding velocities, as they are in mechanics; instead, they depend on the whole history of the motion of the electron, since they are defined by integrals over all space. Explicitly following up Lorentz's and Wien's suggestions, Abraham set out to place mechanics on an electromagnetic basis. He was convinced that the electron mass was entirely electromagnetic, the first condition of an electromagnetic foundation of mechanics.

Another essential condition was the rigorous exclusion of all nonelectromagnetic forces. Abraham calculated that Lorentz's deformable electron required a nonelectric inner potential energy to preserve equilibrium. Lorentz accepted Abraham's calculation as an extraordinarily important implication of his theory, conceding that if the inner electron energy were not found in experience, the entire theory of the Michelson-Morley experiment would collapse.[58] Abraham considered the need for nonelectric forces as a critical internal flaw of Lorentz's theory, since it excluded a purely electromagnetic basis of mechanics. Others who were inclined to an electromagnetic viewpoint shared this estimate of Lorentz's failure. Alfred Heinrich Bucherer, for one, agreed with Abraham that the contradiction between Lorentz's theory and a purely electromagnetic mechanics was more damaging to the theory than the deflection data of Kaufmann, which seemed to be going against the theory at this time.[59] Bucherer reformulated the electron theory on the basis of another contraction hypothesis, one that obviated the need for an energy of deformation; he supposed that electrons contract in the direction of motion but are incompressible and therefore expand laterally at the same time.[60] Paul Langevin, another proponent of an electromagnetic mechanics, independently proposed the same modified contraction hypothesis shortly thereafter.[61]

The nature of the connections needed to prevent an electron from flying apart by the mutual repulsion of its parts was totally unknown. Abraham offered a solution to this problem at the same time that he answered his basic objection to Lorentz's theory. He proposed an electron that did not undergo deformation when in motion, elevating the kinematic description of a rigid body to a fundamental equation of his theory.[62] He referred to the idea of rigid connections in Hertz's *Principles of Mechanics*; these connections do no work and so when applied to electrons they conserve electro-

[57] M. Abraham, "Prinzipien der Dynamik des Elektrons," *Ann. Phys.*, 1903, *10*:105–179.

[58] Lorentz discussed this in his 1904 address "Ergebnisse und Probleme der Elektronentheorie" to the Elektrotechnischer Verein zu Berlin; *Collected Papers*, Vol. VIII, pp. 76–124.

[59] This is brought out in Bucherer's and Abraham's remarks at the end of M. Planck, "Die Kaufmannschen Messungen der Ablenkbarkeit der β-Strahlen in ihrer Bedeutung für die Dynamik der Elektronen," *Phys. Z.*, 1906, *7*:753–761, esp. pp. 760–761.

[60] Bucherer first introduced his electron hypothesis in his textbook, *Mathematische Einführung in die Elektronentheorie* (Leipzig: Teubner, 1904).

[61] Langevin, "La physique des électrons," p. 267.

[62] Abraham, "Prinzipien der Dynamik des Elektrons."

magnetic energy, and no other form of energy needs to be admitted. He explicitly dissociated himself from Hertz's unifying objective of a mechanical physics. Admitting that he borrowed a detail from Hertz's mechanical writings, he stressed that his direction was diametrically opposed to that of Hertz and all those who sought a mechanical synthesis.

Abraham's alternative version of the electron theory and especially his conception of a rigid electron helped direct the center of electrodynamic interest in the first decade of the twentieth century to the problem of the velocity dependence of the electron mass. Investigations of the velocity dependence were expected to decide between the deformable and the rigid electron. Abraham's rigid constraints were not universally regarded as a satisfactory solution. Poincaré produced an explanation of electron cohesion and stability in 1906[63] in a paper on the foundations of Lorentz's theory, an explanation Lorentz accepted. Yet his model electron admitted in its interior a nonelectromagnetic energy, which did not go down well with the advocates of an electromagnetic physics.

A central figure in the circle of followers of the electromagnetic view was Kaufmann, whose tables comparing Becquerel-ray deflections with the predicted values from the deformable- and rigid-electron theories were reproduced in nearly every publication on electron dynamics in the first years of the century. He emphasized that assumptions about the deformability and substance of the electron had a major bearing on the issue of whether or not electron inertia is wholly electromagnetic. It is significant that Kaufmann, the leading experimentalist in electron dynamics, was a strong proponent of the electromagnetic view of nature. At a talk on the development of the electron concept at the 1901 meeting of the German Natural Scientists and Physicians, he outlined his expectations for an electromagnetic physical science.[64] In detailing the historical steps in the evolution of the electron idea, he, like Lorentz, Wiechert, and the other European electron theorists, emphasized the continuity of the present concepts with those of Weber and Zöllner. Kaufmann closed his discussion by setting out the problems remaining to be examined before an electromagnetic worldview could be established, a worldview he saw as the culmination of a thirty-year historical development. The problems were to show that the electron mass is entirely electromagnetic, to reduce mechanics to electromagnetism, to prove that matter is composed solely of electrons, to relate chemical periodicities to the stable dynamic arrangements of assemblies of electrons, and to experimentally confirm Wien's electron theory of gravitation.

Lorentz responded to the active development of the electron theory into an electromagnetic basis for all of physics. Like Abraham, he welcomed Poincaré's momentum, and he praised Abraham's use of it. In 1903 he deduced Abraham's expression for electromagnetic momentum, or rather the time rate of change of this expression, together with Maxwell's ethereal stresses, starting from a variational principle in mechanics.[65] He had produced the same calculation in 1895, at which time he had remarked on its apparent incompatibility with a stationary ether. Now, following

[63] H. Poincaré, "Sur la dynamique de l'électron," *Rendiconti del Circolo matematico di Palermo*, 1906, *21*:129–176.

[64] W. Kaufmann, "Die Entwicklung des Elektronenbegriffs," *Verh. Ges. Dtsch. Naturf. Ärzte*, 1901, Pt. 1, 115–126.

[65] H. A. Lorentz, "Contributions to the Theory of Electrons," *Proceedings of the Royal Academy of Amsterdam*, 1903, *5*:608; *Collected Papers*, Vol. III, pp. 132–154.

Poincaré and Abraham, he recognized in the concept of electromagnetic momentum an essential component of an ether-based electrodynamics. Lorentz went on to deduce d'Alembert's principle and the principle of least action from the laws of electromagnetism. His interest in relating mechanics and electron theory had changed. In 1892 he had begun with d'Alembert's principle, giving the mechanical symbols an electromagnetic interpretation; now, following Abraham closely, he began with the electron theory, deriving variational laws from it and noting that these laws resemble the laws of mechanics when electromagnetic quantities are associated with the mechanical symbols. Lorentz had gone full circle: first he affirmed the mechanical foundation of the equations of the electron theory; then he bypassed it; finally he indicated, though more cautiously than Wien or Abraham, a suggestive route to an electromagnetic interpretation of the laws of mechanics.

In the following year, 1904, Lorentz published a concise restatement of his electron theory.[66] Once more he was prompted in part to go over it all again by additional optical and electrical experiments on the influence of the earth's motion through the ether. There was a new optical challenge in the failure of Lord Rayleigh and D. B. Brace in 1902 and 1904 to discover double refraction in transparent media due to the earth's motion. A positive second-order result was expected, since by Lorentz's theory transparent media, like all bodies, contract in the direction of motion. And a new electrical difficulty appeared in F. T. Trouton and H. R. Noble's unsuccessful attempt in 1903 to detect a turning couple on a charged condenser. According to the theory there ought to be a second-order effect tending to orient the plates of the condenser parallel to the earth's motion. Lorentz had another object in 1904—a theoretical one. In 1900 Poincaré had observed that Lorentz's explanations of the absence of first-order and second-order influences of the earth's motion were entirely different.[67] That was not the way to construct theory in his judgment, and he called upon Lorentz to provide a single explanation, rigorously predicting a null effect valid for all orders of smallness. Lorentz acknowledged the force of Poincaré's objection.

In 1904 Lorentz was not exclusively concerned with equations for the interior of a dielectric, so that he did not drop certain second-order terms, as he had in 1899, when he assumed that electron displacements and displacement velocities are infinitely small. Consequently his 1904 disproof of unwanted influences of motion was general (though he still failed to obtain the strict invariance of the field equations that Poincaré desired).

Lorentz now made explicit what had been implicit before: his theory applied only to bodies which move with velocities less than that of light, for by his formulas the inertia and energy of bodies become infinite at that velocity. This was extremely important, and Lorentz highlighted it by incorporating the velocity limitation in the title of his paper. He did not say that superior velocities could not occur in nature, but only that they had no place in his theory. That an absolute limit really exists, and that the velocity of light is that limit, was a common and much-discussed conjecture at the

[66] H. A. Lorentz, "Electromagnetic Phenomena in a System Moving with any Velocity Smaller than That of Light," *Versl. Kon. Akad. Wet. Amst.*, 1904, *12*:986; reprinted in A. Einstein, *et al.*, *The Principle of Relativity*, trans. W. Perrett and G. B. Jeffery (New York:Dover, n.d.), pp. 11–34.

[67] Poincaré, "Relations entre la physique expérimentale et la physique mathématique," pp. 22–23.

time, encouraged by the mounting confirmation of electron theory. The suggestion that a great, but finite, velocity plays the role of infinity for the motion of all bodies had of course a profound meaning for conventional dynamics.

After introducing his equations and their transformations, Lorentz devoted the remainder of his 1904 paper to five hypotheses, some new and some familiar. Their purpose was to endow the transformation formalism and its consequences with physical meaning. They add up to an impressive statement of the revolution in molecular-dynamical thinking that had evolved within electron theory in the twelve years since 1892. A need to reconcile the stationary ether with experience impelled Lorentz to move beyond the domain of proven optical and electric phenomena; that internal necessity joined a wider, unifying imperative, urging Lorentz toward the consolidation of a new physics of all matter.

The first hypothesis is that a moving spherical electron undergoes a physical deformation, becoming ellipsoidal in shape, and the coordinate transformation is a description of this deformation. The second says that all nonelectric forces, whether between two ponderable particles or between a ponderable particle and an electron, are influenced by motion in the same way as the electrostatic force between two electrons. The third hypothesis states Lorentz's opinion that the origin of electron mass is wholly electromagnetic; a consequence is that Poincaré's electromagnetic momentum is the only kind there is for electrons. The fourth hypothesis is that the influence of motion on the dimensions of individual electrons and on ponderable bodies as a whole is confined to the dimension parallel to the direction of motion; since compensating dilations normal to the motion are excluded, elements of volume, including the volume of an electron, are not invariant (though the charge contained in any volume is conserved, an assumption which determines a transformation rule for charge density). The final supposition is that the masses of all particles, charged or not, vary with motion exactly as electron masses.

At the end of his paper Lorentz compared his formula for the velocity dependence of the transverse mass with Kaufmann's 1902 measurements on Becquerel-ray deflections. According to his theory the transverse mass of an electron moving with speed v through the ether should be greater than the transverse mass of a rest electron in the ratio of 1 to $\sqrt{1-v^2/V^2}$. Lorentz showed that his formula fitted the data as well as the different one Abraham derived from the assumption of a nondeformable electron.

Lorentz's theory was cast in nearly finished form in 1904, by which time it was widely recognized as the dominant theory in physics and its author the leading theorist. Most of the internal theoretical problems had been solved, and the theory seemed supple enough to counter all experimental objections to a stationary ether. By this time Lorentz must have felt that he was working a vein of gold; his theory had explained an impressive list of phenomena including Fizeau's experiment, normal and anomalous dispersion, the Zeeman effect, Faraday's rotation of light, aberration, and the Doppler effect. In a famous lecture at the end of 1904[68] Lorentz reiterated the achievements of the electron theory and spoke of the problems it had yet to solve. He explained again how important it was to determine whether or not all mass is electromagnetic; for, if it were, then all mechanical facts would receive an electromagnetic

[68] Lorentz, "Ergebnisse und Probleme der Elektronentheorie."

interpretation.[69] He conceded that physics had not yet reached that degree of simplicity and all that was known was that the entire mass of electrons is almost certainly electromagnetic. Abraham showed less reserve in his 1904–1905 revision and expansion of A. Föppl's 1894 Maxwellian text; his stated purpose was to shake the foundations of the mechanical view of nature (upon which view Föppl had founded Maxwell's theory).[70] Convinced that the dynamics of electrons rested on a purely electromagnetic basis, Abraham singled out the obstacles still standing in the way of a complete electromagnetic view of nature: first, the forces between electrons and ordinary matter must be placed on an electromagnetic basis; second, ponderable atoms must be reduced to aggregates of electrons in such a way as to give the right molecular and gravitational forces. This was a formidable program for the future, but in Abraham's judgment one not impossible of fulfillment.

Lecturing in St. Louis in 1904 Poincaré too spoke out for a new, universal dynamics.[71] He could already make out its chief features, which were that all inertia increases with velocity and no object can move faster than light. The new dynamics, he knew, would be a development of electron theory, as that theory alone pointed the way to the needed revision. In his lecture Poincaré placed Lorentz's theory at the center of the crisis physics was then entering. The general principles on which modern physics was built were severely threatened, several of them expressly by Lorentz's theory: equality of action and reaction, relativity, and mass conservation, to be specific. Poincaré thought that the further development and modification of Lorentz's theory would resolve the crisis; he urged physicists to continue their probing studies of electron dynamics, a directive he intended to follow himself.

At the same 1904 congress, Poincaré's countryman Langevin talked on the immense fecundity of the electron concept.[72] Like Poincaré he spoke of a new physics brought about by developments in electron theory. The electron theory, and above all Lorentz's, had already achieved a vast, if still incomplete, synthesis of the branches of physics. It had proven itself an admirable instrument for research, constantly posing new questions in all directions. In light of the promise of the electron theory, it seemed natural to Langevin to reverse the interpretation Maxwell gave his analogy between the electromagnetic equations and the Lagrangian form of the equations of mechanics. He believed that physicists should abandon attempts to understand electromagnetism mechanically and seek instead to reduce the laws of mechanics and the concepts of force and mass to the properties of the ether. While he thought that molecular forces were capable of being understood electromagnetically, he did not hold a fully electromagnetic view of nature. Gravitation, as he saw it, obstinately remained outside the electromagnetic synthesis; so did the force that maintains the stability of the electron, and he anticipated a direct connection between that force and gravitation. Provision-

[69] *Ibid.*, p. 101.

[70] In 1904 Abraham published a revised second edition of A. Föppl, *Einführung in die Maxwellsche Theorie der Elektrizität* (Leipzig: Teubner, 1894). He revised in particular Föppl's chapter on the mechanical derivation of Maxwell's equations; he argued that it was more reasonable to reverse Föppl's position and regard the close relation obtaining between mechanical and electrodynamical principles as favoring the electromagnetic rather than the mechanical view of nature. Abraham's companion volume, published the following year, was entirely his own: *Elektromagnetische Theorie der Strahlung* (Leipzig: Teubner, 1905). For his anticipations of an "electromagnetic worldview," see esp. pp. 143–147.

[71] H. Poincaré, "The Principles of Mathematical Physics," *The Monist*, 1905, *15*: 1–24.

[72] Langevin, "La physique des électrons."

ally he regarded gravitation as a mode of activity of the ether entirely distinct from its electromagnetic modes, admitting, however, the possibility of an electromagnetic explanation of gravitation and even proposing an experiment to test it. His talk reflected the central place electromagnetic ideas had come to occupy in physics and also the uncertainty still surrounding the ideal of a completely electromagnetic physics. He was absolutely definite on the fundamental point that physicists should no longer look to mechanics for their synthesizing laws and concepts, but to the laws of the ether, which he regarded as the sole reality.

In 1912 Poincaré recalled that physics had just passed through one revolution and was now threatened by a new, even more radical one.[73] The new revolution he spoke of was still on the horizon; it was the revision that physical principles would have to undergo to accommodate the newly discovered discontinuities of Planck's quantum theory of 1900. By the other recent, but prior, revolution, he meant the one spearheaded by Lorentz's electron theory. That revolution has since been largely conceded to Einstein's 1905 principle of relativity, which attained most of the results of Lorentz's theory. The striking novelty and continuing good standing of the relativity principle and the quantum theory, both following closely upon the consolidation of the electron theory, have tended to obscure the contemporary reputation of Lorentz's work. Toward the end of his life Einstein wrote that physics had absorbed so much of Lorentz's achievement that its unexpected, audacious character had been largely forgotten.[74] There is an important historical truth in Poincaré's and Einstein's observations: before the advent of quanta and relativity the electron theory had worked profound changes in the foundations of physics, a fact well know at the time.

Although in its programmatic implications for all physics the classical electron theory remained ultimately unfulfilled, it was an extraordinarily important phase in the development of physics. It immensely clarified Maxwell's theory, establishing the field as an independent reality, distinct from ordinary matter. This act of clarification posed at the same time the leading problem for the future—that of connecting the discrete particle and the continuous field in a way that does not lead to contradictions with experience. Lorentz carried classical physics to its furthest stage of clarity, precision, and unity. At the same time he clearly located its inherent limitations, defining the problem areas from which the subsequent great revolutions identified with relativity and quanta arose.

III. DIFFICULTIES WITH THE ELECTROMAGNETIC VIEW OF NATURE

For Lorentz the electron theory held it greatest promise as a theory of universal validity around 1900. After that, signs began appearing which seemed to qualify that promise, the most important of which occurred at the juncture of electron theory and the thermodynamics of radiation. From 1900 on, Lorentz devoted a substantial body of work to understanding the thermodynamic relations of heated bodies and their electromagnetic radiations from the viewpoint of electron theory; the direction of his thought at this time was to seek an electromagnetic foundation for the thermodynamics of radiation as well as for other branches of physics. He attempted to found

[73] H. Poincaré, "The Quantum Theory," *Mathematics and Science: Last Essays*, trans. J. W. Bolduc (New York: Dover, 1963), p. 75.

[74] Einstein, "H. A. Lorentz, His Creative Genius and His Personality."

the universal validity of Boltzmann's and Wien's radiation laws on the ubiquity and uniform properties of electrons[75] and to prove the direct dependence of these laws on the basic equations of electron theory.[76] The formulas of Boltzmann and Wien involved the function $f(T, \lambda)$, which G. R. Kirchhoff had defined as the ratio of emission to absorption of radiation of wavelength λ by a body at absolute temperature T. The function f also characterizes the state of the ether in a black-body enclosure, and it is this significance which Lorentz, like Boltzmann and Wien, turned to.

At first Lorentz did not try to find the form of f, since any derivation required assumptions about the unknown mechanism of absorption and emission. It was not until 1903 that he became persuaded of the probable nature of at least one mechanism for transforming radiant energy.[77] He came to it through the electron theory of metals, a subject which he had just turned to (he devoted roughly half of his famous 1904 lecture on the results and problems of electron theory to the electron-based properties of metals). It was this subject that uniquely brought into common focus the great themes of nineteenth-century physics: electromagnetism, thermodynamics, and kinetic theory. Precisely for this reason the incompatibility of the foundations of the several departments of physics became most apparent here. Lorentz recognized Weber as the pioneer in this subject; but it was the recent developments by J. J. Thomson, E. Riecke, and, above all, by Paul Drude[78] that stimulated his interest.

Drude was strongly attracted to the electron theory and was one of the first to talk of a purely electromagnetic mass. In his theory of metals he assumed that a conductor contains vast numbers of free electrons, moving randomly like molecules of a gas, and that when an electric force is applied, a unidirectional motion is superposed on the random one. Measurements by E. Hagen and H. Rubens in 1903, showing that the absorptivity and reflectivity of metals for long wavelengths involve no other property than their conductivity—a purely electrical quantity—provided Lorentz with his clue: Drude's mechanism of current conduction must also be the mechanism of absorption and hence of emission of radiation of long wavelengths. Following Drude's assumptions that heat in metals is the unordered motion of free electrons and that free electrons obey the equipartition theorem of statistical mechanics, Lorentz found the ratio of emissive to absorptive power of a metal plate in the wavelength interval λ to $\lambda + d\lambda$ to be $16/3(\pi\alpha T/\lambda^4)\, d\lambda$, which is also the energy of radiation in the interval of a black body maintained at temperature T.

Lorentz pointed out that his black-body formula agrees with the long wavelength limit of the quantum formula that Planck had derived in 1900, a coincidence which struck him as highly remarkable considering the widely different assumptions in the two cases.[79] It was characteristic of Lorentz to spell out what was incomplete in his work and what was still unknown; he stressed that his theory is valid only for long wavelengths and that Planck's applies to the whole spectrum. So it was Lorentz, an origi-

[75] H. A. Lorentz, "The Theory of Radiation and the Second Law of Thermodynamics," *Versl. Kon. Akad. Wet. Amst.*, 1900, *9*:418; *Collected Papers*, Vol. VI, pp. 265–279.

[76] H. A. Lorentz, "Boltzmann's and Wien's Laws of Radiation," *Versl. Kon. Akad. Wet. Amst.*, 1901, *9*:572; *Collected Papers*, Vol. VI, pp. 280–292.

[77] H. A. Lorentz, "On the Emission and Absorption by Metals of Rays of Heat of Great Wave-Lengths," *Versl. Kon. Akad. Wet. Amst.*, 1903, *11*:729; *Collected Papers*, Vol. III, pp. 155–176.

[78] P. Drude, "Zur Elektronentheorie der Metalle," *Ann. Phys.*, 1900, *1*:566 and 1900, *3*:369.

[79] Lorentz, "On the Emission and Absorption by Metals," pp. 168–169.

nator of the electron theory, who first intimated the possible limits of the theory. Starting from the electron theory and from a mechanism appropriate to the theory, he arrived at the limiting case of the radiation law; and he did not see how to extend his theory to Planck's general case. Here is a cogent reason why it was Lorentz of all physicists, barring Einstein, who was most deeply concerned with Planck's theory in its earliest years. His sketch in 1903 of the essential physical ideas of the quantum theory seems to have been the first theoretical discussion of the subject after Planck's own.

In 1908 Lorentz came out in support of Planck's theory;[80] it was then that he emphasized the profound antithesis between the quantum hypothesis and the electron theory. At a mathematical congress in Rome that year Lorentz spoke on Planck's and James Jeans' theories of black-body radiation. His object was to prove that the union of the electron theory with Hamilton's equations of motion and J. W. Gibbs' statistics leads inescapably to Jeans' radiation law, which, like his own of 1903, agrees with experience only in the case of long wavelengths. He said that the alternative, Planck's theory, demands far-reaching changes in electron theory. He pointed out that this is easily seen, since an accelerating electron should emit rays of all wavelengths, a result incompatible with the hypothesis of energy elements whose magnitude depends on wavelength. At the time of his lecture he had not yet decided between the two theories. Wien, however, called his attention to experiments showing that for short wavelengths a body emits much less light in proportion to its absorbing power than that predicted by Jeans' theory. This proves, Lorentz said in a note appended to the published version of his talk, that any theory that bases itself on the electron theory and the equipartition theorem has to be profoundly revised.[81] Later in the year he elaborated that note: he had "long hoped," he confessed, "that it would be possible to escape the universal applicability of that theorem [equipartition] by combining electron theory and kinetic theory." He added, "this hope has not been fulfilled."[82] He was now ready to concede that the interaction of matter and ether takes place by means of vibrating charged particles to which Gibbs' statistics, for unknown reasons, are inapplicable.

Lorentz thus accepted the quantum theory as the only theory capable of explaining the complete spectrum of black-body radiation, while at the same time regarding it as very incompletely understood in its connection with the other branches of physics and in particular with electron theory. In his 1906 Columbia University lectures, which he elaborated and published in 1909 as *The Theory of Electrons*, a systematic treatise touching on all areas of the vast domain of electron theory, he devoted only a few paragraphs to Planck's theory, chiefly to point out that it was successful where the electron theory failed.[83] Lorentz apologized in the preface for his inadequate treatment of Planck's theory of black-body radiation, a highly interesting matter "belonging more or less" to electron theory.[84] As time passed, it became clearer that it

[80] H. A. Lorentz, "Le partage de l'énergie entre la matière pondérable et l'éther," *Nuovo Cimento*, 1908, *16*:5; *Collected Papers*, Vol. VII, pp. 317–343, esp. pp. 341–343.

[81] *Ibid.*, p. 342.

[82] H. A. Lorentz, "Zur Strahlungstheorie," *Phys. Z.*, 1908, *9*:562; *Collected Papers*, Vol. VII, pp. 344–376, quotation on pp. 344–345.

[83] H. A. Lorentz, *The Theory of Electrons* (2nd ed., New York: Dover, 1952), pp. 78–80.

[84] Lorentz's 1909 "Preface," *ibid.*

belonged less rather than more to the electron theory, at least in the theory's classical formulation.

The sense of the first Solvay Congress in 1911 was that the electron theory was incompatible with quanta and that it could not be made compatible without far-reaching reform. The Congress and especially its published proceedings [85] went far to redefine the central problems for fundamental physical theory. Niels Bohr's doctoral dissertation in 1911 was a reformulation of Lorentz's electron theory of metals on more general principles.[86] In his dissertation Bohr pointed to persuasive evidence of the ultimate incompetence of mechanics and electrodynamics on the molecular level. His 1913 quantum theory of atoms and molecules,[87] which gave sharp focus to the quantum problems and intimated their enormous fruitfulness, was based on the explicit denial of the validity of ordinary mechanics and the classical electron theory in the atomic domain. Lorentz's theory continued to be worked on, but its concepts were increasingly recognized as unsuited for the basic reconstruction of physical theory demanded by the quantum hypothesis.

While the quantum question raised fundamental doubts about the classical electron theory, the electromagnetic view of nature was challenged in an historically complicated way by another, contemporary development. In his first paper on special relativity in 1905[88] Einstein showed that Lorentz's theory was compatible with the postulational basis he proposed for electrodynamics. Reversing Lorentz's logic, Einstein made relativity a postulate rather than a problem of the electron theory. From this and the postulate of the constancy of the velocity of light, he deduced the Lorentz transformations and other results that had been made known through Lorentz's theory. To reconcile Lorentz's theory with the principle of relativity, Einstein showed that it was necessary to accept two propositions: all inertial frames of reference are physically equivalent, which means there is no reason to assume the existence of an ether fixed to a particular one of them; and Lorentz's local time is, in fact, the true time. Lorentz admired, but never embraced, Einstein's physical reinterpretation of the equations of electron theory. The consequences of his and Einstein's interpretations were identical, and he regarded the choice between them as a matter of taste. To the end of his life he believed that the ether existed and that absolute space and time were meaningful concepts.

For several years after 1905 physicists seldom distinguished between Einstein's and Lorentz's formulations of the electron theory.[89] They referred interchangeably to the "Lorentz," the "Lorentz-Einstein," and the "relativity" theories. Physicists working in electrodynamics were preoccupied with electron dynamics, and relativity had nothing at all to say about electron structure. Einstein made this point emphatically in a published discussion with Paul Ehrenfest in 1907 on the differences between Abraham's and Lorentz's electrons.[90] Relativity, he explained, was not a closed electrodynamic

[85] *La théorie du rayonnement et les quanta*, ed. P. Langevin and M. de Broglie (Paris: Gauthier-Villars, 1912).

[86] N. Bohr, *Studier over metallernes elektrontheori* (Copenhagen, 1911).

[87] N. Bohr, "On the Constitution of Atoms and Molecules," *Phil. Mag.*, 1913, *26*:1–25, 476–502, 857–875.

[88] A. Einstein, "On the Electrodynamics of Moving Bodies," *Ann. Phys.*, 1905, *17*:891–921; Einstein (*et al.*), *The Principle of Relativity*, pp. 37–65.

[89] Hirosige, "Theory of Relativity and the Ether," p. 42.

[90] A. Einstein, "Bemerkungen zu der Notiz von Hrn. Paul Ehrenfest: 'Die Translation deformierbarer Elektronen und der Flächensatz,'" *Ann. Phys.*, 1907, *23*:206–208.

system, but a heuristic principle concerned with measurements and rigid bodies, applicable to all theories. In applying it to the electron theory in 1905 he had assumed that the electron is a rigid body. In doing so he did not agree with Abraham's view that a purely electromagnetic electron dynamics could be constructed on the basis of this assumption. He observed to Ehrenfest that the introduction of a rigid scaffolding was nothing else than the introduction of external forces to establish equilibrium with the electrodynamic forces. He explained that his relativity principle yielded the laws of motion of a rigid electron without assuming anything about the distribution of charge in the electron, which it had been necessary to do in the older electrodynamics to make the problem determinate. Relativity did not shed light on the electron problems that physicists were most concerned with at the time.[91]

The chief reason for the preoccupation of physicists with electron dynamics was its bearing on the electromagnetization of the electron theory and, beyond that, of physics generally. This connection is nicely borne out in a discussion following a talk by Planck on Kaufmann's experiments at the 1906 meeting of the German Natural Scientists and Physicians.[92] A good number of the leading investigators of electron dynamics participated: Planck, Kaufmann, Bucherer, Abraham, Sommerfeld, R. Gans, and C. Runge. Einstein's relativity postulate (which was identified with Lorentz's electron theory in this discussion) and Abraham's and Bucherer's electron theories were compared for their agreement with experiment and for their theoretical satisfactoriness. Abraham's theory fit Kaufmann's most recent data best, but this was not the main issue of the discussion. Abraham and Bucherer raised a theoretical objection to Lorentz's theory on the grounds that it required a nonelectromagnetic equilibrating force and therefore was not a purely electromagnetic theory. Planck was the only one present to stand up for Lorentz's theory. He argeed with Abraham that the real advantage of the rigid electron was that it raised the possibility of a purely electromagnetic electron theory, and that if the rigid electron were established, it would be very beautiful for this reason. But he pointed out that the rigidity of the electron was, for the time being, only a postulate, and one that was in competition with the relativity postulate. The postulates appeared to him to be incompatible, and he found Lorentz-Einstein's the more sympathetic of the two. Arnold Sommerfeld, replying to Planck, suggested that physicists under forty would prefer the "electrodynamic postulate" and those over forty the "mechanical-relativistic postulate." In his view the Lorentz-Einstein theory was a throwback to the mechanical era; it was not built on purely electromagnetic concepts and therefore seemed passé. Lorentz's theory had given the original impetus to the program for an electromagnetic physics, and to Abraham's and Bucherer's modifications of his theory. Now, especially through its association with Einstein's relativity postulate, Lorentz's theory was seen to stand in opposition to the electromagnetic viewpoint in physics and in this sense to be mechanistic and conservative.[93] For the younger physicists the electromagnetic concepts clearly pointed to the future physics.

M. J. Klein has analyzed the exchange between Einstein and Ehrenfest in "Thermodynamics in Einstein's Thought," *Science*, 1967, *157*:509–516, esp. pp. 515–516.

[91] Hirosige, "Theory of Relativity and the Ether," pp. 41–42.

[92] Planck, "Die Kaufmannschen Messungen."

[93] Hirosige has analyzed the discussion following Planck's 1906 paper, emphasizing the important fact that the participants regarded the electromagnetic view as revolutionary, the relativity postulate as conservative ("Theory of Relativity and the Ether," pp. 48–49).

Sommerfeld's remark in the Planck discussion is a trustworthy barometer of the leading physical thought in 1906. Throughout his career Sommerfeld was uncommonly sensitive to the most promising direction in which to develop a theory. His early work closely reflected the shifting, dominant trends in electrodynamic research. His first publication in theoretical physics was a mechanical representation of Maxwell's electromagnetic field, inspired by his study of William Thomson.[94] Like many of his European colleagues, Sommerfeld soon came to feel that nothing would come of the mechanical approach, and beginning in 1904[95] he published several long, difficult papers on a nonmechanical electron theory. He based his work on Abraham's rigid, spherical electron. He was especially interested in the suggestion of an electromagnetic explanation of the mass concept and in the lively question of whether or not electrons can travel faster than light. He analyzed the cases of volume and surface charge distributions for the rigid electron and for speeds greater and less than that of light, concluding with Wiechert in 1905 that one could not speak of electromagnetic mass with speeds above that of light. Shortly after, Sommerfeld judged his electrodynamic labors unfruitful, having been persuaded by Hermann Minkowski in 1908 of the superiority of Einstein's relativity postulate.[96]

Many others like Sommerfeld were converted to the relativity theory by Minkowski's writings.[97] The experimental data also soon lent support to the relativity postulate, favoring the Lorentz-Einstein mass-velocity formula. Around 1910 the relativity postulate began to be recognized as a universal law and not merely an elaboration of Lorentz's electron theory.[98] The relativity theory yielded a mass-velocity dependence that applied to all bodies, whatever their form and nature. Because it stood above assumptions about the structure of the electron, the relativity postulate weakened the electromagnetic argument. To be sure, the postulate left open the question of the electromagnetic origin of mass—the leading question of the electromagnetic program; but for this very reason the postulate tended to remove the theoretical grounds for believing in a purely electromagnetic origin of electron mass. In a discussion following his address on the electron theory at the 1921 Solvay Congress, Lorentz recalled that physicists used to believe that the electron mass is entirely electromagnetic because the mass varies with velocity in the way the theory predicted. But later, Lorentz said, relativity taught physicists that conclusions about the electromagnetic origin of electron mass were not necessarily correct, since all bodies show the same variability of mass.[99] The possibility of an entirely electromagnetic mass was not disproved, but the question gradually lost its early interest and promise as the relativity concept took hold.

IV. LATER DEVELOPMENTS OF THE ELECTROMAGNETIC VIEW OF NATURE

It was entirely possible to accept some form of the relativity principle and continue to hold an electromagnetic view of nature. For a long time Einstein's repeated appeals to give up the ether went largely unheeded. Bucherer in 1908 and 1909 brought forward

[94] Sommerfeld, "Mechanische Darstellung."

[95] A. Sommerfeld, "Zur Elektronentheorie," *Nach. Ges. Wiss. Göttingen*, 1904, pp. 99–130, 363–439; 1905, pp. 201–235.

[96] A. Sommerfeld, "Autobiographische Skizze," American Philosophical Society Library.

[97] Hirosige, "Theory of Relativity and the Ether," pp. 46–48.

[98] *Ibid.*, pp. 43–45.

[99] *Atoms and Electrons* (Paris: Gauthier-Villars, 1923), p. 20.

experimental evidence in support of the Lorentz-Einstein theory and at the same time declared his belief in the immaterial ether as the substratum of matter.[100]

Textbooks on the electron theory, such as Bucherer's in 1904[101] and Abraham's in 1905,[102] which included pronouncements on the electromagnetic-ether foundations of physics, continued to be written long after the publication of Einstein's relativity theory. Gustav Mie published a textbook based on the electromagnetic viewpoint in 1910,[103] the year Einstein's theory began to be widely understood and the stationary ether abandoned. Mie was an early advocate of an electromagnetic physics; in 1903 he had pictured the ultimate constituents of the physical world as massless electrical centers in a world ether.[104] In the foreword of his 1910 textbook he said that physics was now pervaded by an electromagnetic, as opposed to a mechanical, way of thinking, and this was due largely to Lorentz's sharpening of Maxwell's ideas. The purpose of his textbook, Mie said, was to diffuse the electromagnetic viewpoint among a larger audience. Despite the fundamental significance for physics of the electromagnetic view of nature, the concept was still largely unfamiliar to those outside the narrow circle of physical researchers. The world ether, he asserted, was the only reality; and it was necessarily a nonmechanical reality. Dispensing with mechanics was in his opinion the alpha and omega of the electromagnetic way of thinking in the form that Lorentnz gave to it. The aim of physics, he said, was to explain material atoms as singularities in the ether and to reduce mechanics to electromagnetic processes and laws. This aim entailed a complete break with the centuries-old mechanical tradition, and although the break was difficult, it was absolutely unavoidable. Mie noticed that many physicists were now giving up the word "ether," but he did not go along with them. The word was misleading only when it connoted something mechanical; it was a perfectly good word for the immaterial world substance whose physical relations were described by Maxwell's equations. He recognized that Einstein's relativity postulate was more extensive than Lorentz's theory, applying to all physics, and he argued that the postulate was compatible with a world-pervading substance.

Mie emerged as a major figure in the later phase of the electromagnetic program. In 1912 he introduced a new theory of matter that gave mathematical expression to the physical anticipations of the electromagnetic view of nature.[105] David Hilbert, Hermann Weyl, and others wrote on his theory, and for a time it rivaled Einstein's general relativity theory. Mie thought that at the moment experimental research on the nature of atoms was unproductive and was unable to shed light on the role of Planck's quanta. What experiment needed was a new foundation for the theory of matter to guide it. Mie's goal was to explain the existence of indivisible electrons and to relate this explanation to gravitation. He assumed that material atoms are composed of electrons, and that electrons are places of high electric and magnetic field intensities in the world ether where Maxwell's equations and ordinary mechanics no longer hold. He further assumed that all phenomena in the material world can be explained by

[100] Hirosige, "Theory of Relativity and the Ether," p. 49.

[101] Bucherer, *Mathematische Einführung in die Elektronentheorie.*

[102] Abraham, *Elektromagnetische Theorie der Strahlung.*

[103] G. Mie, *Lehrbuch der Elekrizität und des Magnetismus. Eine Experimentalphysik des Weltäthers für Physiker, Chemiker, Elektrotechniker* (Stuttgart: F. Enke, 1910).

[104] G. Mie, *Die Neuern Forschungen über Ionen und Elektronen* (Stuttgart: F. Enke, 1903), p. 40.

[105] G. Mie, "Grundlagen einer Theorie der Materie," *Ann. Phys.*, 1912, *37*: 511–534.

electric particles and the electromagnetic field. Finally, he assumed that the relativity principle has universal validity. He showed that his assumptions led to the gravitational theory Abraham had published earlier in 1912. Mie's theory was able to circumvent the rigid constraints of Abraham's electron and the nonelectromagnetic energy that Poincaré's electron required to assure equilibrium; this was greeted as a progressive step by proponents of an electromagnetic physics.

Mie's nonlinear electrodynamics was an indication of the continuing vitality of the electromagnetic directive in physical research. But the quantum features of nature were not convincingly or fruitfully subsumed under the classical field concept. Nor were the uncertainties about the ultimate constituents of nature raised by radioactive phenomena favorable to a belief in the simplistic goal of the early electromagnetic view of nature. Many basic problems connected with the structure of atoms and radiation had to be solved before the final objective of the electromagnetic view of nature could be assessed. Quanta, the most severe challenge to classical physics, were not necessarily incompatible with an electromagnetic view of nature; but most physicists found it more productive to work piecemeal toward a new mechanics than to search for quantum solutions in a new, wholistic field theory.

Einstein was one who did not follow the majority. He did not look for a new mechanics of quanta; his objective was closer to that of the electromagnetic view of nature.[106] Unconvinced that electromagnetism was a sufficient basis for all of physics, and persuaded that the Maxwell-Lorentz theory was inexact, Einstein founded his researches on the universal relativity postulate rather than on electrodynamic assumptions. In strenuous, largely unpublished efforts in the years around 1909,[107] Einstein tried to recast the equations of the electron theory to remove the outstanding obstacle in the way of a purely electromagnetic electron theory: he wanted to circumvent the requirement of nonelectromagnetic forces to guarantee the permanence of an electron by deriving electrons and their properties solely from a revised set of electromagnetic field equations. He had another purpose, too; he wanted to incorporate light quanta, whose existence he had inferred in 1905, into the field equations, solving the quantum problem at the same time he solved the electron problem. He was unsuccessful in his ambitious attempts to construct a new electron theory, and in 1911 he returned to a line of research he had sketched in 1907. He sought a gravitational and, subsequently, a unified gravitational and electromagnetic field theory in the context of his general relativity theory. A principal objective of his later field theories was to deduce particles and their laws of motion from the equations of the total field. He anticipated that the discrete processes of the quantum theory would emerge from a correct formulation of the field theory problem.

Einstein's postulational derivation of the field equations did not satisfy those who sought electromagnetic foundations for physics. In the wake of the dramatic 1919 solar-eclipse confirmation of Einstein's gravitational theory, Wiechert[108] published an alternative gravitational theory based on the idea he had proposed nearly thirty years earlier—that all matter is composed of electric particles and that the particles are structures in a world ether. He reasoned that since electrodynamics taught that

[106] I discuss the relation of Einstein to Lorentz and the electromagnetic view of nature in "Einstein, Lorentz, and the Electron Theory."

[107] *Ibid.*

[108] E. Wiechert, "Die Gravitation als Elektrodynamische Erscheinung," *Ann. Phys.*, 1920, *63*:301–381.

all mass is electromagnetic, the logical step was to show that electromagnetism is the origin of gravitation.

Lorentz greatly admired Einstein's gravitational and general relativity theories, and he made fundamental contributions to them in 1914–1917. Lorentz regarded the physical space of general relativity as essentially fulfilling the role of the ether of the older electron theory. Einstein saw it this way, too. The final home of Lorentz's electron theory and of the field theory ideal it inspired was the general relativity theory and the field theories associated with it. The electromagnetic view of nature had not been attained, but it had defined the problems for, and was absorbed in, a broader unified field view of nature.

V. SUMMARY AND CONCLUSIONS

Lorentz's electron theory had roots both within the mechanical tradition and outside it. The basic equations were provided with a mechanical derivation to begin with, and the theory was based on the view that the fundamental unit of electricity was borne by an inertial corpuscular body that moved according to the laws of mechanics. For the rest, however, Lorentz built on electromagnetic concepts. He adopted contiguously acting, finitely propagated forces, which could be construed mechanically but which lay outside the main tradition of mechanical physics. The fundamental entities that his equations described—the stationary ether and electric charge—were inherently nonmechanical. The ether did not have mechanical mass, and its electric and magnetic energies were nonmechanical. Moreover, the ether did not experience a mechanical reaction from the electric particles it acted on, in contradiction with the mechanical law of action and reaction. To remove the contradiction the theory had to admit the existence of an electromagnetic momentum, another explicitly nonmechanical concept. Lorentz's explanation of the Michelson-Morley and other second-order experiments on the earth's absolute motion led to the replacement of yet another mechanical concept: the constant Newtonian mass of the electron and of the material molecule was superseded by the concept of a velocity-dependent mass, related to or identical with the electromagnetic concept of self-reaction. The same experiments demanded that moving electrons undergo an electromagnetic deformation and that the deformation apply to all mechanical bodies, too. The dimensional contraction of the electron or material molecule was not caused by a mechanical resistence of the ether, but was solely an accompaniment of the circumstances of motion. Lorentz identified the velocity of light as the upper limit of the velocity of electrons and of mechanical bodies alike, a restriction that was unknown in the mechanical view of nature. In sum, Lorentz constructed an electron dynamics that reduced the status of conventional dynamics to that of a first approximation valid for small velocities. The electron theory promised to replace molecular mechanics as the synthesizing theory in all domains of physical science.

It was in part because Lorentz's theory came so close to being a universal, purely electromagnetic physics that his successors modified it and promulgated an electromagnetic view of nature. They introduced alternative assumptions about the structure of the electron to eliminate the single remaining impurity—the nonelectromagnetic force required to maintain the equilibrium of the electron. Once they had established the electron theory on unobjectionable electromagnetic foundations, they intended to interpret material atoms, the laws of mechanics, and molecular and gravitational forces as modes of activity of electrons and the electromagnetic ether or of the electromagnetic ether alone.

Lorentz did not speak out for this extreme reductionism in an unguarded way. He thought it was likely that all matter was ultimately electrical, but this was no more than a reasonable hypothesis; and although he saw the appeal and occasional advantage of regarding electrons as structures in the ether, he preferred to treat them as bodies existing independently of the ether. The leading European theorists of Lorentz's generation, Poincaré and Planck especially, were early persuaded of the general correctness and fruitfulness of the electron theory. But it was the next generation of physicists that was most responsive to the universalist prospects opened up by the electron theory. The younger physicists, those in Germany particularly, saw their elders—Maxwell, Thomson, Boltzmann, Hertz—as having been misguided in their pursuit of mechanistic invention and mechanical synthesis. The promise of mechanics as the unifying science seemed to them to be played out. They were immensely impressed instead by the discoveries arising from the new concept of the electromagnetic field. I have discussed a number of young, influential German physicists who were sympathetic to the electromagnetic program. All were under forty in 1900, and all did their university study within the period 1881–1897. It was in the middle of this period, in the late 1880s, that Hertz empirically confirmed Maxwell's electromagnetic waves; it was universally assumed that the ether was confirmed at the same time. The experiments of Hertz had an overwhelming impact on physics, and they occurred in the formative years of the generation that went on to dedicate itself to raising the electromagnetic ether to the status of the basic building block of nature.

There were manifold reasons why numbers of physicists maturing around 1900 were an iconoclastic generation in their disrespect for the traditional mechanical foundations of natural science. From the middle of the previous century the physics discipline had instilled in its recruits a high respect for the critical examination of the foundations of the whole of physics and its branches. The discipline-sanctioned preoccupation with foundations underlay the late-nineteenth-century critiques of mechanics and of the mechanical worldview. There was special concern over the disparateness of the concepts of mechanics and those of electromagnetism and thermodynamics. The energetic, electromagnetic, and relativistic worldviews and other theoretical disjunctions, such as the quantum hypothesis, were interconnected consequences of the exercise of the critical function in combination with the traditional search for unity. The orientation toward methodological and epistemological questioning in the half century prior to 1900 prepared the way for profound departures from the mechanical way of viewing nature. Physicists starting their careers around 1900 had been nurtured on critiques of the axioms of mechanics and the mechanical concepts of mass and force, and they had been exposed to analyses of the incompleteness of mechanics in its own domain and of the unsatisfactoriness of its claim to be the foundation for all of physics. A leading objection to mechanics was not that it was inadequate so much as that it was too accommodating, too prolific of possibilities of explaining the phenomena. There were attempts within mechanics to correct for its indeterminateness by reformulating it into a closed system. But another reaction was to abjure mechanical constructions altogether, since they were not unique and therefore had no permanent significance. The other kind of mechanical explanation, one that was abstracted from any particular mechanism, was in vogue after Maxwell, but it did not penetrate deeply into things and was ultimately judged unsatisfactory.

To many temperaments an electromagnetic understanding of the phenomena appealed as something deeper than a mechanical understanding. The whole cultural configuration at the turn of the century was implicated in the change from mechanical to electromagnetic thinking. The immaterial electromagnetic concepts were attractive in the same measure that the inert, material imagery of mechanics was displeasing. The ether, whose properties were considered to be exactly described by the concise, elegant equations of the electron theory, stood in marked contrast to ordinary matter, whose complexity was believed incapable of ever being exactly described. In the mechanical phase of physics, electromagnetism seemed complex because its mechanical elucidations were intricate. By 1900 electromagnetic phenomena were widely regarded as the simplest of all, and the previously self-evident mechanical phenomena, such as gravitation, inertial motion, and heat, now appeared to be complex. The ether was thought to be understood in the sense that its equations were known; at the same time it was thought to be incomprehensible, a totally abstract, dematerialized body, unlike anything accessible to human experience. The physicists who were prone to an electromagnetically based physics regarded it as vain to try to look through Maxwell's equations at the mechanism beyond. There was nothing pictorial or tangible to grasp; the ether was an insensible being, full of motion, the final term of physical analysis. Its ineffability evoked frequent philosophical and aesthetic appreciations, reflecting the satisfaction physicists found in the dematerialization of their science. In this article I have focused on developments internal to the electron theory, showing how mechanics was displaced by an electromagnetically founded dynamics and how the electron theory served as a source of a new set of worldview concepts. I have not undertaken the difficult task of fully analyzing the conditions—conditions lying at the interface of science and the larger culture—that weakened physicists' allegiance to mechanical principles and made them uncommonly sensitive to worldview perspectives at the end of the nineteenth century.

One of the practical functions the electromagnetic view of nature served was to direct the selection of problems in electrodynamic research. The decision as to the possibility of replacing the mechanical by the electromagnetic worldview turned on experiments on the velocity dependence of electron mass and, more critically, on the resolution of theoretical problems concerning electron equilibrium and deformation. These problems were exhaustively mined in the early years of the twentieth century. The electromagnetic and mechanical worldviews were juxtaposed within the same field of vision pending the determination of which part of the electron mass is electromagnetic and which part Newtonian. The expectation was that there would prove to be no need for admitting a Newtonian component. This expectation seemed to be confirmed shortly after 1900, with the result that the countless analogies that subsisted between mechanisms and electrodynamic processes assumed a new aspect. The close, formal parallels between mechanical and electromagnetic laws were no longer seen as being favorable to the mechanical view of nature. With the same right, the advocates of an electromagnetic viewpoint argued, the parallels could be taken as revealing electromagnetic processes underlying the mechanical ones. The converse interpretation had arisen only because of the historical circumstance that mechanics was developed before electromagnetism. The greatest emphasis was placed on constructing a purely electromagnetic electron dynamics; the intention was to persuade the physical community of the misdirection of its habitual analogies. Physical science was once again united, this time on true concepts and exact laws. The anomie in physical research in the period of dissolution of the mechanical consensus was ended, or so it seemed for a time to the electromagnetic generation.

The electron theory together with its promise of an electromagnetic foundation of mechanics and beyond that of a completely electromagnetic physics was the central focus of revolutionary expectations in the first decade of the century. Historical reconstruction has tended incorrectly to locate the immediate origins of the expectations in Planck's quantum theory of 1900 and in Einstein's relativity theory and light-quantum hypothesis of 1905. It fact, until about 1910 few physicists devoted serious attention to quanta, let alone anticipated a nonclassical physics of quanta. Nor before that time was relativity generally recognized as being anything more than a form of Lorentz's electron theory; moreover, the relativity postulate and Lorentz's theory were widely regarded as outmoded, since they seemed not entirely emancipated from the mechanical worldview.

The conditions making possible the quantum and relativity innovations were consequences of the inherent difficulties of bringing the other domains of physics into agreement with electrodynamics. The potential, incentive, and precedent for innovation around 1900 can only be properly assessed by recognizing the dominant place of electrodynamic thinking in physics. Planck came to the quantum theory from attempts to provide thermodynamics with a fundamental electromagnetic basis. Both the relativity theory and the light-quantum hypothesis originated in Einstein's analysis of the inner disharmony between the concepts of the electron theory and those of mechanics. The mechanical view of nature had been rejected in Europe by the beginning of the twentieth century, a fact that is seldom remarked on. Neither the quantum nor the relativity theory brought it about; nor was Maxwell's theory responsible, as it is often said to have been. It was the electron theory that first showed precisely in which ways mechanical concepts and laws might be superseded: the electron theory channelled the discontent over indeterminate mechanical analogies and hypotheses into a constructive, alternative worldview. By 1900, the year when Lorentz's theory became widely accepted, the electron theory had already abrogated most of the concepts and laws of mechanics and had supplanted them with definite electromagnetic analogues. Quanta and relativity, being the sources of continuing, paradoxical developments in physical theory, have largely eclipsed the historical circumstance that—in their day—the electron theory and the associated electromagnetic view of nature represented the most significant shift in the intellectual horizons of physicists in two hundred years. A transformation of worldview occurred wholly within what, by convention, we have come to regard as nonrelativistic classical physics.

In the long run the quantum and relativity theories worked against the electromagnetic program. The quantum properties of matter and radiation challenged the most basic principle of physics—the continuity of dynamical processes—and the original electron theory eventually lost its credibility as an exact theory. As the radical implications of quanta became increasingly recognized, the vision of an imminent resolution of the basic problems of physical theory through classical electromagnetic foundations seemed naively premature. For its part, special relativity transformed the concepts of space and time, the only remaining concepts in mechanics that the electron theory had left untouched. In Einstein's view the transformation entailed the abandonment of the ether; his view gradually gained acceptance and weakened the electromagnetic program. The most serious effect that relativity had on the electromagnetic view of nature was that it rendered vague the status of the electromagnetic-mass question and other questions concerning electron properties. The relativistic electrodynamics yielded all the testable electron dynamical formulas without having to be concerned with the shape, substance, and charge distribution of electrons—problems which had been central in the prior electrodynamics but which after the advent of relativity were never resolved.

Although the electromagnetic point of view entered electron theory textbooks early in the century, a second generation of physicists was not trained to continue the tradition. Physics was in a time of rapid transformation, and the universalist goals formulated within the original electron theory were unhelpful in solving the increasingly central problems of atomic structure and spectra. The highly innovative, visionary program of an electromagnetic physics of 1900 came to appear increasingly conservative after 1910 or so. The quantum hypothesis pointed toward a physics based on acausality and discontinuity, concepts antithetical to the electromagnetic view. The relativity theory displaced the electron theory as the most fruitful source of synthesizing concepts in physics. At the same time the relativity theory incorporated its predecessor's basic objective: the field-theoretical ideal of the electron theory and the electromagnetic program was assimilated into the universalist program of general relativity.