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(*b*. Hamburg, Germany, 22 February 1857; *d*. Bonn, Germany, 1 January 1894)

physics.

Hertz was born into a prosperous and cultured Hanseatic family. His father, Gustav F. Hertz, was a barrister and later a senator: His mother was the former Anna Elisabeth Pfefferkorn. He had three younger brothers and one younger sister. Hertz was Lutheran, although his father's family was Jewish (Philipp Lenard, Hertz's first and only assistant and afterward a fervent Nazi, conceded that one of Germany's great men of science had "Jewish blood"). At age six Hertz entered the private school of Richard Lange, a taskmaster who had no patience with error. His mother watched closely over his lessons, determined that he should be—as he was—first in his class. On Sundays he went to the *Gewerbeschule* for lessons in geometrical drawing. His skill in sketching and painting marked the limit of his artistic talent; he was totally unmusical. Very early Hertz showed a practical bent; at age twelve he had a workbench and woodworking tools. Later he acquired a lathe and with it made spectral and other physical apparatus. He had an uncommon gift for languages, both modern and ancient. He left Lange's school at fifteen to enter the Johanneum Gymnasium, where he was first in his class in Greek; at the same time he took private lessons in Arabic.

After his *Ahitur* in 1875 Hertz went to Frankfurt to prepare for a career in engineering. He spent his year of practical experience there in construction bureaus, reading during his free hours for the state examination in engineering. After a short spell in 1876 at the Dresden Polytechnic, he put in his year of military service in 1876–1877 with the railway regiment in Berlin. He then moved to Munich in 1877 with the intention of studying further at the Technische Hochschule there. Since his Gymnasium days, however, he had had conflicting leanings toward natural science and engineering. While preparing for engineering he had regularly studied mathematics and natural science on the side. With his father's approval and promise of continuing financial support, he matriculated in 1877 at the University of Munich instead of at the Technische Hochschule. He was relieved at having decided on an academic and scientific career after long vacillation and was confident that he had decided rightly. To him engineering meant business, data, formulas—an ordinary life, on a par with bookbinding or woodworking—and he was uninterested. Although the Technische Hochschule had a good physics laboratory, a course of study there led to state examinations and usually to a practical career. The university by contrast promised a life of never-ending study and research, one that suited Hertz's scholarly, idealistic tastes; he knew that he wanted above all to be a great investigator.

Hertz spent his first semester at the University of Munich studying mathematics. Following the advice of P. G. von Jolly, he read Lagrange, Laplace, and Poisson, learning mathematics and mechanics in their historical development and deepening his identification with investigators of the past. Elliptic functions and the other parts of the newer mathematics he found overly abstract, believing that they would be of no use to the physicist. Although Hertz thought that, when properly grasped, everything in nature is mathematical, he was in his student days—as throughout his career—interested primarily in physical and only indirectly in mathematical problems. It was in these first months in Munich that he developed his strong, if not strongly original, mathematical talent. It was expected at this time that an intending physicist have a grounding in experimental practice as well as in mathematics, and accordingly Hertz spent his second semester at Munich in Jolly's laboratory at the university and in F. W. von Beetz's laboratory at the Technische Hochschule. He found the laboratory experience immensely satisfying, especially after his intensive mathematical studies; it was to be a lifelong pattern with him to alternate between predominantly experimental and predominantly theoretical studies. In Germany in the 1870's the ideal physicist was expected to be equally at home with mathematics and apparatus; by temperament and talent Hertz embodied the ideal.

After a year in Munich, Hertz was eager to make the customary student migration. In consultation with Beetz he decided against Leipzig and Bonn in favor of Berlin. It was a momentous decision, for it brought him together with Hermann von Helmholtz, who was to have a profound influence on him throughout his career. Immediately upon arriving in Berlin in 1878, Hertz was drawn into Helmholtz' circle of interests; he noticed an announcement of a prize offered by the Berlin Philosophical Faculty for the solution of an experimental problem, concerning electrical inertia. Although he had had only one year of university study, he wanted to begin original research and try for the prize. Helmholtz, who had proposed the problem and had great interest in its solution, provided Hertz with a room in his Physical Institute, directed him to literature on the problem, and paid daily attention to his progress.

Outside the laboratory Hertz attended Kirchhoff's lectures on theoretical physics but found little new in them. He went occasionally to French plays, and he joined the crowd of officers at Heinrich von Treitschke's lectures on socialism. But he found that nothing really mattered except his research. He responded eagerly to the intensive research environment in Berlin and in German physics in general. He wrote home that his great satisfaction lay in seeking and communicating new truths about nature. Occupied any other way, he felt a useless member of society; private study as opposed to research seemed selfish and indulgent. Hertz showed himself to be an extremely persistent and self-disciplined researcher. His belief in the conformity of the laws of nature with the laws of human logic was so strong that to discover a case of nonconformity would make him highly uncomfortable: he would spend hours closed off from the world, pursuing the disagreement until he found the error. He won the Philosophical Faculty prize in 1879, earning a medal, a first publication in *Annalen der Physik* in 1880, and Helmholtz' deepening respect.

While Hertz was finishing his work on the Philosophical Faculty problem in 1879, Helmholtz asked him to try for another, much more valuable prize offered by the Berlin Academy. The prize was for an experimental decision on the critical assumptions of Maxwell's theory, a problem Helmholtz had designed expressly for his most talented student. Hertz declined, feeling that it would take him three years and that the outcome was uncertain in any case. Instead he wrote a doctoral dissertation on electromagnetic induction in rotating conductors, a purely theoretical work that took him only three months to complete. It was not a pioneering work but a thorough study of a problem that had been partially treated by many others, from Arago and Faraday to Emil Jochmann and Maxwell. He submitted his dissertation in January 1880 and took his doctoral examination the following month, earning a *magna cum laude*, a distinction rarely given at Berlin.

In 1880 Hertz began as a salaried assistant to Helmholtz in the practical work of the Berlin Physical Institute, a position he held for three years. He found the supervisory chores tedious, but they left him time to complete the research for fifteen publications and with them to begin establishing a reputation. Hertz's work in his Berlin period is difficult to summarize because of its diversity. The majority of his publications were on electricity; in addition to those on electromagnetic induction and the inertia of electricity, he published on residual charge in dielectrics and, most important, on cathode rays. In two papers in 1883 he concluded that cathode rays were not streams of electrical particles as many investigators had supposed, but invisible ether disturbances producing light when absorbed by gas. In other papers he developed a new ammeter and new hygrometer, revealing that he had retained his boyhood fascination and dexterity with instruments. His early dual attraction to engineering and physics was reflected in his research into elastic solid theory, which led to a publication in an engineering journal on a new, absolute measure of the hardness of materials. Yet another of his Berlin researches dealt with the evaporation of liquids; in this he displayed his command of thermodynamics and kinetic theory, a principal branch of nineteenth-century physics to which he did not contribute directly.

The Berlin Physical Society began meeting in the Physical Institute at the time Hertz took up his assistant's post there. He attended regularly, enjoying the sense of being at the center of German physics. He read his papers to the Society; and although he thought the discussions trival, he liked being in the company of Helmholtz, du Bois-Reymond, and other famous members.

As assistant in the Institute, Hertz came into closer relations with Helmholtz, often dining with him and his family. He sometimes found Helmholtz' halting, ponderous speech annoying, but he never doubted that Helmholtz was Germany's greatest physicist. Although his position at the Institute had great advantages—he was near Helmholtz and had at hand the finest research facilities in Germany—Hertz shared the usual ambition of wanting to advance to a regular faculty appointment. To do so, it was first necessary to be a *Privatdozent*, an unsalaried lecturer at the bottom of the university hierarchy. He did not want to be one at Berlin, for there were already too many *Privatdozenten* there. It was at this time that mathematical physics began to be recognized as a separate subdiscipline in Germany, and Hertz's opportunity came when the University of Kiel requested a *Priuaidozent* for the subject. Kirchhoff recommended Hertz for the job.

In 1883 Hertz moved to Kiel, where he discovered that he was a successful lecturer; by the second semester he drew fifty students, an impressive number for a small university. The limitation of Kiel was that it had no physics laboratory. Although Hertz fitted one out in his own house, he did not get deeply into experimental work in his two years at Kiel; and it proved a source of frustration and restlessness for him. His publications from this time consisted of three purely theoretical papers: one on meteorology, one on magnetic and electric units, and one on Maxwell's electrodynamics. The last, his first deep study of Maxwell's work, was by far the most important result of his enforced isolation from laboratory work in Kiel. Ultimately important, too, for his development was his extensive reading in the philosophical writings of Duhring, Fechner, Kant, Lotze, and Mach. When Kiel offered Hertz an associate professorship in 1885, he refused it. Unlike his Kiel successor, Max Planck, he did not want a position as a purely theoretical physicist. The Karlsruhe Technische Hochschule wanted to hire him as professor of physics; once he saw the Karlsruhe Physical Institute, he knew he wanted to move.

Hertz spent four years at Karlsruhe, from 1885 to 1889. His stay began inauspiciously; for a time he was lonely and uncertain about what research to begin next. In July 1886, after a three-month courtship, he married Elisabeth Doll, the daughter of a colleague; and in November 1886 he began the experimental studies that were to make him world-famous. In the rich Karlsruhe physical cabinet he came across induction coils that enabled him to tackle the problem on Maxwell's theory that Helmholtz had set for the 1879 Berlin Academy prize. By the end of 1888 he had gone beyond the terms of Helmholtz' problem and had confirmed the existence of finitely propagated electric waves in air. All the time he was in close touch with Helmholtz, sending him his papers to communicate to the Berlin Academy for quick publication before sending them later to *Annalen der Physik*. He published a total of nine papers from his electrical researches in Karlsruhe. They drew immediate, widespread recognition, which led to another and final move for Hertz.

In September 1888 the University of Giessen tried to hire Hertz away from Karlsruhe. The Prussian *Kultusminhierium* pressed him to refuse, and to consider Berlin instead, where he would go as Kirchhoff's replacement. But Hertz did not want to go back to Berlin—not yet, anyway, and definitely not as Kirchhoff's successor. At thirty-one he felt that he was too young for a major position in German physics; he felt that he would be pulled away from his researches too soon. And, as he knew from Kiel, he was not a mathematical physicist—which was what Berlin wanted. Helmholtz thought Hertz was correct in refusing, but he did not try to influence him in any way; he told Hertz that if he came to Berlin, he would find him laboratory space in the Physical-Technical Institute, the new national physical research laboratory that he headed. In December 1888 the Prussian *Kultusministerium* offered Hertz the physics professorship at the University of Bonn. He gladly accepted, more for Bonn's beautiful and quiet setting on the Rhine than for its scientific prospects. In 1889 Clark University in Worcester, Massachusetts, almost tempted him to head its new physical institute, one as splendid as Berlin's (Hertz would have gone if he had not been married); and in 1890 the University of Graz failed to entice him there as Boltzmann's successor.

Hertz moved to Bonn in the spring of 1889. He and his family took over the house where his predecessor, Rudolf Clausius, had lived for fifteen years; the continuity had precious historical significance for him. He found the Bonn Physical Institute cramped and the apparatus in a jumble, and he spent much of his time putting things in order. He had students now who worked in the Institute on his electromagnetic ideas. Hermann Minkowski, then a *Privatdozent* in mathematics, was greatly drawn to Hertz and worked in the Institute. Philipp Lenard became Hertz's assistant there in the spring of 1891. The main advantage of the Bonn position over that at Karlsruhe was that it required less teaching and left Hertz more time for research. In Bonn he continued the theoretical study of Maxwell's theory that he had begun in Karlsruhe; this research led to two classic papers on the subject, published in *Annalen der Physik* in 1890. He subsequently tried a miscellany of experiments, only one of which led to a publication: in the summer of 1891 he returned to the subject of cathode rays, studying their power of penetrating metal foils. In the spring of 1891 he began the research that would occupy him almost exclusively until his death: a purely theoretical study of the principles of mechanics inspired by Helmholtz' new work on the principle of least action. The one distraction from his mechanical study was the request at the end of 1891 by J. A. Barth, the publisher of *Annalen der Physik*, that he collect his papers on electric waves for publication in book form. Hertz dedicated the collection to Helmholtz.

Even before Hertz had finished his researches on electric waves, he began to receive international recognition. In 1888 he was awarded the Matteucci Medal of the Italian Scientific Society. In 1889 he won the Baumgartner Prize of the Vienna Academy of Sciences and the La Caze Prize of the Paris Academy of Sciences; in 1890 he won the Rumford Medal of the Royal Society, and in 1891 the Bressa Prize of the Turin Royal Academy. Between 1888 and 1892 he was elected a corresponding member of several major scientific societies, including the Berlin Academy of Sciences, the Manchester Literary and Philosophical Society, the Cambridge Philosophical Society, and the Accademia dei Lincei. He was invited to give a major address on his electric wave experiments at the 1889 Heidelberg meeting of the German Natural Scientists and Physicians. He enjoyed the sense of moving on equal terms in Heidelberg with the leading German physicists, notably Helmholtz, Kundt, Kohlrausch, Wiedemann, and Siemens. To receive the Rumford Medal he visited England, where he was feted by Crookes, Lodge, FitzGerald, Stokes, William Thomson, Strutt, and most of the other important British physicists and electrical engineers.

At the time Hertz moved to Karlsruhe he complained of toothaches; and early in 1888, in the midst of his electric wave researches, he had his teeth operated on. Early in 1889 he had all his teeth pulled out. In the summer of 1892 his nose and throat began hurting so badly that he had to stop work. At first he thought it was hay fever, and he went to the spas. But he found no cure; and from this time on, he was in almost constant pain from a malignant bone condition that his physicians did not understand well. He missed the fall semester of 1892 but taught again in the spring of 1893. He had several head operations which gave him only temporary relief; he was often depressed. He began lecturing in the fall of 1893, while working on the last stages of his book on mechanics. On 3 December 1893 he sent most of his manuscript to the press; on 7 December he gave his last lecture; on 1 January 1894 he died of blood poisoning. He was thirty-six.

Hertz left behind his wife and two daughters, Johanna and Mathilde, all of whom emigrated from Nazi Germany in 1937 to settle in Cambridge, England.

When Hertz entered physics in the 1870's, electrodynamics was in a disorganized state. Theories had multiplied in its fifty years of development, and each had its own following. In Germany the leading theories were those of Weber and F. E. Neumann. Although both theories shared the fundamental physical assumption that electrodynamic actions are instantaneous actions at a distance, they differed in their formulations and in their assumptions about the nature of electricity. Neumann's theory was one of electrodynamic potential, mathematically abstract and physically independent of atomistic assumptions. Weber's, by contrast, was above all an atomistic theory, according to which electricity consisted of fluids of particles of two signs and possessed mechanical inertia. Any pair of Weberian particles interacted through a force or potential modeled in part after Newtonian gravitational attraction; Weberian interaction differed from the Newtonian in that it depended not only on the separation of the particles but also on their relative motion.

Electrodynamic thinking in Britain was based on physical assumptions about electrodynamic actions very different from those of Weber and Neumann. Inspired by Faraday's contention that instantaneous action at a distance was illogical and that the origin of electrodynamic actions was not in particulate electric fluids but in the condition of the space or medium intervening between ponderable bodies, Maxwell constructed a new mathematical theory of the electromagnetic field.

He conceived of the field as a mechanical condition of dielectric media, the ether of free space being a special case of such media. A central contention of Maxwell's theory was that light consisted of electromagnetic waves in dielectric media. It should be remarked that in suggesting a unification of the two separate branches of physics-electricity and optics—Maxwell's theory was not unique; for as Maxwell's contemporaries Riemann and Ludwig Lorenz showed, it was possible to modify action-at-a-distance theories to yield finitely propagated electric waves analogous to light waves.

Like rational mechanics, electrodynamics had an elaborate mathematical development; but unlike rational mechanics, it had not yet found its common principles. Helmholtz characterized electrodynamics at this stage as a "pathless wilderness," and he accordingly called for experiments to test more fundamentally the assumptions of the contending theories.

Beginning in 1870, Helmholtz turned his attention to electrodynamics; his object was to bring order to electrodynamics by casting the contending theories into a form that would expose their experimentally detectable differences. For this purpose he constructed a general theory of electrodynamics; its equations included as special cases those of Weber, Neumann, and Maxwell. Helmholtz' was an action-at-a-distance theory, since it regarded dielectric polarization as the displacement of bound charges under the influence of an electric force existing independently of a medium. Helmholtz showed that the three theories agreed in their predictions of electrodynamic phenomena associated with closed currents, but that they differed in their predictions of phenomena accompanying the oscillatory surgings of electricity of unclosed currents. He emphasized that it was only by attending to the phenomena accompanying unclosed currents that a decision might be made between the competing theories and a consensus brought to this important branch of physics.

In 1871 Helmholtz was called to Berlin to take up his first professorial position in physics. His move had immense importance for the subsequent development of electrodynamics. Helmholtz now had a physical institute and physics students, and he used this institutional opportunity to pursue his program for the reorganization of electrodynamics. It was a matter of great significance to Helmholtz to bring about a consensus in electrodynamic principles; by comparison it was a matter of little significance that it was achieved through the British conception of electrodynamic action and not through the action-at-a-distance conception that Helmholtz shared with other German electricians.

To encourage experimental work in the notoriously difficult domain of unclosed currents, Helmholtz proposed for the prize of the Berlin Philosophical Faculty in 1878 a problem dealing with an implication of Weber's theory: when oscillations of electricity are set up in an unclosed circuit, Weber's hypothetical electrical inertia should reveal itself in a retardation of the oscillations. Through the experiments that Helmholtz had suggested on the self-induction of doubly wound spirals, Hertz won the Philosophical Faculty prize; he proved that the inertia of electricity is either zero or less than a very small value, thereby lending experimental support to Helmholtz' theoretical judgment of the improbability of Weber's theory.

To encourage further the experimental decision between electrodynamic theories Helmholtz proposed through the Berlin Academy of Sciences in 1879 a second prize problem, this one in connection with the behavior of unclosed circuits in Maxwell's theory. Central to Maxwell's theory was the assumption that changes in dielectric polarization yield electromagnetic effects in precisely the same manner as conduction currents do. Helmholtz wanted an experimental test of the existence of these effects or, conversely, of the electromagnetic production of dielectric polarization. Although at the time Hertz declined to try the Berlin Academy problem because the oscillations of Leyden jars and open induction coils which he was familiar with did not seem capable of producing observable effects, he kept the problem constantly in mind; and in 1886 shortly after arriving in Karlsruhe he found that the Riess or Knochenhauer induction coils he was using in lecture demonstrations were precisely the means he needed for undertaking Helmholtz' test of Maxwell's theory.

In 1884. at Kiel, Hertz had already carried out a study of Maxwell's theory. It was a theoretical response to Helmholtz' general problem of deciding between rival electrodynamic theories. Whereas Helmholtz had shown that the experimental decision lay with unclosed currents, Hertz showed that a theoretical decision could be made on the basis of predictions for closed currents. Hertz proved that Maxwell's equations were compatible with the physical assumptions shared by all electrodynamic theories and that the equations of the contending theories were not. He concluded that if the choice lay solely between Maxwell's equations and the equations of the other type of theory, then Maxwell's were clearly preferable; he did not, however, endorse Maxwell's physical interpretation of his equations, in particular Maxwell's denial of action at a distance. Indeed when Hertz returned to Maxwell's theory in Karlsruhe, he did so within the action-at-a-distance framework of Helmholtz' general theory of 1870. With it he felt more at home, less committed to unproved hypotheses than with Maxwell's theory.

Hertz's first experiments in Karlsruhe in 1886 were intended to determine the influence of dielectrics such as pitch and paraffin on the inductive communication of sparks between primary oscillatory and detector circuits. Only in 1888 did it occur to him that the center of interest in Maxwell's theory was its assertion of the finite propagation of electric waves in air. Originally Helmholtz had intended to include in the Berlin Academy problem the option of testing whether or not air and vacuum behave electromagnetically like solid dielectrics, as Maxwell's theory required them to do. But the test had seemed too difficult at the time, and it was struck from the options, only to be restored later by Hertz in his own way. It was not until after Hertz had turned to the production of electric waves in air—in fact, only after he had published his first experiments on waves—that he at last dropped Helmholtz' action-at-adistance viewpoint; in 1889 he announced that he could describe his results better from Maxwell's contiguous action viewpoint.

Hertz knew of Helmholtz' attempt in 1871 to measure the velocity of propagation of transient electromagnetic inductive effects in air by the delay time between transmission and reception; Helmholtz' experimental arrangement was limited, and he had been able to establish only a lower limit on the velocity of about forty miles per second. Hertz did not know of G. F. FitzGerald's theoretical discussion of the possibility of producing nontransient electric waves in the ether; nor did he know of the attempts to detect electromagnetic waves in wires by 0. J. Lodge, another early follower of Maxwell. It is not certain if Hertz knew of the many observations by Edison, G. P. Thompson, D́avid Hughes, and others of the communication of electromagnetic actions over considerable distances; in any case, the observations were generally interpreted as ordinary inductions and therefore not of fundamental significance.

The influence of distance in the communication of electromagnetic actions was not significant until a theory was worked out to show its significance. Maxwell had not provided such a theory, having been mainly concerned to draw the optical rather than the invisible electromagnetic consequences of his theory. In his *Treatise on Electricity and Magnetism* (1873) he gave no theory of oscillatory circuits or of the connection between currents and electromagnetic waves. The possibility of producing electromagnetic waves in air was inherent in his theory, but it was by no means obvious and was nowhere spelled out. Hertz's proof of such waves was in part owing to his theoretical penetration into Maxwell's thought.

Hertz's proof was the result of his experimental inventiveness. He produced electric waves with an unclosed circuit connected to an induction coil, and he detected them with a simple unclosed loop of wire. He regarded his detection device as his most original stroke, since no amount of theory could have predicted that it would work. Across the darkened Karlsruhe lecture hall he could see faint sparks in the air gap of the detector. By moving it to different parts of the hall he measured the length of the electric waves; with this value and the calculated frequency of the oscillator he obtained the velocity of the waves. For Hertz his determination at the end of 1887 of the velocity—equal to the enormous velocity of light—was the most exciting moment in the entire sequence of experiments. He and others saw its significance as the first demonstration of the finite propagation of a supposed action at a distance.

Early in the course of his Karlsruhe experiments Hertz noticed that the spark of the detector circuit was stronger when it was exposed to the light of the spark of the primary circuit. After meticulous investigation in which he interposed over sixty substances between the primary and secondary sparks, he published his conclusion in 1887 that the ultraviolet light alone was responsible for the effect—the photoelectric effect. He was convinced that the effect had profound theoretical meaning for the connection of light and electricity, even though the meaning was obscure at the time. His experiments left no doubt of the reality of the effect, and soon other experimenters were studying it intensively. Hertz, however, did no more work on it, since it was a digression from his original purpose—the examination of the physical assumptions of Maxwell's theory.

Hertz followed up his determination of the finite velocity of electric waves by performing a series of more qualitative experiments in 1888 on the analogy between electric and light waves. Passing electric waves through huge prisms of hard pitch, he showed that they refract exactly as light waves do. He polarized electric waves by directing them through a grating of parallel wires, and he diffracted them by interrupting them with a screen with a hole in it. He reflected them from the walls of the room, obtaining interference between the original and the reflected waves. He focused them with huge concave mirrors, casting electric shadows with conducting obstacles. The experiments with mirrors especially attracted attention, as they were the most direct disproof of action at a distance in electrodynamics. They and the experiments on the finite velocity of propagation brought about a rapid conversion of European physicists from the viewpoint of instantaneous action at a distance in electrodynamics to Maxwell's view that electromagnetic processes take place in dielectrics and that an electromagnetic ether subsumes the functions of the older luminiferous ether.

It was far from clear to physicists, however, precisely to what theory they were subscribing when they declared themselves followers of Maxwell. The impressive, extraordinarily rapid consensus that Hertz's experiments brought about had not fully realized the program Helmholtz had laid down twenty years before of clarifying the principles of electrodynamics. There remained the vexing question of what Maxwell's theory really meant. In two theoretical papers in 1890 Hertz set about bringing perfection of form to the theory that, in his judgment, was perfect in its physical content. The content was clear; it was that electromagnetic phenomena are caused by polarizations in a dielectric medium filling otherwise empty space. The problem was to construct a consistent form that expressed the content faithfully, that banished all suggestion of distance forces and the associated electric fluids.

The first of Hertz's theoretical papers dealt with the electrodynamics of bodies at rest. In the introduction he maintained that Maxwell's theory, as formulated in the *Treatise*, contained traces of action at a distance, the route he thought Maxwell, like himself, had taken to Maxwell's theory. To attain a consistent contiguous action theory, Hertz eliminated the vector potentials from the fundamental equations of the theory, a residue from the concept of action at a distance and a scaffolding that unnecessarily complicated the formalism. He also eliminated Maxwell's distinction between the polarization and the electric force in the free ether, a distinction intelligible only within the framework of action at a distance. In denying the existence of distance forces, Hertz asserted that the polarizations of the medium were the only things really present; and in denying the electrical fluids from which the distance forces were supposed to proceed, he treated electricity, or charge, as merely a convenient abbreviation. In Britain, Heaviside had worked on a closely parallel reformulation of Maxwell's theory since 1885; Hertz knew of Heaviside's work, but his own contained a more searching critique of the physical content of Maxwell's theory.

According to Hertz, Maxwell's equations contained everything that was secure in Maxwell's theory. This was the sense of his dictum in the introduction to *Electric Waves:* "Maxwell's theory is Maxwell's system of equations." He did not offer the dictum as a final phenomenological position; rather he meant that any search for the mechanical basis of electrodynamics should start from Maxwell's equations—or, more accurately, from Hertz's form of ihe equations—and that the mechanical investigations of the past were irrelevant to the present state of the science. Accordingly in 1890 Hertz postulated the equations of the theory, instead of deriving them from a mechanical model of the ether. He proposed the symmetrical relations between the electric force *E* and the magnetic force *H* in the free ether (where forces and polarizations are identical):

where *c* is the speed of light. (The units are Gaussian. Hertz wrote his equations with the opposite sign because he used a left-handed coordinate system. He wrote them in components, too, rather than in vector notation.) Hertz's achievement in his first theoretical paper in 1890 was to simplify the formalism, to bring forward the logical structure of Maxwell's theory consistently interpreted as a contiguous action theory.

In his second theoretical paper, Hertz applied Maxwell's equations to moving, deformable bodies. Maxwell had not treated this problem systematically in the *Treatise* although, unknown to Hertz, he had done so elsewhere. Hertz recognized that to develop an electrodynamics of moving bodies, it was first necessary to specify whether or not the ether moves with bodies. For his part he would assume that the ether is mechanically dragged by moving bodies. The first ground for this assumption was that within the restricted domain of electromagnetic phenomena there was nothing incompatible with the idea of a dragged ether. The second ground was that its denial entailed the complication that two sets of electric and magnetic vectors had to be assigned to each point of space, one for the ether and one for the independently moving body. He recognized at the same time that a dragged ether was an unsure foundation for electrodynamics; it was incapable of explaining optical phenomena such as stellar aberration and Fizeau's experiment, phenomena which pointed to the independence of the motions of ponderable matter and the ether. He surmised that a correct theory would distinguish between the state of the ether and the state of the matter embedded in it at each point. He thought that to attempt a theory with a more probable interpretation of the ether would be premature and would require more arbitrary hypotheses than the present theory. The sole value he placed on his theory of electromagnetic forces in moving bodies was its systematic arrangement.

Hertz brought an unparalleled clarity to Maxwell's theory, organizing its concepts and its formalism so that others were able quickly to go beyond him. In underscoring the limitations of his formulation of Maxwell's theory he delineated the central problems for future research. Thus Hertz's electrodynamic theory was the last to be concerned exclusively with electrodynamic phenomena in the narrow sense. Subsequent developers of Maxwell's theory rejected Hertz's conception of the ether because of its inability to account for optical as well as electrodynamic phenomena. The most important developer was the Dutch theoretical physicist H. A. Lorentz, who constructed his electron theoretical extension of Maxwell's theory in 1892 in response to the optical insufficiency of Hertz's electrodynamics of moving bodies. In contradistinction to Hertz, Lorentz distinguished the electromagnetic field from ponderable matter by conceiving of the ether as stationary instead of dragged. This and Lorentz' other leading assumption of the molecular nature of electricity constituted the most fruitful foundation for the subsequent development of Maxwell's theory at the turn of the century.

Hertz's final years were devoted almost entirely to exploring the theoretical implications of Maxwell's electrodynamics for the rest of physics. In his 1889 Heidelberg lecture on his work on electric waves he said that from now on the ether would be the most fundamental problem in physics. Its understanding would elucidate major subsidiary problems, such as the nature of electricity, gravity, and mass. The suggestion of Hertz's work on Maxwell's electrodynamics was that a properly etherial physics would eliminate force as a fundamental concept. Hertz developed this suggestion in his last major work, his posthumously published *Principles of Mechanics*.

In a general way Hertz was guided in his mechanical studies by Mach's 1883 historico-critical analysis of mechanics, but he was once again guided specifically by problems Helmholtz had mapped out. In a series of papers in the 1880's Helmholtz had argued that a system of mechanics that included Newton's laws of motion together with the assumption of Hamilton's principle can explain all physical phenomena. Sharing Helmholtz' universalist goal for mechanics, Hertz regarded Helmholtz' work on Hamilton's principle as the furthest advance of physics. In another series of papers in the 1880's Helmholtz had constructed a mechanical analogy of the second law of thermodynamics based on monocyclic systems of hidden, moving masses. The analogy suggested to Hertz a way to reformulate mechanics without introducing forces as a fundamental concept.

Hertz accepted Kirchhoff's demonstration that mechanics can be represented in terms of three concepts alone: mass, space, and time. By contrast, the usual representations of mechanics included a fourth concept, either force or energy. Hertz explained in the introduction to the *Principles* that to construct a mechanics capable of accounting for the lawful interaction of perceptible bodies it was necessary to add a hypothesis to the three concepts. The hypothesis was that in addition to perceptible masses the universe contained hidden, moving masses bound to one another by rigid constraints. Under Hertz's hypothesis forces appeared neither in the microcosm nor in the macrocosm; the imperceptible universe was constituted of the same entities as the perceptible one.

At the head of his mechanics Hertz placed a single law of motion: the path of a system in 3 *n*-dimensional space is as straight as possible, subject to rigid constraints, and the system traverses the path with uniform motion. Any observable system acted upon by forces is in reality only a part of a larger force-free system that includes hidden masses. Hertz showed that the usual formulations of mechanics—Newton's, Lagrange's, and Hamilton's—can be deduced as theorems from his law of motion.

Like Helmholtz and such other contemporaries as Ludwig Boltzmann, Hertz sought to realize the historical goal of uniting the parts of physics through mechanics. Through the nineteenth century mechanics had come to pervade physics in increasingly insistent ways, and Hertz thought it was time that mechanics was given such foundations that it was exactly coterminous with physics; mechanics should no longer allow motions that do not occur in nature, nor should it exclude motions that do occur. Rejecting the view that mechanics was a branch of mathematics with unchanging principles, Hertz viewed it as the science of the actual actions and connections of nature. As such, mechanics was subject to change when the state of knowledge of physics changed—as it had with Hertz's confirmation of contiguous action in the electromagnetic ether.

Hertz opened the *Principles* with the observation that "all physicists agree that the problem of physics consists in tracing the phenomena of nature back to the simple laws of mechanics." It was one of the last times the statement could be made, and even then there were those who were disinclined to accept any longer the mechanical view of nature. The *Principles* was published on the eve of a great debate over world views, and as the most ambitious attempt to encompass all natural knowledge within mechanics it was a focus of discussion in the debate. Those, such as W. Wien and M. Abraham, who sought to derive all physics, including mechanics, from Maxwell's laws characterized their goal as diametrically opposed to that of Hertz. of reactions to the *Principles* by others who found the mechanical world view congenial, Helmholtz' may be taken as representative. While preferring a more abstract mathematical approach in physics to Hertz's hypothesis of hidden masses, Helmholtz admired the logic, generality, and unifying objective of Hertz's mechanics. His concern was that Hertz had not troubled to provide examples of the hypothetical mechanism of hidden masses in actual mechanical problems. He thought that it would be difficult to apply Hertz's principles—as indeed it turned out to be—and that at present they constituted only an ingenious program that might have great heuristic value for future research. It seems that the heuristic value was not realized, and apart from its role in the world view debate the major importance of the *Principles* has been as a classic of nineteenth-century philosophy of science.

Hertz's chief contribution to physics was in bringing about a decision regarding the proper principles for representing electrodynamics. His experimental researches in Karlsruhe settled once and for all the long conflict in nineteenth-century physics over the merits of action at a distance versus contiguous action. After Hertz it was eccentric to continue to advocate action at a distance in electrodynamics—or for that matter in any other part of physics. By the 1870's, when Hertz began his career, thermodynamics had been secured on the basis of its two fundamental laws; but the other principal branch of physics, electrodynamics, was encumbered with a proliferating collection of competing theories, and physicists showed little will or ability to settle its fundamentals and secure an agreement. More than any other physicist, Helmholtz responded to the primary need of the discipline at this time of putting electrodynamics in order.

It was not the least of Hertz's gifts to perceive that Helmholtz had more to offer him than did Kirchhoff or any other German physicist with whom he had early contact. Hertz's relation to Helmholtz was as a disciple, but not one unduly wedded to any of Helmholtz' methods. His dependence on Helmholtz was of a different sort; it lay in his recognition of Helmholtz' sure grasp of the central, soluble problems of physics. In his brief career Hertz revealed himself not as an innovator of concepts but as one having an uncommonly critical and lucid intelligence in addressing the conceptual problems of physics that others, Helmholtz above all, had marked out.

Hertz's researches on electric waves vindicated the Helmholtzian ideal of the physicist as one whose competence embraced both experiment and mathematics. Hertz entered physics at the right time for one of his abilities to make a critical contribution; because the outstanding problem of physics was the disorderly condition of electrodynamics, what was needed was someone with the theoretical power to analyze the competing theories and with the experimental judgment to produce the evidence that would persuade the physical community that a decision between the theories had been reached.

In the last quarter of the nineteenth century many German physicists, Hertz and Helmholtz among them, were intensely concerned to bring unity to the parts of their science; and they looked to mechanics for the source of unifying concepts. Much of the interest in thermodynamics at this time centered on its mechanical foundations. Once the principles of electrodynamics, like those of thermodynamics, were secure, Hertz turned to an investigation of the mechanical foundations of an ethereal physics. Instead of inventing mechanisms for the ether, he looked at the mechanical problem from a more general point of view. Convinced that the received mechanical principles were unsuited for the task of representing contiguous action processes in the ether, he refounded the science of mechanics on alternative principles that would provide a natural mechanical basis for electrodynamics as well as for the other parts of physics.

Hertz sought a basic understanding of nature; despite his origins in engineering and despite the fact that he made his major discoveries in an engineering school while teaching technical electricity, he did not concern himself much with the practical implications of electric waves. Others soon did, however. In the early 1890's the young inventor Guglielmo Marconi read of Hertz's electric wave experiments in an Italian electrical journal and began considering the possibility of communication by wireless waves. Hertz's work initiated a technological development as momentous as its physical counterpart.

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II.*Untersuchungen über die Ausbreitung der elektrischen Kraft* (Leipzig, 1892), translated by D. E. Jones as *Electric Waves* (London, 1893), with pref. by William Thomson. There is a paperback reprint of the 1893 English ed. (New York, 1962). A second German ed. was published in 1894, appearing as vol. II of the collected works. The volume contains all but one of Hertz's experimental and theoretical papers on Maxwell's theory (the omitted one is Hertz's 1884 theoretical comparison of Maxwell's and the opposing electrodynamics, which is included in vol. I). The 12 papers in the volume were published between 1887 and 1890. In addition it contains an extract from a publication on rapid electric oscillations by Wilhelm von Bezold and an introduction by Hertz. The first part of the introduction is, in Helmholtz' words, a frank "inner psychological history" of Hertz's route to the experimental proof of electric waves; the second part is a theoretical analysis of the meaning of Maxwell's theory.

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Russell Mc Cormmach