vaguely that the electronic orbits in the superconducting states must be irregular or "particular." Kammerlingh Onnes discussed a possible connection between the electron structures of the few superconducting elements according to Bohr's new theory of the periodic system. Langevin suggested that the discontinuous vanishing of resistance was perhaps a result of a phase change in the material. He was apparently unaware that the suggestion had already been tested experimentally in Leiden, where Keesom's x-ray analyses proved that no change in phase was involved. Owen Richardson proposed a model according to which the electrons could move freely along orbits tangential to each other, and Auguste Piccard wondered whether lightning was perhaps a superconducting phenomenon at normal temperature.

Neither the Solvay discussions nor other contemporary attempts to understand superconductivity brought the subject any closer to an explanation than before the war. As Einstein wrote in 1922, in his only contribution to the literature on superconductivity, "With our wide-ranging ignorance of the quantum mechanics of composite systems we are far from able to compose a theory out of these vague ideas. We can only rely on experiment" (Dahl 1992, 106). Incidentally, this was possibly the first time that the term "quantum mechanics" occurred in a scientific publication.

When the range of ignorance of quantum mechanics was drastically narrowed after 1925, it turned out that a theoretical understanding of superconductivity did not follow in any simple way from the new theory of quanta. Superconductivity was eventually given a satisfactory quantum-mechanical explanation, but it took a long time and many failed attempts until the strange phenomenon was fully understood. A phenomenological theory was developed in 1935 by the brothers Fritz and Heinz London, and in 1957 superconductivity was finally explained on a microscopic basis by the Americans John Bardeen, Leon Cooper, and Robert Schrieffer. We shall look at this later development in chapter 24.

Chapter 7

EINSTEIN'S RELATIVITY, AND OTHERS'

THE LORENTZ TRANSFORMATIONS

THE THEORY OF relativity has its roots in nineteenth-century optics. With the success of Augustin Fresnel's wave theory of light, the question of bodies moving through the ether came into focus. According to a theory Fresnel had suggested in 1818, a moving transparent body would partially drag along the ether. In that case, the velocity of light propagating through a body moving relative to the ether with velocity v would be changed by a fraction of the body's velocity, depending on the quantity v/c, where c is the velocity of light in vacuum. Fresnel's theory accounted for a large number of later optical experiments, which showed that it was impossible to detect, to the first order of v/c, the motion of the earth through the ether. When the elastic theories of light were replaced by Maxwell's electromagnetic theory, the situation was the same: Any theory of electrodynamics of moving bodies had to include the "Fresnel drag." In his first electron version of Maxwell's theory, published in 1892, Lorentz interpreted the Fresnel drag as a result of the interaction between light and the charged particles ("ions," later electrons) in the moving body. However, Lorentz was concerned that his theory was unable to explain an experiment that the American physicist Albert Michelson and his collaborator Edward Morley had performed five years earlier and that Michelson had first made in 1881.

The famous 1887 Michelson-Morley experiment was an attempt to measure the motion of the earth relative to the ether by means of an advanced interferometer technique. The experiment was performed at the Case School for Applied Science in Cleveland, Ohio, where Michelson was a professor of physics. It was to be expected that no first-order effects would be detected, but the Michelson-Morley experiment was precise to the second order, that is, dependent on the tiny quantity $(v/c)^2$. According to Lorentz's theory, the ether drift should be detectable to this order of precision, contrary to the null result of the experiment. The lack of a detectable motion of the earth through the world ether was surprising to both theorists and experimentalists. Rather than accepting the result, for a period Michelson considered the experiment to be a failure. "Since the result of the original experiment was negative, the problem is still demanding a solution," he maintained (Holton 1988, 284). The disagreement between theory and experiment caused Lorentz to modify his theory by assuming what was later called the Lorentz contraction, namely, that the length of a body moving in the direction of the earth's motion will shrink by a factor $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$ or, to the second order of $\beta = v/c$, $1 - \beta^2/2$. The quantity γ is known as the Lorentz factor. Unknown to Lorentz, a similar explanation had been proposed by the Irish physicist George FitzGerald in 1889, although without including the formula. For this reason, it is sometimes referred to as the FitzGerald-Lorentz contraction. Both FitzGerald and Lorentz assumed that the hypothetical contraction was caused by changes in the molecular forces, but at the time none of them could provide an explanation for the assumption.

Lorentz's first explanation of Michelson's result was clearly ad hoc and not even based on his electrodynamic theory. During the following decade he greatly developed the theory, and in 1899 the Dutch theorist was able to derive the length contraction from the more general transformation formulas between the coordinates of a body moving through the ether and those of one at rest with regard to the ether. Lorentz wrote these transformations in a more complete form in 1904, the same form that we know today. He was not, however, the first to put the full "Lorentz transformations" in print. As a purely mathematical transformation, they can be found in a work on the Doppler effect published by Woldemar Voigt as early as 1887. More to the point, in 1900 Larmor derived the equations from his own version of electron theory. By means of the Lorentz-Larmor transformations, the null result of the Michelson-Morley experiment could be explained easily. Indeed, it followed from Lorentz's theory that there could be no detectable effects of uniform motion through the ether, not just to the second order in v/c, but also to all orders.

The Lorentz transformations make up the formal core of the special theory of relativity, and at first glance it might thus seem that Einstein's theory was preceded by the electron theories of Lorentz and Larmor. However, this was not the case at all. In spite of having obtained the same transformations as Einstein in 1905, Lorentz interpreted them in a very different way. First, Lorentz's was a dynamic theory in which the transformations could be ascribed a physical cause, the interaction between the ether and the electrons of the moving body. The length contraction was seen as a compensating effect arising because of the body's motion through the ether. The earth, according to Lorentz, really moved through the ether, only the ether wind was not measurable, in accordance with Michelson's result. Second, Lorentz's ether was an essential part of his theory, in which it functioned as an absolute frame of reference. For example, he maintained (implicitly in 1904 and explicitly in 1906) the existence of absolute simultaneity. That this concept does not agree with the modern interpretation of the time transformation only illustrates the difference between the theories of Lorentz and Einstein. In both theories, the transformation reads $t' = \gamma(t - vx/c^2)$, where t' is the time in the system moving with velocity v relative to the (x,t) system. But Lorentz considered the transformation to be a mathematical device and the "local time" t' to have no real meaning. There was, he thought, only one real time, t (which he called general time). As another aspect of the difference in interpretation, Lorentz did not arrive at the relativistic formula for addition of velocities which, in the relativistic framework, follows straightforwardly from the kinematic transformations.

Although Lorentz, Larmor, and most other physicists stuck to the ether and the associated concepts of absolute space and time, there were also dissenting voices. Ernst Mach had strongly criticized Newton's concept of absolute space and his philosophically-based criticism was well known, not least to the young Einstein. Mach also criticized Newton's notion of absolute time (as had others before him), which he claimed was metaphysical because it did not rest on either experience or intuition. Referring to Mach's criticism of the mechanical world picture in his 1889 book *The Science of Mechanics*, Einstein recalled in his autobiographical notes that "this book exercised a profound influence upon me in this regard while I was a student" (Schilpp 1949, 21).

No sketch of the prehistory of relativity, however brief, can avoid mentioning Henri Poincaré alongside Lorentz. Based on his conventionalist conception of science, around 1900 the French mathematician questioned whether the simultaneity of two events could be given any objective meaning. As early as 1898 he wrote, "Light has a constant speed. . . . This postulate cannot be verified by experience, . . . it furnishes a new rule for the definition of simultaneity" (Cao 1997, 64). Two years later, at the Paris world congress of physics, Poincaré discussed whether the ether really existed. Although he did not answer the question negatively, he was of the opinion that the ether was at most an abstract frame of reference that could not be given physical properties. In his *Science and Hypothesis* of 1902, Poincaré declared the question of the ether to be metaphysical, just a convenient hypothesis that some day would be discarded as useless. In his address to the St. Louis congress in 1904, he examined critically the idea of absolute motion, argued that Lorentz's local time (t') was no more unreal than his general time (t), and formulated what he called the relativity principle, namely, the impossibility of detecting absolute, uniform motion. His formulation of 1904 is worth quoting: "According to the Principle of Relativity the laws of physical phenomena must be the same for a 'fixed' observer as for an observer who has a uniform motion of translation relative to him . . . there must arise an entirely new kind of dynamics, which will be characterized above all by the rule, that no velocity can exceed the velocity of light" (Sopka and Moyer 1986, 293). Up to this point, Poincaré's intervention in the discussion had been mainly programmatic and semiphilosophical. In the summer of 1905, without knowing about Einstein's forthcoming paper, he developed an electrodynamic theory that in some respects went beyond Lorentz's. For example, he proved the relativistic law of addition of velocities, which Lorentz had not done, and also gave the correct transformation formula for the charge density. Apart from restating the principle of relativity as "a general law of nature," Poincaré modified Lorentz's analysis and proved that the Lorentz transformations form a group with the important property that $x^2 + y^2 + z^2 - c^2t^2$ is invariant, that is, remains the same in any frame of reference. He even noticed that the invariant could be written in the symmetric way $x^2 + y^2 + z^2 + \tau^2$ if the imaginary time coordinate $\tau = ict$ was introduced. Poincaré's theory was an important improvement, a relativity theory indeed, but not *the* theory of relativity. Strangely, the French mathematician did not follow up on his important insights, nor did he show any interest in Einstein's simultaneously developed theory of relativity.

Einsteinian Relativity

When twenty-six-year-old Albert Einstein constructed the special theory of relativity in June 1905, he was unknown to the physics community. The paper he submitted to the *Annalen der Physik* was remarkable in several ways, quite apart from its later status as a work that revolutionized physics. For example, it did not include a single reference and thus obscured the sources of the theory, a question that has been scrutinized by later historians of science. Einstein was not well acquainted with the literature and came to his theory wholly independently. He knew about some of Poincaré's non-technical works and Lorentz's work of 1895, but not about Lorentz's (or Larmor's) derivation of the transformation equations. Another puzzling fact about Einstein's paper is that it did not mention the Michelson-Morley experiment or, for that matter, other optical experiments that failed to detect an ether wind and that were routinely discussed in the literature concerning the electrodynamics of moving bodies. There is, however, convincing evidence not only that Einstein was aware of the Michelson-Morley experiment at the time he wrote his paper, but also that the experiment was of no particular importance to him. He did not develop his theory in order to account for an experimental puzzle, but worked from much more general considerations of simplicity and symmetry. These were primarily related to his deep interest in Maxwell's theory and his belief that there could be no difference in principle between the laws of mechanics and those governing electromagnetic phenomena. In Einstein's route to relativity, thought experiments were more important than real experiments.

Most unusually at the time, the first and crucial part of Einstein's paper was kinematic, not dynamic. He started with two postulates, the first being the principle of relativity formulated as "the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good"; the other postulate was "that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body." As to the ether, Einstein briefly dismissed it as superfluous. From this axiomatic basis, he proceeded to considerations about apparently elementary concepts, such as length, time, velocity, and simultaneity. His aim was to clarify these fundamental concepts; by very simple arguments, he first showed that simultaneity cannot be defined absolutely but depends on the state of motion of the observers. He next applied this insight to show that there were no consistent notions of absolute time and absolute length of a body. The (Lorentz) transformations between a stationary system and another moving uniformly with respect to it were derived purely kinematically.

Contrary to those of Lorentz and Poincaré, Einstein's formulas related to real, physically measurable space and time coordinates. One system was as real as the other. From the transformation equations followed the formula for addition of velocities, the contraction of moving bodies, and the time dilation, that is, that time intervals are relative to the velocity of the observer. Einstein's transformed time was as real as any time can be and, in this respect, quite different from Lorentz's local time. The addition of two velocities u and v gives the final velocity $V = (u + v)/(1 + uv/c^2)$ and, as Einstein noted, this implies the counterintuitive result that the velocity of light is independent of the velocity of its source.

The foundation of the theory of relativity was given in the kinematic part, and more specifically in its two postulates. It was only in the second part that Einstein justified the title of his paper, "On the Electrodynamics of Moving Bodies." He derived the transformation formulas for electric and magnetic fields which, according to Einstein, were relative quantities in the same way as space and time coordinates. But although the field quantities were relative to the state of motion, the law that governed them was not: The Maxwell-Lorentz equations, Einstein proved, have the same form in any frame of reference. They are relativistically invariant. According to Einstein's theory, many physical quantities are relative to the motion of the observer, but other quantities (such as electrical charge and the velocity of light) and the basic laws of physics remain the same. And it is these invariants that are fundamental. For this reason, Einstein originally would have preferred to call his theory "the invariant theory," a name that might have prevented many misunderstandings. The name "relativity theory" was introduced by Planck in 1906 and quickly became accepted. Ironically, Planck considered the essence of Einstein's theory to be its absolute, not its relative, features.

In 1892 Lorentz had postulated the force that acts on a charge q moving in a magnetic field (the Lorentz force, $\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}/c$). Einstein kept the law but changed its status. He was able to deduce it in a simple manner from his transformations and thus reduce it to a derived law. At the end of his paper, Einstein considered the mass and energy of moving electrical charges, electrons. His electrons differed from those investigated by contemporary electrodynamicists, for Einstein's were primitive quantities; he was not interested in questions of their shape or internal structure. He predicted that the kinetic energy of an electron would vary with its speed as $m_0c^2 (\gamma - 1)$, where m_0 is the mass of the slowly moving electron, its rest mass. From this result, there is but a small step to the equivalence between mass and energy, a step Einstein took in another paper of 1905. There he derived what is possibly the most famous law of physics, $E = mc^2$. In Einstein's words: "The mass of a body is a measure of its energy-content; if the energy changes by L, the mass changes in the same sense by $L/9 \times 10^{20}$, the energy being measured in ergs, and the mass in grams."

Most readers of Einstein's paper probably considered it to be a contribution to the then-fashionable electron theory and paid less attention to its kinematic part. But Einstein was no electron theorist and his theory was, in accordance with the postulates on which it built, entirely general. The results were claimed to be valid for all kinds of matter, whether electrical or not. Einstein indicated his distance from contemporary electron theory by writing that his results, although derived from the Maxwell-Lorentz theory, were "also valid for ponderable material points, because a ponderable material point can be made into an electron (in our sense of the word) by the addition of an electric charge, *no matter how small*" (Miller 1981, 330; emphasis in original). This kind of "electron" had no place within the electromagnetic worldview. Equivalence between mass and energy was well known in 1905, but in a more narrow, electromagnetic interpretation (see chapter 8). Einstein's $E = mc^2$ was completely general.

Einstein's theory was taken up and discussed fairly quickly, especially in Germany. Its true nature was not recognized immediately, however, and it was often assumed to be an improved version of Lorentz's electron theory. The name "Lorentz-Einstein theory" was commonly used and can be found in the literature as late as the 1920s. The most important of the early relativity advocates was Max Planck, who was instrumental not only in putting his authority behind the theory, but also in developing it technically. Planck was greatly impressed by the theory's logical structure and unifying features. He recognized it to be a fundamental theory that encompassed both mechanics and electromagnetism and was happy when he discovered, in 1906, that the theory of relativity could be presented in the form of a principle of least action. Planck also developed the dynamics of particles according to Einstein's theory and was the first to write down the transformation laws for energy and momentum. Another important advocate was the Göttingen mathematician Hermann Minkowski who, in a 1907 lecture, presented relativity theory in a four-dimensional geometrical framework with a strong metaphysical appeal. Minkowski introduced the notion of a particle's worldline and explained enthusiastically how radical a break with the past the theory of relativity was: "Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality" (Galison 1979, 97). However, Minkowski considered Einstein's theory to be a completion of Lorentz's and interpreted it, wrongly, to be within the framework of the electromagnetic worldview.

Thanks to the works by Planck, Minkowski, Ehrenfest, Laue, and others, by 1910 Einstein's theory of relativity had gained firm support and was probably accepted by a majority of elite theoretical physicists. *Annalen der Physik* became the chief journal for a growing number of articles in which the theory was tested, examined conceptually and technically, and applied to new areas, and the old physics recast into relativistic frames. Outside Germany the reception was slower and more hesitant, but whether or not they accepted the theory in a physical sense, by 1910 many physicists used its equations. At that time, the theory was little known outside the physics community. It took some time for relativity to diffuse to the average physicist and, naturally, even longer to enter physics textbooks. The growing familiarity of the special theory of relativity is illustrated by Sommerfeld's famous *Atombau und Spektrallinien*, which was intended to be a book mainly for students and nonexperts in atomic physics. In the first three editions, from 1919 to 1922, Sommerfeld started his chapter on fine structure theory with an eighteen-page introduction to the theory of relativity. In the 1924 edition, he replaced the introduction with the optimistic comment that the theory of relativity was now common knowledge to all scientists.

From Special to General Relativity

> My first thought on the general theory of relativity was conceived two years later, in 1907. The idea occurred suddenly. . . . I came to realize that all the natural laws except the law of gravity could be discussed within the framework of the special theory of relativity. I wanted to find out the reason for this, but I could not attain this goal easily. . . . The breakthrough came suddenly one day. I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a deep impression on me. This led me to the theory of gravity. (Einstein 1982, 47)

This was how Einstein, in a 1922 address, described the start of the route that led him to one of the most fundamental theories ever in the history of science. In spite of interesting technical contributions by David Hilbert, Gunnar Nordström, and a few others, general relativity was very much Ein-

A Scientific Mass Suggestion (1920). Although noisy and fairly numerous, the antirelativists failed to impede the progress of German theoretical physics in the 1920s and, instead, marginalized themselves. It was only after 1933, when a new political system had seized power, that antirelativism became of some, if still only limited, importance in German science.

Chapter 8

A REVOLUTION THAT FAILED

IN PREVIOUS CHAPTERS we have often mentioned the electromagnetic worldview as the main contender to the mechanical view of physics. It may seem strange to deal with this incorrect worldview after having described the advent of the true theory of relativity, for after 1905 physicists must surely have recognized that the electron theory (in its broad meaning) was inferior to relativity. Perhaps they should have to, but they did not. In fact, the electromagnetic worldview experienced its zenith just after 1905, and it took at least five more years until it was recognized that this grand attempt to formulate a new basis for physics was probably not tenable.

The Concept of Electromagnetic Mass

As mentioned in chapter 1, at the turn of the century the mechanical worldview was under attack and on its way to be replaced by a view based on electromagnetic fields. The more radical and elaborate version of the new conception, known as the electromagnetic worldview, emerged about 1900 and flourished for about a decade. Its core program was the full reduction of mechanics to electromagnetism, a new physics in which matter had disappeared as a substance and been replaced by effects of electromagnetic fields—electrons. The program was based on developments in electrodynamics in the 1880s and 1890s, during which period a less complete electromagnetic view of nature emerged and resulted in the electron theories of Larmor, Lorentz, and Wiechert. In this process, two traditions played a role. One, of importance only to Lorentz and Wiechert, was the corpuscular electrodynamical tradition of Weber and his followers, which operated with electrical particles in instantaneous interaction, but without a field concept; the other tradition, on the contrary, was firmly rooted in Maxwellian field electrodynamics. Already in 1894, Wiechert had clearly expressed the conviction that material mass might be an epiphenomenon and that the only true mass was of electromagnetic origin, consisting of the hypothetical electrical particles he depicted as excitations in the ether. Wiechert's suggestion anticipated the electromagnetic worldview, but his work in this area was somewhat overshadowed by the works of Lorentz and German theorists such as Max Abraham and Adolf Bucherer.

In 1881, young J. J. Thomson showed that when a charged sphere moves through the ether, it will acquire a kind of apparent mass, analogous to a sphere moving through an incompressible fluid. For a sphere with charge *e* and radius *R*, he found the electromagnetically induced mass to be $m' = 4/15\ e^2/R^2c$. This first introduction of electromagnetic mass was later improved by the excentric British engineer-physicist Oliver Heaviside, who in 1889 derived the expression $m' = 2/3\ e^2/R^2c$. Contrary to Thomson, who did not think of the "apparent mass" as real, Heaviside considered it as real as the material mass. It was part of the sphere's measurable or "effective" mass. A further improvement was obtained by Wilhelm Wien in 1900, in a paper significantly titled "On the Possibility of an Electromagnetic Foundation of Mechanics." Wien confirmed Heaviside's expression in the limit of small velocities and added the important result that the electromagnetic mass would depend on the velocity and differ from Heaviside's if the velocity approached the velocity of light. Exactly how the mass of an electron, or any charged body, would depend on the velocity quickly became a problem of crucial importance in the new electron physics. Wien's paper of 1900 has been seen as the first clear pronouncement of the electromagnetic worldview, which (in spite of Wiechert's earlier formulation) is justified insofar that Wien assumed that all mass was of electromagnetic nature. Matter, Wien argued, consisted of electrons, and electrons were particles *of* electricity, not tiny spheres on which electricity resided. Moreover, he contended that Newton's laws of mechanics had to be understood electromagnetically and, if a complete correspondence could not be achieved, electron theory was the more profound and fundamental theory of the two.

The first detailed electron model was constructed by Max Abraham, a Göttingen physicist who had graduated under Planck in 1897. According to Abraham, writing in 1902, the most important question in physics was this: "Can the inertia of electrons be completely accounted for by the dynamical action of its field without using the help of mass which is independent of the electric charge?" (Goldberg 1970, 12). It was, in part, a rhetorical question. Abraham believed it *had* to be answered affirmatively. He made a detailed study of the dynamics of the electron in a paper of 1903, which in more than one way contrasted with Einstein's relativity paper two years later. Whereas Einstein's paper was mathematically simple, Abraham's was a mathematical tour de force; and whereas Einstein's filled 31 pages, Abraham's was no less than 75 pages. Both works appeared in *Annalen der Physik*, a journal that often included papers of a length that would be unheard of in modern physics journals. In his works of 1902–1903, Abraham argued that the only kind of electron that could be understood fully in terms of electromagnetism was a rigid sphere with a uniform surface or volume charge distribution. For such an electron, he calculated its mass—arising purely from the electron's own fields—and found a velocity variation which, to the first order of $\beta^2 = (v/c)^2$, can be written $m = m_0(1 + 2/5\ \beta^2)$. Here, m_0 denotes the electromagnetic rest mass, $2/3\ e^2/R^2c$. We shall shortly return to Abraham's important work, which was not the only electron theory of the period.

The idea of mass varying with velocity was part of Lorentz's research program as he developed it from 1899. Lorentz's approach differed from that of Wien and Abraham, and he was reluctant to follow them in their belief that all mass is electromagnetic. In 1904, however, he overcame his natural caution and in his theory of the electron from that year he supported the electromagnetic worldview. Not only was the mass of his electron of electromagnetic origin, but he also argued that all moving matter (whether consisting of electrons or not) must obey the mass-variation characteristic of electrons. In 1906, in a lecture given at Columbia University, he stated, "I for one should be quite willing to adopt an electromagnetic theory of matter and of the forces betwen material particles." He continued: "As regards matter many arguments point to the conclusion that its ultimate particles always carry electric charges and that these are not merely accessory but very essential. We should introduce what seems to me an unnecessary dualism, if we considered these charges and what else there might be in the particles as wholly distinct from each other" (Lorentz 1952, 45). Lorentz's electron was, however, different from Abraham's rigid particle. It was a deformable electron, meaning that it would contract in the direction of motion and thus acquire an ellipsoidal shape instead of the spherical shape it had at rest. Abraham objected to this feature of Lorentz's theory because the stability of the electron would require some nonelectromagnetic force; this, Abraham claimed, went against the spirit of the electromagnetic worldview. Exactly what this spirit was could, however, be debated; not all physicists saw in Abraham's theory the essence of the electromagnetic worldview. Thus, in 1908 Minkowski considered the rigid electron to be "a monster in relation to Maxwell's equations" and wittily remarked that "approaching Maxwell's equations with the concept of the rigid electron seems to me the same thing as going to a concert with your ears stopped up with cotton wool" (Miller 1981, 350).

For the variation in mass, Lorentz deduced the famous inverse-square-root expression that is today exclusively associated with Einstein's theory of relativity: $m = m_0(1 - \beta^2)^{-\frac{1}{2}}$ or, approximately, $m = m_0(1 + 1/2\ \beta^2)$. It is readily seen that the practical difference between Lorentz's and Abraham's formulae is small and that it requires electrons at very high speeds to distinguish experimentally between them.

Abraham's rigid and Lorentz's deformable electrons were the most important models, but not the only ones. The German physicist Adolf Bucherer, and independently Paul Langevin in Paris, proposed in 1904 yet another model, characterized by an invariant volume under motion so that the electron's contraction in one dimension would be compensated by inflation in the other. The Bucherer-Langevin theory led to a mass-velocity relationship different from both Abraham's and Lorentz's. In order to decide among the different theories—including Einstein's, which was usually seen as a variant of Lorentz's—appeal had to be made to the precision experiments. Before we turn to the experiment-theory issue, we shall consider some of the wider aspects of the electromagnetic world picture.

Electron Theory as a Worldview

By 1904 the electromagnetic view of the world had taken off and emerged as a highly attractive substitute for the mechanical view that was widely seen as outdated, materialistic, and primitive. As an indication of the strength of the new theory, it was not only discussed in specialized journals, but also began to appear in physics textbooks. For example, Bucherer introduced his electron theory in a 1904 textbook. Of more importance was the textbook in electrodynamics that Abraham published the same year and which, in its several editions, became widely used both in Germany and abroad during more than twenty years. The work was a revision of a textbook on Maxwell's theory written by August Föppl in 1894 (used by, among others, the young Einstein), but whereas Föppl had given a mechanical derivation of Maxwell's equations, Abraham used his revised version to reverse Föppl's priority between mechanics and electromagnetism. In a companion volume of 1905, Abraham came out without much reserve as a missionary for the electromagnetic worldview.

In commemoration of the centenary of the United States' purchase of the Louisiana Territory, a Congress of Arts and Sciences was held in St. Louis in September 1904. Among the physics delegates were several international leaders of physics, including Rutherford, Poincaré, and Boltzmann. The general message of many of the addresses was that physics was at a turning point and that electron theory was on its way to establishing a new paradigm in physics. In his sweeping survey of problems in mathematical physics, Poincaré spoke of the "general ruin of the principles" that characterized the period. Poincaré was himself an important contributor to electron theory and he was now willing to conclude that "the mass of the electrons, or, at least, of the negative electrons, is of exclusively electro-dynamic origin . . . [T]here is no mass other than electro-dynamic inertia" (Sopka and Moyer 1986, 292). The address of another French physicist, thirty-two-year-old Paul Langevin, was more detailed, but no less grand, no less eloquent, and no less in favor of the electromagnetic world picture. Langevin argued for his own (and Bucherer's) model of the electron, but the detailed structure of the electron was not what really mattered. The important thing was the coming of a new era of physics. As Langevin explained in his closing words:

> The rapid perspective which I have just sketched is full of promises, and I believe that rarely in the history of physics has one had the opportunity of looking either so far into the past or so far into the future. The relative importance of parts of this immense and scarcely explored domain appears different to-day from what it did in the preceding century: from the new point of view the various plans arrange themselves in a new order. The electrical idea, the last discovered, appears to-day to dominate the whole, as the place of choice where the explorer feels he can found a city before advancing into new territories. . . . The actual tendency, of making the electromagnetic ideas to occupy the preponderating place, is justified, as I have sought to show, by the solidity of the double base on which rests the idea of the electron [the Maxwell equations and the empirical electron]. . . . Although still very recent, the conceptions of which I have sought to give a collected idea are about to penetrate to the very heart of the entire physics, and to act as a fertile germ in order to crystallize around it, in a new order, facts very far removed from one another. . . . This idea has taken an immense development in the last few years, which causes it to break the framework of the old physics to pieces, and to overturn the established order of ideas and laws in order to branch out again in an organization which one foresees to be simple, harmonious, and fruitful. (ibid., 230)

Evaluations similar to Langevin's, and often using the same code words and imagery, can be found abundantly in the literature around 1905. They rarely included references to quantum theory or the new theory of relativity.

The methodology behind the electromagnetic research program was markedly reductionistic. Its aim was to establish a unitary theory of all matter and forces that exist in the world. The basis of the theory was Maxwellian electrodynamics, possibly in some modified or generalized version. It was an enormously ambitious program. When it was completed, nothing would be left unexplained—at least in principle. In this sense, it was clearly an example of a "theory of everything." Elementary particles, atomic and quantum phenomena, and even gravitation were held to be manifestations of that fundamental substratum of the world, the electromagnetic field. Attempts to explain gravitation in terms of electromagnetic interactions went back to the 1830s, when such a theory was proposed by the Italian physicist Ottaviano Mossotti. Later in the century the idea was developed in mathematical details by the Germans Wilhelm Weber and Friedrich Zöllner, who based their theories on the notion of electrical particles in instantaneous interaction. Electrogravitational theories continued to be discussed after field electrodynamics became the dominant framework of electricity and magnetism. For example, in 1900 Lorentz derived, on the basis of his electron theory, a gravitational law that he considered a possible generalization of Newton's. Attempts to unify the two basic forces of the universe, usually by reducing gravitation to electromagnetism, was part of the electromagnetic program, but in spite of much work, no satisfactory solution was found.

The electromagnetic worldview was also a matter of interest outside physics and was ocassionally discussed by philosophers. It even entered politics, as illustrated by Lenin's *Materialism and Empiriocriticism*, a political-philosophical work written while Lenin was an emigré in Geneva and London in 1908. In his attempt to formulate a dialectical-materialistic conception of nature, Lenin quoted passages from Poincaré, Righi, Lodge, and other physicists to the effect that physics was in a state of crisis. "The electron," wrote the future leader of the Soviet Union, "is as *inexhaustible* as the atom; nature is infinite, but it *exists* infinitely." What Lenin meant by this is not quite clear, but then perhaps it was not intended to be clear.

The revolutionary atmosphere in theoretical physics is further illustrated by a meeting of the German Association of Scientists and Physicians that took place in Stuttgart in 1906, that is, after the introduction of Einstein's relativity. Most of the leading electron theorists participated and the general opinion was in favor of the electromagnetic worldview in its pure form as developed by Abraham, for instance. Lorentz's theory was criticized for its reliance on a nonelectromagnetic stabilizing force; only Planck defended Lorentz's (and Einstein's) theory against this theoretical objection. The rigid electron was incompatible with the relativity postulate, Planck argued, and this spoke in favor of the Lorentz theory. To Abraham and his allies, it spoke against it. Among the allies was thirty-seven-year-old Arnold Sommerfeld, who would later become a leader of quantum and atomic physics, but at that time had specialized in the fashionable electron theory. Sommerfeld made it clear that he considered the Lorentz-Einstein theory hopelessly conservative, an attempt to save what little could be saved of the old and dying mechanistic worldview. Although Planck admitted that the electromagnetic program was "very beautiful," it was still only a program, he countered, and one that could hardly be worked out satisfactorily. To Sommerfeld, such an attitude was unwarranted "pessimism."

Generational revolts are often parts of revolutionary movements and, according to Sommerfeld, the new paradigm in physics held special appeal to the younger generation: "On the question of principles formulated by Mr. Planck," Sommerfeld said, "I would suspect that the gentlemen under forty will prefer the electrodynamic postulate, those over forty the mechanical-relativistic postulate" (Jungnickel and McCormmach 1986, 250). The generalization was probably fair enough, although there were exceptions. One of them was Einstein, Sommerfeld's junior by ten years. Another was Lorentz, well above the forty-year-old limit. Less than a decade after the Stuttgart meeting, the situation between revolutionaries and conservatives had reversed. Now, Abraham wrote in 1914, "physicists of the old school must shake their heads in doubt on this revolution in the conception of mass. . . . The young mathematical physicists who filled the lecture halls in the epoch of its influence were enthusiastic for the theory of relativity. The physicists of the older generation, . . . mainly regarded with scepticism the bold young men who undertook to overthrow the trusted foundations of all physical measurement on the basis of a few experiments which were still under discussion by the experts" (Goldberg 1970, 23).

One of the important issues in the worldview discussion was the status of the ether. There was a wide and confusing variety of views about the ether and its relationship to the electron theory, but only a minority of physicists wanted to do without the ether. The majority view around 1905 seems to have been that the ether was an indispensable part of the new electron physics—indeed, another expression of the electromagnetic field. For example, in his Columbia University lectures of 1906, Lorentz spoke of the ether as "the receptacle of electromagnetic energy and the vehicle for many and perhaps all the forces acting on ponderable matter . . . we have no reason to speak of its mass or of forces that are applied to it" (Lorentz 1952, 31). The ether survived the attack on the "old physics," but it was a highly abstract ether, devoid of material attributes. Thus, in 1909 Planck wrote that "Instead of the so-called free ether, there is absolute vacuum . . . I regard the view that does not ascribe any physical properties to the absolute vacuum as the only consistent one" (Vizgin 1994, 17). Planck was not the only one to use the term "vacuum" synonymously with "ether." From this position, there is but a small step to declare the ether nonexistent. This was precisely the conclusion of the German physicist Emil Cohn, a specialist in electrodynamics who developed his own ether-free version of electron theory between 1900 and 1904. One could consistently deny the relativity principle and the ether, as Cohn did; or deny the relativity principle and accept the ether, as Abraham did; or accept both the relativity principle and the ether, as Lorentz did; or accept the relativity principle and deny the ether, as Einstein did. No wonder many physicists were confused.

Mass Variation Experiments

The answer to the confusion was obviously experiments. In principle, at least, it should be possible to test the predictions of the various theories and, in this way, decide which came nearest to the truth. In fact, the first experiments made in order to determine the distribution between mechanical and electromagnetic mass had already been performed at the time Abraham proposed his electron model. Walter Kaufmann, the Göttingen physicist who in 1897 had measured the charge-to-mass ratio of cathode rays simultaneously with Thomson, started a series of experiments in 1900 in which he deflected beams of electrons in electric and magnetic fields. In order to find the velocity-dependent part of the electron's mass (that is, the electromagnetic mass), electrons of extreme speeds were necessary; for this purpose, Kaufmann used beta rays, which had recently been identified with electrons moving with speeds up to 90 percent or more of the velocity of light.

Kaufmann, who was not only an excellent experimenter but also an able theorist, was an early advocate of electron theory and the electromagnetic world picture. There is little doubt that his enthusiasm for the new physics colored his interpretations of his experimental data. In 1901 he concluded that about one-third of the electron's mass was of electromagnetic origin. When he was confronted with Abraham's new theory, he quickly reinterpreted his data and managed to come to a quite different conclusion, namely, that the entire mass of the electron was electromagnetic, in agreement with Abraham's view. Kaufmann and Abraham were colleagues at Göttingen University and this personal relationship, as well as Kaufmann's deep sympathy for the electromagnetic worldview, led Kaufmann to claims that were not justified by his data alone. In 1903 he concluded that not only beta ray electrons, but also cathode ray electrons, behaved in accordance with Abraham's theory.

After 1905, when Lorentz's theory (or the "Lorentz-Einstein theory") appeared as a competitor to Abraham's, Kaufmann performed new experiments in order to settle the question of the variation of mass with velocity. The complex experiments led to results that apparently refuted Lorentz's theory, but agreed reasonably well with Abraham's and also with the predictions of Bucherer and Langevin. In light of the new data, Kaufmann concluded that the attempt to base physics on the relativity postulate "would be considered as a failure." His experiments were eagerly discussed at the 1906 Stuttgart meeting, where most of the participants were on Kauffman's side, for the rigid electron and against the deformable electron and the relativity principle. It was realized, however, that the correct interpretation of the experiments was far from straightforward, and Planck warned that there were many uncertainties and questionable points in Kaufmann's analysis. He therefore suggested that the experiments were unable to decide between the theories of Abraham and Lorentz and that new experiments were needed.

The reactions of the theorists differed. Abraham was happy to accept Kauffman's conclusion, and Lorentz, much less happily, accepted it too. Lorentz felt that his entire theory was threatened—indeed, proved wrong. As he wrote to Poincaré, "Unfortunately my hypothesis of the flattening of electrons is in contradiction with Kaufmann's new results, and I must abandon it. I have, therefore, no idea of what to do" (Miller 1981, 337). Philosophically speaking, Lorentz acted as a "falsificationist," in accordance with Karl Popper's philosophy of science. It was not so with Einstein, whose response was rather in agreement with the recommendations made by the philosopher Imre Lakatos. Einstein at first ignored Kaufmann's alleged refutation, but suspected that errors had entered the reduction of data and their interpretation. Yes, the experiments disagreed with the theory of relativity but, no, that did

not imply that the theory was wrong: It must mean that the experiments were wrong. "In my opinion," Einstein wrote in 1907, "both theories [Abraham's and Bucherer-Langevin's] have a rather small probability, because their fundamental assumptions concerning the mass of moving electrons are not explainable in terms of theoretical systems which embrace a greater complex of phenomena" (ibid., 345). Einstein's attitude (and Planck's, too) was not simply to deny the validity of Kaufmann's experiment because it disagreed with a favored theory. Einstein and Planck went deeply into the experimental details, analyzed the entire situation carefully, and then concluded that there were good reasons to suspect systematic errors.

In any case, Einstein's youthful confidence in his theory soon turned out to be warranted. In experiments of 1908, Bucherer, as competent as Kaufman in theory and experiment, measured the electric and magnetic deflection of beta rays in a manner different from Kaufmann's. His results were different too, leading to a confirmation of the Lorentz-Einstein theory. In regard of the fact that Bucherer had himself proposed a rival theory of electrons, which had received some support from Kaufmann's experiments, it is noteworthy that he did not hesitate in criticizing these experiments and conclude from his own that only Lorentz's theory was viable. At that time, Bucherer had lost confidence in his own theory of the constant-volume electron because it was contradicted by dispersion phenomena. He therefore considered his experiment to be a test between only two alternatives, Abraham's and Lorentz's. Bucherer's experiments were far more transparent than Kaufmann's and more difficult to criticize. But of course they were not beyond criticism, and did not make up a crucial experiment in favor of the Lorentz-Einstein theory. During the following years experiments continued, mostly in Germany, and it took some time until the experimental situation stabilized with the result that it became generally accepted that the Lorentz-Einstein mass variation was experimentally confirmed. By 1914, the question was largely settled. It was not a complete stabilization, though, and discussions continued many years after Einstein's theory had become accepted and the electromagnetic view of nature fallen into oblivion.

We shall not carry on with this story except to mention that the question of the mass variation acquired a political dimension after 1920, when anti-relativism began to flourish in parts of German cultural life. Many conservative physicists longed for the day when Einstein's theory would be replaced by a theory based on the ether or electromagnetic concepts. Ironically, among these conservatives were some of the former advocates of the electromagnetic worldview who, years earlier, had considered themselves bold progressives in their fight against old-fashioned mechanicism. Abraham, once an arch-revolutionary, was one of those who never accepted relativity and protested against an ether-free physics. Bucherer, another of the electromagnetic revolutionaries and unwillingly a contributor to the victory of relativity, became in the 1920s an ardent antirelativist on the right wing of German physics. In this situation, new experiments were made on the electron's variation of mass, sometimes with the clear intention of refuting the theory of relativity. And indeed, some of the antirelativists concluded that their experiments confirmed Abraham's old theory, while refuting Einstein's. Other physicists, including Bucherer, accepted the Lorentz-Einstein formula but were careful to distinguish between the formula and Einstein's theory. "Today," Bucherer wrote in 1926, "the confirmation of the Lorentz formula can no longer be adduced as proving the Einsteinian theory of relativity" (Kragh 1985, 99).

Decline of a Worldview

The electron experiments were one factor in the decline of the electromagnetic worldview, but they formed only one factor among many. Whereas experiments are subject to experimental testing, worldviews are not. In fact, the possibility of a fully electromagnetic physics, comprising all aspects of physical reality, was never disproved, but rather melted away as it gradually lost its early appeal. It is difficult to be a revolutionary for a longer period, especially if the high hopes of a better future show no sign of becoming reality. By 1914, at the latest, the electromagnetic worldview had lost its magic and the number of its advocates diminished to a small crowd at the periphery of mainstream physics. Shortly before the outbreak of the World War I, Emil Warburg edited a book in a series called *Contemporary Culture* (*Kultur der Gegenwart*), with thirty-six summary articles on different fields of physics. Among the authors of this semiofficial work were leading physicists within the German culture, including Wiechert, Lorentz, Rubens, Wien, Einstein, Kaufmann, Zeeman, and Planck. The content of the book may give some indication of the composition of physics at the time:

Mechanics	79 pages
Acoustics	22 pages
Heat	163 pages
Electricity	249 pages
Optics	135 pages
General Principles	85 pages

The chapters on heat included not only blackbody radiation, but also Einstein's article on "Theoretical Atomistics," that is, the kinetic theory of matter. Among the thirteen articles in the category of electricity, there was one about wireless telegraphy, one about x-rays, and two dealing with radioactivity. The article on the theory of relativity, written by Einstein, was placed

in the General Principles category. The electromagnetic worldview was barely visible and entered only indirectly in Lorentz's article on "The Maxwell Theory and the Electron Theory."

Why did the electromagnetic program run out of power? The process of decline was a complex one that involved both scientific reasons and reasons related to changes in the period's cultural climate. As mentioned, experimental predictions, such as those arising from Abraham's theory, did not agree with the results of actual experiments. On the other hand, this was hardly a major cause for the decline, for the rigid electron was not a necessary ingredient of the electromagnetic worldview. More important was the competition from other theories that were either opposed to the electromagnetic view or threatened to make it superfluous. Although the theory of relativity was sometimes confused with Lorentz's electron theory or claimed to be compatible with the electromagnetic worldview, about 1912 it was evident that Einstein's theory was of a very different kind. It merely had nothing to say about the structure of electrons and with the increasing recognition of the relativistic point of view, this question—a few years earlier considered to be essential—greatly changed in status. To many physicists, it became a pseudo-question. As the rise of relativity theory made life difficult for electromagnetic enthusiasts, so did the rise of quantum theory. Around 1908, Planck reached the conclusion that there was a fundamental conflict between quantum theory and the electron theory, and he was cautiously supported by Lorentz and other experts. It seemed that there was no way to derive the blackbody spectrum on a purely electromagnetic basis. As quantum theory became more and more important, electron theory became less and less important. The worst thing that can happen to a proclaimed revolution is that it is not needed.

In general, electron theory had to compete with other developments in physics that did not depend on this theory, and after 1910 new developments in physics attracted interest away from the electron theory. So many new and interesting events occurred, so why bother with the complicated and overambitious attempt to found all of physics on electromagnetic fields? Rutherford's nuclear atom, isotopes, Bohr's atomic theory, the diffraction of x-rays by crystals, Stark's discovery of the electric splitting of spectral lines, Moseley's x-ray-based understanding of the periodic system, Einstein's extension of relativity to gravitation, and other innovations absorbed the physicists' intellectual energy and left the electromagnetic worldview behind. It was a beautiful dream indeed, but was it physics? Much progress took place in atomic physics and as the structure of the atom became better understood, it became increasingly difficult to uphold the electromagnetic view. The positive charge had been a problem in atomic theory since 1896, when the Zeeman effect indicated that electrons carry a negative charge. A theory of matter in harmony with the electromagnetic worldview needed positive electrons,