LOOMIS, ELIAS (*b.* Willington, Connecticut, 7 August 1811; *d.* New Haven, Connecticut, 15 August 1889), *meteorology, mathematics, astronomy.*

Loomis graduated from Yale College in 1830, and was a tutor there from 1833 to 1836. He became professor of mathematics and natural philosophy at Western Reserve College, in Hudson, Ohio, in 1836, although he spent the first year of his appointment in further study in Paris. From 1844 to 1860 he was professor at the University of the City of New York. In 1860 he accepted a call to Yale, where he stayed until the end of his life. After the early death of his wife, Loomis led a rather isolated life, centered around his work, his only diversion being the compilation of an extensive genealogy of the Loomis family. He was member of the National Academy of Sciences and of scientific societies in the United States and Europe.

Loomis' interest was divided among several branches of science. Most of his scientific achievements were of a practical, rather than a theoretical, nature. His work, reflecting his conviction that the laws governing natural phenomena can be uncovered only by studying observed data, was carried out with utmost precision, and his research, although not always original, was highly valued because of its great reliability. In his own time, however, Loomis was better known for the publication of a large number of textbooks on mathematics, astronomy, and meteorology than for his scientific investigations.

Loomis made his most important contributions in the field of meteorology. In 1846 he published the first "synoptic" weather map, a new method of data representation that in the following decades exerted a profound influence on the formulation of theories of storms. This method became of fundamental importance in the development of weather prediction. The weather maps presented in Loomis' paper brought clarification to the heated controversy between J. P. Espy and W. C. Redfield concerning the surface wind pattern in storms. Later, Loomis essentially followed Espy in regarding thermal convection, reinforced by the latent heat released during condensation of water vapor, as the chief factor in storm formation. As soon as weather maps began to be published on a daily basis in the United States, in 1871, Loomis embarked on a long series of meticulous statistical investigations of cyclones and anticyclones. His results effectively supported the convection theory of cyclones.

Throughout his life Loomis was strongly interested in geomagnetism. In 1833–1834 he conducted a series of hourly observations of the earth's magnetic field and mapped his results for the United States. In 1860 Loomis prepared the first map of the frequency distribution of auroras and pointed out that the oval belt of most frequent auroras was not centered on the geographic pole but approximately paralleled the lines of equal magnetic dip.

Loomis devoted much of his time to astronomical investigations. These studies dealt mainly with the observation of meteors and the determination of longitude and latitude of various localities. Together with D. Olmsted he rediscovered Halley's comet on its return in 1835 and computed its orbit.

BIBLIOGRAPHY

I. Original Works. Loomis published a large number of his papers in the *American Journal of Science and Arts*, including his investigations on the aurora borealis (1859–1861) and a series of twenty-three papers entitled "Contributions to Meteorology" (1874–1889). A complete bibliography of Loomis' works is to be found in H. A. Newton, "Biographical Memoir of Elias Loomis," in *Biographical Memoirs. National Academy of Sciences*, **3** (1895), 213–252. Collections of Loomis' papers and correspondence are to be found in the Manuscripts and Archives Department of the Beinecke Rare Book and Manuscript Library at Yale University.

II. Secondary Literature. The most complete biographical notice is H. A. Newton, cited above. See also F. Waldo, "Some Remarks on Theoretical Meteorology in the United States, 1855 to 1890," in *Report of the International Meteorological Congress, Chicago*, August 21–24, 1893, edited by O. L. Fassig as *Bulletin. Weather Bureau, United States Department of Agriculture* **2**, pt. 2 (1895), 318–325.

Gisela Kutzbach

LORENTZ, HENDRIK ANTOON (*b.* Arnhem, Netherlands, 18 July 1853; *d.* Haarlem, Netherlands, 4 February 1928), *theoretical physics.*

Lorentz' father, Gerrit Frederik Lorentz, owned a nursery near Arnhem. His mother, the former Geertruida van Ginkel, died when he was young; and his father married Luberta Hupkes when the boy was nine. Lorentz attended primary and secondary schools in Arnhem and was always the first in his class. From an early age he was drawn to physical science, although he also read widely in Victorian novels and Reformation history. He was unusually quick with foreign languages, inferring grammar and idiom from context. Although he grew up in Protestant circles, he was a freethinker in religious matters; he regularly attended the local French church to improve his French.

By the time Lorentz matriculated at the University of Leiden in 1870, his primary interests were mathematics and physics. He became close friends with the astronomy professor, Frederick Kaiser, and followed his lectures on theoretical astronomy with keen interest. He also attended the lectures of Pieter Leonhard Rijke, the only professor of physics at the time. After a year and a half Lorentz passed his candidate's examination in mathematics and physics and returned to Arnhem to prepare for his doctoral examination and to write his dissertation. He lived at home for seven years, studying on his own and teaching in the evening high school. It was at this time that he bought an edition of Fresnel's collected works, the first reference volume he owned beyond the usual textbooks. He admired Fresnel above any of the early physical authors (as he came to admire Hertz above any of the modern ones), being impressed by his logical clarity and by the sure physical intuition that enabled him to overcome a limited mathematical skill. Following his French master, Lorentz cultivated clarity and physical insight as his own special talents.

Theoretical physics tended to be an isolated activity for the early specialists in the discipline; Lorentz, like his contemporary J. W. Gibbs and like Einstein somewhat later, carried out highly original researches on the central problems of physics while removed from direct contact with other active researchers. Lorentz needed only to make the short trip to Leiden's physics laboratory to borrow Maxwell's works and to keep in touch with the current specialist physics literature. His linguistic fluency was a marked asset in his Arnhem years, enabling him to command a wide range of physical writings in French, German, and English. Trained in Leiden and working in Arnhem, his receptivity to outside influences was not inhibited by any dominant local school of physics. He passed his doctoral examination *summa cum laude* in 1873 and received his doctorate in 1875, at age twenty-one; his dissertation was on physical optics, the subject Fresnel had made his own but which Lorentz treated from the viewpoint of Maxwell, as interpreted by Helmholtz.

Lorentz remained at Arnhem after receiving his doctorate, uncertain whether to follow a career in physics or mathematics. His uncertainty was in part a reflection of the professional condition of physics. Although he did some optical and electromagnetic experiments at Arnhem, he was strongly drawn to the theoretical aspects of physics; at this time, however, theoretical physics was only starting to be organized as an independent discipline within physics; and the prospects for a career in the discipline were problematic. The importance of Lorentz' thesis was early recognized in his own country, as was his academic promise generally; and in 1877 he was offered a chair of mathematics at the University of Utrecht. That same year the University of Leiden offered him its new chair of theoretical physics, which had originally been intended for J. D. van der Waals. Lorentz accepted the appointment, resolving his career uncertainty; he was not yet twenty-five. The Leiden theoretical physics chair was the first of its kind in the Netherlands, and one of the first in Europe. Lorentz holds a major place in the history of physics for his part in shaping the new role of the discipline as well as for his scientific contributions.

In 1881 Lorentz married Aletta Kaiser, a niece of his former astronomy teacher. Their first daughter, Geertruida Luberta, was born in 1885; their second, Johanna Wilhelmina, in 1889. Their first son died in infancy; their second, Rudolf, was born in 1895. Lorentz' elder daughter remembers him as constantly at his writing desk, yet never seeming to be engaged in hard work. He had none of the mannerisms of the eccentric genius nor of the bookish ascetic. He was a disciplined scholar of regular habits and disposition. He was social, with a marked sense of humor and a gift for conversation; he always enjoyed a cigar and glass of wine with friends. To all who knew him, he seemed a man of remarkable inner harmony.

At Leiden, Lorentz developed his most original contribution to theoretical physics, his celebrated electron theory. He announced and articulated the theory in a series of publications beginning in 1892. In his fifteen years at Leiden prior to 1892, Lorentz had not been uncommonly productive by contemporary standards. He had published an average of one paper a year; in addition he had written two widely used textbooks in Dutch, one on the calculus for physical scientists in 1882 and one on elementary physics in 1888. Lorentz' most productive period began in 1892, when he was almost forty. Between 1892 and 1904—the time during which he largely completed his electron theory—he produced an average of three to four research publications a year. For Lorentz, as for others, the electron theory opened up a vast number of new experimental and theoretical directions. Much of the physics community now looked to Leiden for guidance.

Lorentz' influence on theoretical physics was exerted not only through his writings but also through the personal impression he made on young physicists who came to Leiden from all over the world to hear his lectures. His influence was unwitting in the sense that he did not interfere with others and did not inspire a school of the usual kind. He followed the work of students and younger physicists, but he did not try to influence the direction of their interests; his relations with them were in keeping with his basically private nature, at once kindly and aloof. Einstein and other theorists of the younger generation venerated him, making frequent journeys to Leiden to visit him and hear his thoughts on their latest ideas. They prized him for his intellectual daring and mastery, his thorough familiarity with all areas of physics, and his nonmanipulative, natural leadership. Einstein said Lorentz had been the greatest influence in his life.

In 1905 Lorentz considered moving to the University of Munich as professor of theoretical physics. It was only after the University of Leiden relieved him from the chore of delivering introductory lectures by appointing a third professor of physics that he agreed to stay. Lorentz resigned his Leiden chair in 1912, after thirty-five years of lecturing on all aspects of theoretical physics. He moved to Haarlem, where he served as curator of the physical cabinet in Teyler's Stichting, a museum housing science, art, and coin collections, and as secretary of the Hollandsche Maatschappij der Wetenschappen, an organization to promote private patronage for science. The museum contained a laboratory, which was remodeled after that of the Royal Institution of London for Lorentz's use. For the first time Lorentz had his own laboratory, something the University of Leiden had promised him but failed to deliver, to his great disappointment.

For years Lorentz gave popular physics lectures, a task he liked and took seriously; but chiefly he used the greater freedom of his new post to pursue his theoretical researches. He retained a connection with the University of Leiden as an honorary professor, in which capacity he delivered his famous Monday morning lectures on current problems in physics. In the latter part of his career he performed various services for the government. He was keenly interested in education and served on the government board of education from its founding in 1919 until 1926, helping to reform university examinations and to redistribute professorial chairs among the universities; from 1921 he was president of the department of higher education. He also worked on practical applications of physics for the government; in 1920 he took charge of the calculations for the height of the dike closing the Zuider Zee, devoting years to the completion of the problem.

Lorentz lived all his life in a few close-lying Dutch towns—Arnhem, Leiden, Haarlem—yet he was the most cosmopolitan of physicists. For the first twenty years of his career, his cosmopolitanism was of a restricted, literary kind. After that he began to move outside his Leiden study and lecture room to make personal contact with physicists abroad. He did this at the time his electron theory was securing him a commanding position in physics, which was also the time of a new phase of international awareness of the science. International physics meetings are essentially a twentieth-century phenomenon, although before then physicists of one country sometimes attended physics meetings in another. Lorentz was first drawn out in 1898, when he accepted Boltzmann's invitation to address the physics section of the Düsseldorf meeting of the German Society of Natural Scientists and Physicians. In 1900 he addressed the International Congress of Physics in Paris, a truly worldwide assembly of physicists.

Lorentz' most important international activity in physics was his regular presidency of the Solvay Congresses for physics from their inception in 1911 through 1927, the last meeting before his death. For a quarter-century Lorentz was a kind of institution at these and other international gatherings, where he presided as the willing and acknowledged leader of the physics discipline. Everyone remarked on his unsurpassed knowledge, his great tact, his ability to summarize lucidly the most tangled argument, and above all his matchless linguistic skill. In addition to presiding at congresses, he did a good deal of invited lecturing, further evidence of the increasing internationalism of physics. He spoke on the electron theory and other topics of current physical interest in Berlin in 1904, in Paris in 1905, in New York in 1906, and later in Göttingen, Pasadena, and elsewhere.

After World War I, Lorentz' cosmopolitanism took on a political cast. As president of the physics section of the Royal Netherlands Academy of Sciences and Letters from 1909 to 1921, he used his influence to persuade his countrymen to join the postwar international scientific organizations created by the Allies. He sought to repeal the clauses excluding the Central Powers from the organizations and to restore true internationalism to science. In 1923 he became one of the seven members of the International Commission on Intellectual Cooperation of the League of Nations, succeeding Henri Bergson as its president. Lorentz' efforts to restore internationalism in science made little headway against the powerful nationalisms supporting the scientific boycott and counterboycott of the Central Powers. The continuing divisiveness of science was a source of great unhappiness to him.

In 1902 Lorentz shared the Nobel Prize in physics with his countryman Pieter Zeeman. He also received most of the other honors that ordinarily come to one of his scientific stature: he was awarded the Royal Society's Rumford and Copley medals; he received honorary doctorates from the universities of Paris and

Cambridge; and he was elected a foreign member of the German Physics Society and the Royal Society.

When Lorentz died in 1928, at age seventy-four, he was honored as the greatest cultural figure the Netherlands had produced in recent times. On the day of his funeral the Dutch telegraph and telephone services were suspended for three minutes in tribute. Representatives of the Dutch royalty and government attended his funeral in Haarlem, as did representatives of scientific academies from around the world. Einstein, a leader of the second generation of professional theoretical physicists and representative of the Prussian Academy of Sciences, spoke at the graveside, referring to Lorentz as the "greatest and noblest man of our times."

One of Lorentz' marked characteristics was an uncommon openness to new trains of thought. Again and again Einstein, Erwin Schrödinger, and other theorists sought his opinion, which was at once sympathetic, informed, and critical. Lorentz' openness was rooted partly in temperament and partly in his view of the proper work of the theoretical physicist. In his inaugural lecture at the University of Leiden in 1878, he explained that the object of all physical research was to find simple, basic principles from which all phenomena can be deduced. He warned against placing undue importance on the mental images associated with basic principles or hoping that the principles themselves can be further explained. He believed that we cannot penetrate deeply into the nature of things and that it is therefore unthoughtful to advocate any given approach as the only valid one. Various basic theoretical approaches—such as atoms and distance forces, contiguous action in a material plenum, and vortex-ring atoms—should be explored at the same time by different investigators, for only then could physicists compare approaches and decide which one leads to the simple basic principles. Much of Lorentz' lifework was spent in critically examining others' theories and helping them seek out simple principles, an activity that conformed to his understanding of the critical function of the theoretical physicist. It should be remarked that in his activities as critic and as constructor of physical theories, Lorentz was strongly sympathetic to certain approaches. However, he had an uncommon ability to distinguish between sympathy and critical judgment in his appraisal of theories. This ability—basically a trait of temperament—underlay in large part his seemingly contradictory roles as strongly committed theorist and openminded critic.

Lorentz' most important work was in optical and electromagnetic theory; to follow its bearing on the development of physics, we shall have to look at the state of the fields as he found them in the 1870's. Optical thinking was then dominated by the elastic-solid theory of the luminiferous ether, which had been developed by Fresnel, Cauchy, Neumann, Stokes, and others. The theory had major difficulties. One was the presence of longitudinal as well as transverse waves in elastic solids, whereas in optical phenomena only transverse waves were known. Another was the failure of elastic solids to yield Fresnel's fraction for the light reflected at the interface of two optical media. These and other difficulties resulted in an accumulation of hypotheses. The longitudinal wave could be disregarded if its velocity of propagation were assumed to be infinite. Certain properties of the passage of light through optical media could be explained by assuming different densities for the ether inside and outside of matter; certain others, by assuming different elasticities for the ether inside and outside matter. The state of optical theory in the 1870's was, in a word, unsatisfactory.

The state of electrodynamics in the 1870's was at least as unsatisfactory as that of optics. There was little agreement on the proper theoretical principles for developing electrodynamic theory. The two most successful electrodynamic theories in Germany were those of Weber and Neumann. Both theories had originated in the mid-1840's, and Weber's especially had been extensively developed since then. Encompassing all electric and magnetic phenomena, Weber's theory was based on the hypothesis that an electric current consisted of two fluids of electric particles of opposite signs moving in opposite directions. It was also based on the hypothesis of a central, instantaneous, action-at-a-distance force between pairs of electric particles. The force was analogous to the gravitational attraction between material particles, except that it depended on the relative motion as well as on the separation of the particles and was attractive or repulsive according to the signs of the particles. Weber's motion-dependent force had an unclear relation to the energy principle, and was challenged for this reason. Neumann's theory of induced electric currents was based on the hypothesis of a position- and motion-dependent force between two elements of electric current rather than between pairs of electric particles. Both theories followed Ampère's in referring magnetism to elementary circular electric currents.

Several other electrodynamic theories were subsequently put forward in Germany. Riemann in 1858 and Neumann in 1868 advanced theories modeled after Weber's; they differed in that they postulated a finite velocity of propagation of electric action, introducing retarded potentials for that purpose. Encouraged by the closeness of the values for the speed of light and the ratio of the electromagnetic and electrostatic measures of electricity—a ratio that had units of velocity and that entered all Weber-type force laws—Riemann identified light with the propagation of electric action. Neumann, however, was more impressed by the differences between light and the finitely propagated potential of his theory, rejecting the suggestion that they were the same thing. Clausius introduced another variant of Weber's theory in the mid-1870's, assuming only a single mobile electric fluid and a force between two electric particles that was noncentral and that depended on the absolute, rather than relative, motion of the particles.

A prominent non-German electrodynamic theory was that proposed by the Danish physicist Ludwig Lorenz in 1867. From Kirchhoff's equations—which stemmed from Weberian electrodynamics—for the motion of electricity, Lorenz, with the use of retarded potentials, showed that periodic electric currents behave like the vibrations of light, concluding that light itself consists of electric currents. Another prominent non-German Continental theory was proposed by the Swedish physicist Erik Edlund in 1871. Edlund derived Weber's fundamental law by assuming a single, particulate electric fluid—which he thought was probably the luminiferous ether—and by assuming that electric actions are finitely propagated. Whereas Lorenz broke with action at a distance, Edlund did not; whereas Edlund assumed an electric ether, Lorenz did not. The disagreements multiplied.

The several Continental electrodynamic theories resulted in a maze of incompletely tested hypotheses, and no immediate experimental decision seemed likely. The conflicting hypotheses centered on several issues: the number—whether one or two—of mobile electric fluids; the existence of an electric ether; the identity of light with electric motions; the nature of the forces between electric fluid particles, to which belonged the questions of central or noncentral forces, and of the relative or absolute motion that entered the force laws; and the relation of motion-dependent forces to the principles of dynamics, especially to the energy principle.

Contributing further to the profusion of electrodynamic principles was the very different theoretical tradition that had developed in Britain during the same period. Drawing on Faraday's and William Thomson's work, Maxwell proposed a mathematical theory of electricity and magnetism in papers in the 1850's and 1860's and in his comprehensive *Treatise on Electricity and Magnetism* in 1873. Rejecting action at a distance and the associated particulate electric fluids of Continental electrodynamics, Maxwell based his theory on the concept of an electromagnetic medium. The essential point of the theory was that the electromagnetic medium supported transverse vibrations that propagated at the speed of light. The theory promised to be fruitful, especially in the prediction it shared with certain Continental theories that light is an electric phenomenon. Maxwell took seriously the optic implications of his theory, investigating a number of optical problems: notably, the pressure exerted by light, the propagation of light in crystals, the relation between electric conductivity and optical opacity of metals, and the magnetic rotation of the plane of polarization of light. He failed, however, to derive the laws of the reflection and refraction of light, the problem that had proved so embarrassing to the elastic-solid optical theories.

For all its promise, Maxwell's theory—in the form, or various forms, in which he left it—was a source of great perplexity for many of its close readers. Ehrenfest recalled that Maxwell's *Treatise* seemed a "kind of intellectual primeval forest, almost impenetrable in its uncleared fecundity." The theory was unclear in precisely those basic features that differentiated it from most Continental theories. Maxwell did not elucidate the nature of electric charge, a concept that had received clear, if not unanimous, interpretations in terms of particulate electric fluids in the action-at-a-distance theories. Indeed, Maxwell refused to commit himself to any position on the nature of electricity. Sometimes he spoke of it as the process of dielectric polarization; in reverse fashion he spoke at other times of polarization as a motion of electricity. He sometimes likened the motion of electricity to that of an incompressible fluid, without intending that the reader should think that electricity is an incompressible fluid. In the *Treatise* he spoke of a "molecule of electricity"; he added, however, that this way of speaking was "out of harmony with the rest of this treatise."

Conceding only that electricity was a physical quantity, Maxwell cautioned against assuming that "it is, or is not, a substance, or that it is, or is not, a form of energy, or that it belongs to any known category of physical quantities." It is small wonder that his Continental interpreters found the task of clarifying the concept of charge to be both essential and difficult. They found Maxwell's concept of the electromagnetic field equally difficult to grasp. Maxwell did not distinguish between the roles of the medium and ordinary matter in electromagnetic processes. The clear distinction in the Continental theories between distance forces—the counterpart of Maxwell's field—and the electricity they arise from and act upon is entirely absent from Maxwell's theory.

The eventual clarification of the conceptual basis of Maxwell's theory was aided immeasurably by a paper that Helmholtz published in 1870. The purpose of his paper was to bring order to electrodynamics by examining the major rival theories for their agreement with dynamical principles and by exposing their differing, testable consequences. To do this he generalized Neumann's electrodynamic potential between two current elements to encompass Maxwell's and Weber's theories; each of the three theories was characterized by a numerical parameter entering the formulas of the general theory. Because of the recent interest in the velocity of propagation of electric actions and because of its great significance for physics, Helmholtz applied his general induction law to the case in which an electrically and magnetically polarizable medium is present. In the spirit of action-at-a-distance theories, he assumed that the electric interaction of bodies depends in part on direct distance forces and in part on the polarization of the medium, which in turn depends on the distance forces and is the source of new distance forces. He showed that the electric displacement in a dielectric obeys the same wave equations as the displacement of ponderable particles in an elastic solid.

Helmholtz thought that the resulting "remarkable analogy" between the motions of electricity and the motions in the luminiferous ether were consequences of the older action-at-a-distance electrodynamics no less than they were of Maxwell's special hypotheses. He concluded that finitely propagated transverse waves of polarization in a dielectric medium were possible without basic changes in the foundations of action-at-a-distance electrodynamics. His general theory also yielded longitudinal waves, which in the special case of Maxwell's theory were propagated with infinite velocity. From his critique of the rival electrodynamic theories, Helmholtz argued that Weber's theory was untenable and that Maxwell's theory, as he had interpreted it, should be taken seriously. Many Continental physicists approached Maxwell's theory through Helmholtz; his action-at-a-distance formulation of the theory rendered it intelligible to physicists nurtured in the Continental tradition, and his favorable judgment assured it serious attention.

Helmholtz recognized that resolution of the difficulties of optical theory might be directly related to resolution of the difficulties of electrodynamics, and this clear recognition was the starting point for Lorentz' optical researches. Lorentz chose his dissertation topic as a result of a footnote in Helmholtz' 1870 paper, which pointed to the superiority of Maxwell's electromagnetic theory of light over the older elastic-solid theories in yielding the crucial interface conditions required by Fresnel's laws of reflection and refraction.

In 1875 Lorentz submitted to the University of Leiden his doctoral dissertation on electromagnetic optics, "Sur la théorie de la réflexion et de la réfraction de la lumière" (translated from the original Dutch). Although he had studied Maxwell's papers, his starting point was Helmholtz' action-at-a-distance general theory. He was not opposed in principle to Maxwell's contiguous-action point of view, but he felt that Maxwell's theory was incompletely developed and that in its present form it relied on more special and unconfirmed hypotheses than Helmholtz' did. Lorentz' dissertation reveals his characteristic blend of incisive clarity and unifying vision. He opened with a comparative critique of the older wave theories of light and of the new electromagnetic theory of light. He then reproduced Helmholtz' derivation of the wave equation for the propagation of variations in the state of polarization, applying it successively to the reflection and refraction of light by isotropic media, crystal optics, total reflection, and the interaction of light and metals.

The main result of Lorentz' dissertation was his electromagnetic derivation of Fresnel's amplitudes for light reflected at a dielectric interface. He did this without having to make ad hoc assumptions comparable with those of the elastic-solid theory concerning the density and elasticity of the ether. He also showed that in a more natural way than the elastic-solid theories the electromagnetic theory dispensed with embarrassing, unobserved longitudinal vibrations. He concluded that because of its greater simplicity and comprehensiveness, Maxwell's electromagnetic theory of light was to be preferred over the elastic-solid ones. Lorentz closed his dissertation with a prophetic vision of the vast unifying potentiality for physics implicit in the combination of Maxwell's electromagnetic theory of light with the molecular theory of matter, a prospect that proved to be an adumbration of his own future research.

Apart from being the first systematic treatment of electromagnetic optics, one that succeeded where the elastic-solid theories failed most conspicuously, Lorentz' dissertation was significant as a first step toward distinguishing the electromagnetic field from matter and thus clarifying the physical basis of Maxwell's theory. He pointed to Boltzmann's recent experimental investigations of the predicted relation of the specific inductive capacity of gases to their index of refraction as strongly confirming Maxwell's electromagnetic theory of light. He interpreted Boltzmann's results to mean that the ether is the seat of polarizations and that gaseous molecules exert only a small, secondary influence on the specific inductive capacity of the ether pervading the intermolecular spaces; in this sense he viewed the ether as the only proper dielectric.

In a sequel paper in 1878, on the optical theory of matter, Lorentz began the research program he had sketched at the close of his dissertation; and in so doing he further strengthened his distinction between the roles of matter and the ether. He developed there a theory of the dispersion of light by assuming that material molecules contain charged harmonic oscillators and that the ether everywhere—except possibly in the immediate vicinity of the molecules—has the same properties that it does in a vacuum. Lorentz accounted for the dispersion of light in a body in the following way: incident light waves in the ether cause the electric particles in the body to vibrate; the vibrating particles send out secondary waves in the ether which interfere with the incident ones, thus making the velocity of propagation of light through the body depend on frequency. In his 1878 paper Lorentz predicted a relation between the density of a body and its index of refraction, a relation that became known as the Lorentz-Lorenz formula for its independent development by the Danish physicist in 1869.

In the 1880's Lorentz' continuing interest in electromagnetism was reflected in a paper on the force between two current elements regarded from the point of view of Continental electrodynamics, and in another on the Hall effect and the electromagnetic rotation of the plane of polarization of light. His continuing interest in the ether was reflected in a study of the aberration of light in 1886, in which he concluded that Fresnel's view of the luminiferous ether was superior to Stokes's. Unlike Stokes, Fresnel in his theory of aberration assumed that the ether near the earth did not participate in its motion. Lorentz thought that the hypothesis of the complete transparency of matter to the ether was implicit in Fresnel's whole theory.

Lorentz' chief interest in the 1880's was not, however, electromagnetism and optics but the molecular-kinetic theory of heat. The science of thermodynamics had been largely completed by his day, and he did not participate in its construction. But the molecular-kinetic interpretation of thermodynamics was far from complete, and he worked on a number of its problems; for one, he corrected Boltzmann's proof of the *H*-theorem. Lorentz was strongly receptive to the kinetic theory, as he was to the molecular viewpoint in physics in general, the theme he had enlarged on in his inaugural lecture at the University of Leiden.

From the 1890's, the electron theory dominated Lorentz' researches. In constructing a theory of electrons and fields, he brought together a number of insights he had accumulated over several years of varied researches. The particulate concept of electricity that lay at the basis of his electron theory was conditioned by his long familiarity with Continental electrodynamics and its assumption of particulate electric fluids. It was also conditioned by the same molecular orientation in physics that had prompted his intensive work on the molecular-kinetic theory and, before that, on the interaction of light and molecular matter. Equally fundamental to his electron theory was the concept of the stationary ether, which he had reached through his studies of optical aberration. Finally, his pioneering studies of Maxwellian optics in the 1870's prepared the way for the full, explicit separation of the roles of ether and matter in his electron theory.

The immediate occasion for Lorentz to return to the foundations of Maxwell's theory was Hertz's researches in electromagnetism. In the late 1880's, in response to Helmholtz' program for bringing about an empirical decision between the rival electrodynamic theories, Hertz carried out his influential experiments on Maxwellian electric waves. Following his experimental demonstration of electric waves in air, Hertz made theoretical studies in 1890 of the Maxwellian electrodynamics of stationary and moving bodies. Having abandoned the Helmholtzian action-at-a-distance interpretation of Maxwell's theory with which he had begun his experimental researches, Hertz in his theoretical studies accepted Maxwell's contiguous-action interpretation of electromagnetic processes in the ether, together with his denial of particulate electric fluids. Hertz based his study of the electrodynamics of moving bodies on the concept of an ether that was completely dragged by ponderable bodies. Fully realizing that a dragged ether was in conflict with optical facts, he justified its application to narrowly electrodynamic phenomena on the grounds that it was compatible with such phenomena and that it facilitated a systematic presentation of the theory, the sole purpose of his theoretical study. By assuming a dragged ether, Hertz needed only one set of electric and magnetic vectors instead of the two required by an ether that was separable from matter. He also based his study on his version of Maxwell's equations, which he postulated rather than deriving from mechanical models and principles.

Hertz's experimental and theoretical researches generated widespread interest in Maxwell's theory among Continental physicists. Of the major theoretical statements of Maxwellian electrodynamics following Hertz's researches, several advanced a molecular

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view of electricity together with a stationary ether. Such theories—soon to be called electron theories—were proposed independently in the early 1890's by Lorentz, by Wiechert, and by Larmor. Although the three theories bore large areas of resemblance, they also differed in major respects. Whereas Larmor, for example, viewed electrons as structures in the ether and the ether as the sole physical reality, Lorentz treated electrons and the ether as distinct entities. Of the three theories, Lorentz' gained the greatest authority on the Continent, in part because of its clear, if ultimately unsatisfactory, dualism of electron and field.

In an address to the Dutch Congress of Physics and Medicine in 1891, Lorentz, following Hertz, declared his conversion to contiguous action in electromagnetic processes. Lorentz objected, however, to two features of Hertz's electrodynamics, which prompted his first memoir in 1892 on the electron theory: "La théorie électromagnétique de Maxwell et son application aux corps mouvants." He criticized Hertz's totally dragged ether on well-known optical grounds; and although he admired the clear, succinct mathematical form that Hertz and Heaviside had given to Maxwell's theory, he criticized Hertz's bare postulation of the field equations. Referring to "one of the most beautiful" chapters in Maxwell's *Treatise*, in which Maxwell applied Lagrangian mechanics to elucidate electromagnetism without assuming a detailed mechanism, Lorentz in 1892 continued the mechanical exploration begun by Maxwell. He remarked that "one has always tried to return to mechanical explanations," and properly so, in his opinion. After laying down his own hypotheses concerning the stationary ether and electrons, he applied d'Alembert's principle to derive the field equations and the equations of motion of an electron in the field. Characteristically, Lorentz spelled out at the start the physical suppositions of his theory; it was a constructive effort of exemplary clarity in a science chronically subject to obscurity.

Lorentz incorporated into his electron theory Fresnel's view that the ether penetrates matter (Lorentz held more tenaciously to a stationary ether than even Fresnel, who admitted some dragging), but he rejected Fresnel's further view that the density of the ether varies from substance to substance as well as Neumann's view that the ether differs in elasticity in different substances. For Lorentz the ether had identical properties everywhere, and he was little inclined to speculate about its ultimate nature. He completely separated the ether and ordinary matter; however, since ether and matter were observed to interact, he needed to reestablish their connection. He assumed that their sole connection was provided by positive and negative electrons, which he regarded as small, ponderable, rigid bodies. He assumed that electrons are contained in all molecules of ordinary matter (Lorentz wrote of "charged particles" in 1892, of "ions" in 1895, and of "electrons" only after 1899; in this article the term "electrons" is used throughout, without suggesting that Lorentz had an unchanging view of the properties of electrons during these years).

In contrast with Maxwell and Hertz, Lorentz provided a clear, simple interpretation of electric charge and current and of their relation to the electromagnetic field. A body carries a charge if it has an excess of one or the other kind of electrons. An electric current in a conductor is a flow of electrons; a dielectric displacement in a nonconductor is a displacement of electrons from their equilibrium positions. The electrons create the electromagnetic field, the seat of which is the ether; the field in turn acts ponderomotively on ordinary matter through the electrons embedded in material molecules.

Because Lorentz completely separated ether and matter, he needed only one pair of directed magnitudes—one electric and one magnetic—to define the field at a point, and this was so whether or not matter was present at the point; in this way he answered Hertz's formal objection to a stationary ether that it required two sets of directed magnitudes to define the field at a point, one for matter and one for ether. Lorentz also answered Hertz's objection that particulate electric fluids belonged to action-at-a-distance, not contiguous-action, electrodynamics. By means of his concepts of a stationary ether and of electrons transparent to it, Lorentz constructed a consistent electrodynamics that at the same time rejected action at a distance and retained particulate electric fluids.

For this reason Lorentz characterized his theory as a fusion of Continental and Maxwellian electrodynamics. He retained the clear understanding of electricity of the theories of Weber and Clausius, and at the same time he accepted the crux of Maxwell's theory: the propagation of electric action at the speed of light. In the electrodynamics of Weber and Clausius, two electric particles act on each other with a force that depends on their separation and their motion at the instant of the action. In Lorentz' theory the force on an electron also depends on the position and motion of other electrons, but at earlier instants, owing to the finite propagation of electric disturbances through the mediating ether.

From his understanding of ether and electricity in 1892, Lorentz explained the interaction of light and matter in a way close to that of his optical theory of the 1870's. Light is turned and retarded in its passage through a body owing to the electrons in the molecules of the body; the incident light sets up vibrations in the electrons, which in turn produce light waves that interfere with the original ones and with one another. With this conception Lorentz in 1892 derived the Fresnel drag coefficient, a measure of the motion that a moving transparent body communicates to light passing through it. The coefficient had been confirmed by Fizeau's 1851 experiment on the motion of light in a moving column of liquid and Michelson and Morley's repetition of it in 1886. Among the physical interpretations that had been given to the coefficient, one was that the moving body partially drags the ether with it. Lorentz demonstrated that the drag coefficient resulted from the interference of light and thus did not imply a true, partial dragging of the ether. This demonstration was the single most impressive achievement of his first memoir on the electron theory, inspiring Max Born to refer to it, rightly, as one of the "most beautiful examples of the might of mathematical analysis in the physical world."

Although in 1892 Lorentz believed that it was important to relate electromagnetic processes to mechanical laws, he had not constructed a wholly mechanistic electrodynamics. In certain respects his ether was inherently a nonmechanical substance. Since his ether occupies the same space as electrons and material molecules, and its properties are unaffected by their coextension, it has no mechanical connection with ordinary matter.

Lorentz' next major exposition of his electron theory was *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (1895). He no longer derived the basic equations of his theory from mechanical principles, but simply postulated them. He wrote the equations for the first time in compact vector notation; in electromagnetic units the four equations that describe the electromagnetic field in a vacuum are

$$\begin{aligned} \operatorname{div} \mathbf{d} &= \rho, \\ \operatorname{div} \mathbf{H} &= 0, \\ \operatorname{rot} \mathbf{H} &= 4\pi(\rho\mathbf{v} + \dot{\mathbf{d}}), \\ -4\pi c^2 \operatorname{rot} \mathbf{d} &= \dot{\mathbf{H}}, \end{aligned}$$

where $\mathbf{d}$ is the dielectric displacement, $\mathbf{H}$ the magnetic force, $\mathbf{v}$ the velocity of the electric charge, ρ the electric charge density, and c the velocity of light. A fifth and final equation describes the electric force of the ether on ponderable matter containing electrons bearing unit charge:

$$\mathbf{E} = 4\pi c^2 \mathbf{d} + \mathbf{v} \times \mathbf{H}.$$

The first four equations embody the content of Maxwell's theory; the fifth equation is Lorentz' own contribution to electrodynamics—known today as the Lorentz force—connecting the continuous field with discrete electricity.

In 1892 Lorentz had briefly discussed the problem of the effects of the earth's motion through the stationary ether; in the *Versuch* he systematically went over the whole problem. Since the ether is not dragged, a moving body such as the earth has an absolute velocity relative to it. The question arises whether or not the earth's absolute velocity is detectable through optical or electromagnetic effects of the accompanying ether "wind." The magnitude of the effects of the wind is measured theoretically by the ratio of the speed of the earth's motion v to the speed of light c. The ratio is small for the earth, but not so small as to be beyond the reach of observation.

The effects of the wind, however, were not observed; and for his theory to be credible Lorentz had to explain why. He showed that, according to the theory, an unexpected compensation of actions eliminates all effects of the ether wind to first-order approximation (neglecting terms involving the very much smaller second and higher powers of v/c). He analyzed the absence of first-order effects of the ether wind in phenomena such as reflection, refraction, and interference with the aid of a formal "theorem of corresponding states." The theorem asserted that to first-order accuracy no experiments using terrestrial light sources could reveal the earth's motion through the ether. By introducing transformations for the field magnitudes, spatial coordinates, and a "local time," Lorentz showed that in first-order approximation the equations describing an electric system in a moving frame were identical with those describing the corresponding electric system in a frame at rest in the ether (for which Lorentz assumed Maxwell's equations to hold exactly).

Lorentz' first-order approximation accounted for nearly all experience with the optics and electrodynamics of moving bodies. Second-order experiments had been performed, however, for which theoretically no compensating actions should occur. The most important second-order experiments were Michelson's interferometer experiment in 1881 and his and Morley's more accurate repetition of it in 1887. Their experiments failed to produce evidence of the second-order ether wind effects expected from Lorentz' theory. The only solution Lorentz could think of was the famous contraction hypothesis that he and Fitzgerald proposed independently at about the same time. Lorentz published an approximate form of his hypothesis in 1892. In 1895 he published an exact form, which stated that the arms of the interferometer contract by a factor of $\sqrt{1 - v^2/c^2}$ in the direction of the earth's motion through the ether. Lorentz regarded the hypothesis as dynamic rather than kinematic, requiring that the molecular forces determining the shape of the interferometer arms are propagated through the ether analogously to electric forces.

In 1899 Lorentz published another important statement of his theory, "Théorie simplifiée des phénomènes électriques et optiques dans des corps en mouvement." It was a response to Alfred Liénard's contention that according to Lorentz' theory, Michelson's experiment should yield a positive effect if the light passes through a liquid or solid instead of air. Lorentz believed that the positive effect was improbable, and he simplified and deepened his theory to support his belief. He now treated his dynamical contraction hypothesis mathematically, as though it were a general coordinate transformation on a par with the local time transformation. Except for an undetermined coefficient, the resulting transformations for the space and time coordinates were equivalent to those he published in his better-known 1904 article: the "Lorentz transformations." In 1899 Lorentz discussed for the first time the extension of his corresponding-states theorem to second-order effects. In connection with this extension he introduced, without thoroughly exploring it, an idea that would soon move to the center of electron theory concerns: the second-order transformations imply that the mass of an electron varies with velocity, and that the mass is different for motions parallel and perpendicular to the direction of translation through the ether. Although he discussed only electrons, his analysis implies that all mass, charged or otherwise, should vary with velocity, an implication that he made explicit in his more comprehensive 1904 paper.

Shortly before 1900 it was empirically established that cathode rays are negatively charged particles and that they are the same regardless of how and from what source they are produced. Since the particulate properties of cathode rays agreed with Lorentz' hypothesis about the nature of electricity, he confidently identified the cathode ray particles with the electrons of his theory. The empirical confirmation of the discrete unit of electricity lent great authority to Lorentz' and others' electron theories. In 1896 Zeeman observed a broadening of the spectral lines when a sodium flame is placed between the poles of a magnet. Lorentz immediately explained the effect on the basis of his electron theory, a result which pointed to his theory as a promising tool for unraveling the complexities of atomic structure.

Lorentz' application of the theory to the Zeeman effect showed that the vibrating electrons in sodium atoms are negative. Moreover, it yielded a value for the ratio of charge to mass of negative electrons which agreed with subsequent estimates by J. J. Thomson, Walther Kaufmann, and others, found by deflecting cathode rays in electric and magnetic fields. The success of Lorentz' analysis of the Zeeman effect further enhanced the standing of his theory. Indeed, at the turn of the century Lorentz' theory could count many solid accomplishments, such as explanations of Fizeau's experiment, of normal and anomalous dispersion, and of Faraday's rotation of light. For both its accomplishments and its promise, Lorentz' electron theory became widely adopted, especially on the Continent around 1900.

In 1904 Lorentz published "Electromagnetic Phenomena in a System Moving With Any Velocity Smaller Than That of Light." He was motivated to make another, nearly final, reformulation of his electron theory by several theoretical and experimental developments. First, Poincaré in 1900 had urged Lorentz not to make ad hoc explanations for each order of null effects, but to adopt instead a single explanation that excluded effects of the earth's motion of all orders. Second, in 1902 Max Abraham had published a rival electron theory based on the hypothesis of a rigid electron. Third, Kaufmann had begun publishing experimental data on the variable mass of moving electrons that seemed to favor Abraham's theory. Finally, new second-order experiments had been performed in 1902–1904 by Lord Rayleigh, D. B. Brace, Frederick Trouton, and H. R. Noble; and Lorentz wanted to discuss their null results in light of his theory. In his 1904 paper Lorentz refined his corresponding-states theorem to hold for all orders of smallness for the case of electromagnetic systems without charges, which meant that no experiment, however accurate, on such systems could reveal the translation of the apparatus through the ether. He also showed that his theory agreed with Kaufmann's data as well as Abraham's theory did. With this paper Lorentz all but solved the problem of the earth's motion through the stationary ether as it was formulated at the time. Poincaré in 1905 showed how to extend Lorentz' corresponding-states theorem to systems that included charges and to make the principle of relativity, as Poincaré understood it, more than approximation within the context of Lorentz' theory.

Lorentz' solution—developed over the years since 1892—entailed a number of radical departures from traditional dynamics; these he spelled out explicitly in 1904. First, the masses of all particles, charged or not, vary with their motion through the ether according to a single law. Second, the mass of an electron is due solely to its self-induction and has no invariant mechanical mass. Third, the dimensions of the electron itself, as well as those of macroscopic bodies, contract in the direction of motion, the physical deformation arising from the motion itself. Fourth, the molecular forces binding an electron and a ponderable particle or binding two ponderable particles are affected by motion in the same way as the electric force. Finally, the speed of light is the theoretical upper limit of the speed of any body relative to the ether; the formulas for the energy and inertia of bodies become infinite at that speed. Thus, to attain a fully satisfactory corresponding-states theorem, Lorentz had to go far beyond the domain of his original electron theory and make assertions about all bodies and all forces, whether electric or not.

The new dynamics of Lorentz' 1904 electron theory was compatible with the leading physical thought of the time. That it was shows how deeply the electron theory—Lorentz' form of it and others'—had changed the foundations of prerelativistic classical physics. To understand the change, we need to look more closely at the place of the electron theory in physics in the years just prior to 1904. In part because of the large and growing number of phenomena encompassed by the electron theory, physicists around the turn of the country extrapolated from it a new physical world view.

Lorentz, Larmor, Wien, Abraham, and others anticipated that mechanics would be replaced by electrodynamics as the fundamental, unifying branch of physics. They believed that mechanical concepts and laws were probably special cases of those of the electron theory. They foresaw a physical universe consisting solely of ether and charged particles, or possibly of ether alone. They were encouraged in their world view anticipations by the mounting experimental evidence for the electromagnetic nature of the electron mass. Lorentz wrote on electromagnetic mass in 1900, urging that experiments be made to determine the exact dependency of the electron mass on velocity. The problem of mass was central not only for its bearing on electron dynamics, but also for its bearing on the question of the electromagnetic foundation of physics and the related question of the connection of the ether and electricity with ordinary matter. Although Lorentz spoke more cautiously than other advocates of the electromagnetic program for physics, he gave it powerful impetus through his own applications of the electron theory. He showed in 1900 that if matter were constituted solely of charged particles, it was possible to give an electron-theoretical interpretation of gravitation as a finitely propagated, etherborne force. In that same year, 1900, he spoke of his belief that the electron theory could be extended to spectroscopy, atomic structure, and chemical forces.

Those physicists seeking an electromagnetic foundation for all of physics recognized the immensity of the reductionist tasks awaiting them. The tasks included the demonstration that all matter is electrical and the further demonstration that molecular and gravitational forces are explicable on wholly electromagnetic grounds. Even within electrodynamic theory itself, however, there were elements of incompleteness, which undermined the classical electromagnetic program for physics. The problem of securing a purely electromagnetic foundation for electrodynamics seemed increasingly unrealizable. The contractile electron at the core of Lorentz' theory presented a major difficulty in this regard.

Following Abraham, Lorentz by 1904 recognized that such an electron contains an energy of deformation that is necessarily nonelectromagnetic. Abraham's theory avoided this nonelectromagnetic dependence, but at the price of postulating a rigid scaffolding for the electron; other electron theorists posed alternative conceptions of the electron's shape, structure, and charge distribution. Another closely related difficulty for the electromagnetic program arose from the need for the electron to be finitely extended in order to avoid infinite self-energy, which in turn required nonelectromagnetic forces or constraints to prevent the finite electron from disintegrating through the electric repulsion of its parts. Yet another formidable difficulty emerged as a result of one of Lorentz' applications of the electron theory. In connection with his electron theory of metals, Lorentz in 1903 derived a formula for the energy distribution in blackbody radiation. He was able to calculate from his theory only the long wavelength limit of the energy spectrum. He recognized that Planck's 1900 quantum theory of blackbody radiation comprehended the entire spectrum; he also recognized that Planck's energy quanta were foreign to the foundations of the electron theory.

In 1908 Lorentz spoke out in favor of Planck's quantum theory as the only theory capable of explaining the complete spectrum of blackbody radiation. He was one of the first to do so and to emphasize the deep antithesis between the quantum hypotheses and those of the electron theory. The discussions of the first Solvay Congress in 1911—which Lorentz chaired—pointed to the conclusion that only through radical reform could the electron theory and the molecular-kinetic theory be made compatible with Planck's theory. Einstein had already long sought a revised electron theory to incorporate light quanta. Bohr's 1913 quantum theory of atoms and molecules was based on an explicit limitation of the validity of the classical electron and mechanical theories in the domain of atomic processes. Lorentz' career was divided roughly in half by the transition from classical to quantum physics. Although he was intensely interested in the new physics, and although he worked with the new quantum axioms and developed their consequences, his heart was never fully in it. He deeply regretted the passing of classical physics.

Einstein's 1905 special relativity paper provided Lorentz' theory with a physical reinterpretation. Reversing Lorentz' logic, Einstein made relativity a principle rather than a problem (Lorentz did not speak of a "principle of relativity" in connection with his own theory until after Einstein's 1905 paper). Likewise, for Einstein the constancy of the velocity of light for all observers was a principle, whereas for Lorentz the constancy was only apparent, a consequence of his theory. From the principles of relativity and the constancy of the velocity of light, Einstein deduced the Lorentz transformations and other results that had first been made known through Lorentz' and others' electron theories. Einstein's and Lorentz' interpretations of the formalisms were, however, very different. For Lorentz, time dilation in moving frames was a mathematical artifice; for Einstein, measures of time intervals were equally legitimate in all uniformly moving frames. For Lorentz the contraction of length was a real effect explicable by molecular forces; for Einstein it was a phenomenon of measurement only.

Einstein argued in 1905 that the ether of the electron theory and the related notions of absolute space and time were superfluous or unsuited for the development of a consistent electrodynamics. Lorentz admired, but never embraced, Einstein's 1905 reinterpretation of the equations of his electron theory. The observable consequences of his and Einstein's interpretations were the same, and he regarded the choice between them as a matter of taste. To the end of his life he believed that the ether was a reality and that absolute space and time were meaningful concepts.

Einstein's special relativity principle began to be widely accepted around 1910. It weakened the goal of a completely electromagnetic physics by questioning the need for an ether. It weakened it even more by questioning inferences from the variation of mass with velocity to the electromagnetic nature of mass. The relativity principle led to the same testable dynamical conclusions as Lorentz' theory, but without relying on the assumptions about electron structure that had been central to electron physics.

The origins of another leading twentieth-century theoretical development, the theory of general relativity, were closely tied to the classical electron theory. Beginning in 1907 and especially from 1911 on, Einstein sought a gravitational and, subsequently, a unified gravitational and electromagnetic field theory in the context of his general relativity theory. Lorentz was strongly sympathetic to the general relativity theory, making fundamental contributions to it in 1914–1917. Lorentz, and Einstein too, regarded the physical space of general relativity as essentially fulfilling the role of the ether of the older electron theory. A principal objective of Einstein's field theoretical proposals was to relate electrons and material particles to the total field in a more satisfactory way than the earlier electron theories had. Einstein wanted above all to remove the radical dualism of continuous field and discrete particle that had characterized Lorentz' electron theory.

The classical electron theory was related through highly complex conceptual developments to later fundamental theories in physics. The Schrödinger and Dirac equations of the 1920's formed the mathematical bases of electron physics refashioned on nonclassical suppositions. These equations, together with the tradition of earlier electron theory investigations of the self-induction and electromagnetic mass of the electron, formed part of the basis for the development of modern elementary particle theory. Further, problems explored in the context of the electron theory have had a continuous history into the nonclassical period; for instance, the problem of the electron structure of atoms and the electron properties of metals.

Although the classical electron theory did not fulfill the anticipations it stirred at the turn of the century of an electromagnetic world view, it worked a profound change in the thinking of physicists and contributed to new world view perspectives. For Lorentz' immediate followers—those who had struggled to comprehend the obscurities of Maxwell's theory in the aftermath of Hertz's confirmation of electric waves—his electron theory was immensely clarifying. The younger generation of European theoretical physicists who learned much of their electrodynamics from Lorentz—Einstein, Ehrenfest, A. D. Fokker—agreed that Lorentz' great idea was the complete separation of field and matter. Einstein called Lorentz' establishment of the electromagnetic field as an independent reality distinct from ponderable matter an "act of intellectual liberation." The act at the same time determined the outstanding problem for future research, one that is still at the heart of theoretical physics. It is the problem of reestablishing the connection of field and particle in a way that does not contradict experience.

Einstein grasped the need to reject the wave theory of light and to modify the concepts of space and time in part from his analysis of the essential duality of Lorentz' theory: its joint foundation in the continuous electromagnetic field and molecular dynamics. Lorentz and his co-workers in electron theory carried classical physics to its furthest stage of clarity, precision, and unity. In doing so, Lorentz identified the strong limitations of the electron theory, defining the problem areas from which ongoing transformations of the foundations of physics arose. He brought classical physics to a state of development that made the need for reform in its fundamental principles evident and urgent to Einstein and other followers; this is the essential historical significance of Lorentz' work.

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RUSSELL MCCORMMACH

LORENZ, HANS (*b.* Wilsdruff, Germany, 24 March 1865; *d.* Sistrans, near Innsbruck, Austria, 4 July 1940), *mechanics, mechanical engineering*.

The son of a teacher, Lorenz grew up in Leipzig, then studied (1885–1889) mechanical engineering at the Dresden Polytechnic Institute, where Gustav Zeuner was his principal teacher. His first professional experience (1890–1893) was with the Augsburg firm of L. A. Riedinger, developing a pneumatic power distribution system, and with the Escher-Wyss Company of Zurich, improving refrigeration compressors (1893–1894).

In 1894 Lorenz established himself in Munich as an independent consulting engineer. He founded, and for the first five years edited, the *Zeitschrift für die gesamte Kälteindustrie*, which quickly became the leading international journal of refrigeration technology. In 1894 he received a Ph.D. from the University of Munich—a rare feat then for an engineer—with a dissertation on the thermodynamic limits of energy conversion.

Lorenz' academic career began with brief appointments as extraordinary professor of applied science at Halle (1896) and Göttingen (1900). In Göttingen he was also director of the Institute for Technical Physics, which had recently been established upon recommendation of the mathematician Felix Klein, and which was to become world famous under Lorenz' successor, Ludwig Prandtl. In 1904 Lorenz was appointed to the chair of mechanics at the newly founded Technische Hochschule of Danzig, a position that he held for the rest of his active career. He also served as director of its materials testing laboratory (from 1909) and as rector (1915–1917). After his retirement in 1934, Lorenz lived in Munich and Sistrans.

Whether any of Lorenz' research efforts will be remembered in history is difficult to judge. Without doubt, however, he was an important figure in his own time. He was active in three areas of engineering: practice, teaching, and research. He was sought as a consultant in the burgeoning refrigeration industry, and his professional leadership was recognized in his election to presidencies and honorary memberships of several scientific societies. As an engineering teacher he was a leading proponent of a distinctive style of scientific engineering that flourished in early twentieth-century Germany. It was his belief that a creative engineer combined mathematical and scientific competence of a high order with the ability to translate actual problems into simple, tangible models (and was occasionally willing to sacrifice mathematical rigor for the sake of practical results). For undergraduates, Lorenz was a difficult teacher, but his advanced courses, as many of his former graduate students (prominent among whom are W. Hort, R. Plank, and A. Pröll) have testified, were unforgettable.

Lorenz' original research is characterized by unbounded versatility. His topics derived from his own engineering practice (pneumatic transmission lines, refrigeration), from his work as head of the materials testing laboratory (buckling, plastic deformation), and from ongoing scientific debates (vibrations, gyroscopes, turbomachinery, turbulent flow), to the war effort (ballistics). In his later years he published a considerable amount of work on astrophysics and astronomy.

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