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The Electromagnetic View of Nature and a World of Ether

Building Theories: Fundamental Questions, Different Styles

Fundamental questions in nineteenth-century chemistry and physics were: What is matter? What are atoms, molecules, and corpuscles? But there were other central questions as well: How does matter interact with other matter? What is the role of the ether? Is electricity a substance, or is it a motion like light and heat? How can we express the properties of matter, ether, electricity, and light mathematically?

In 1867, William Thomson, who was to become Lord Kelvin in 1892, published a widely read paper, "On Vortex Atoms," in which he concerned himself with all these problems and took a firm stand against what he regarded as the old school of Newtonian and Daltonian corpuscles and action-at-a-distance forces. Writing about atoms, and tendentiously maligning chemists, he wrote,

> The only pretext seeming to justify the monstrous assumption of infinitely strong and infinitely rigid pieces of matter, the existence of which is asserted as a probable hypothesis by some of the greatest modern chemists in their rashly-worded introductory statements, is that urged by Lucretius and adopted by Newton—that it seems necessary to account

> for the unalterable distinguishing qualities of different kinds of matter.[1]

Abandoning Newton's "solid, massy, hard, impenetrable, moveable particles," Thomson announced his enthusiasm for a recent postulate of Helmholtz: that matter is an effect of vortex motion in an ether fluid, and that the investigation of the mutual action between vortex rings "is a perfectly solvable mathematical problem" that can serve as the foundation for the treatment of material corpuscles.

In Thomson's view, these vortex atoms could be the basis of a kinetic theory of gases (see chapter 4). Equally, modes of vibration of the vortex atom might account for the line spectra characteristic of the vaporized chemical elements. The period of vibration of yellow sodium light (1/525 millionth of a millionth of a second), for example, might be an approximation of the period of vortex rotation of atoms of sodium vapor. Matter, electricity, and light were all to be explained through a mathematical description of motion in the ether.

What were some of the experiments and ideas leading up to Thomson's point of view? Is his view exemplary of major trends in nineteenth-century chemical and physical science? How widely was the vortex atom accepted, and what did the vortex-in-the-ether have to do with the optical ether? We turn in this chapter to theories of ether, electricity, and light, as worked out mainly by natural philosophers from roughly 1845 to 1895.

Curiously, what this history reveals is a striking difference in preconceptions about modes of scientific reasoning among natural philosophers who were working in different national traditions. In the 1890s the French physicist, historian, and philosopher Pierre Duhem (1861–1916) made an argument for different national styles of theory-building. Similarly, in the early twentieth century, the British physicist Ernest Rutherford (1871–1937) claimed to have been struck

> by the fact that continental people do not seem to be in the least interested to form a physical idea as a basis of Planck's [radiation] theory. They are quite content to explain everything on a certain assumption and do not worry their heads about the real cause of a thing. I must, I think, say that the English point of view is much more physical and much to be preferred.[2]

There was some truth to Duhem and Rutherford's agreement that British physicists were educated to value theories that were pragmatic, concrete, and strongly visual, while, by contrast, Continental strategies of scientific explanation often were rigorous, abstract, and esoteric. To use a now-common stereotype, the British "muddled through" in order to get results that worked efficiently, while French and German scientists demanded orderly and coherent theories founded in first principles. British scientists frequently introduced the newest ideas and tools to their students, while continental scientists, especially French physicists and chemists, often believed that students should be shielded from newly speculative theories in favor of established, classical theories. In addition, Continental scientists, who traditionally received much stronger administrative and financial support from government ministries than did their British counterparts, often belittled the "amateur" and "engineering" affiliations of many British scientists.

Engineering interests were especially strong in the investigations that created the science of electricity during the course of the nineteenth century. This science of electricity was largely built on Michael Faraday's initial laboratory discoveries in the 1820s and 1830s about relationships between electricity and magnetism. From Faraday's experimental investigations there developed rival mathematical traditions of electrodynamics. One was a set of British, or "Maxwellian," theories worked out by William Thomson, J. C. Maxwell, G. G. Stokes, J. J. Thomson (1856–1940), George Francis Fitzgerald (1851–1901), Oliver Joseph Lodge (1851–1940), and Oliver Heaviside (1850–1925). Another was the "Continental" program identified mainly with the German physicists Neuman, Wilhelm Weber, and Helmholtz.[3]

By century's end, the study of electrodynamics not only encompassed the phenomena of electricity, magnetism, and light but aimed to include all physical and chemical phenomena in an electromagnetic theory of the ether. In the 1880s Helmholtz's student Heinrich Hertz (1857–1894) sought a test of rival electromagnetic theories and ended by tipping the balance against Helmholtz and toward Maxwell by creating the electric waves, afterwards called radio waves, that had been predicted by Maxwell.

Experiments to detect the ether, however, continued to fail at century's end, even while Joseph Larmor and Henrik A. Lorentz (1853–1928) worked out theories that turned out to be the last great expressions of the electromagnetic view of nature rooted in the ether. By the 1920s (as we will see in chapters 6 and 7), the "electron" proposed by Larmor and Lorentz no longer needed the ether as its seat.

Ironically, given the ether-bound history of electromagnetic theories during the course of the nineteenth century, Faraday himself abandoned the ether hypothesis toward the end of his career—just when most other scientists were coming to think they could hardly imagine a world without it.

Faraday the Nonconformist in Chemical and Natural Philosophy

The story of Michael Faraday is a success story in the up-by-the-bootstraps tradition that has been part of the mythology of self-help and individualism in English national life. Like Dalton, Faraday has been claimed as a hero for both chemistry and physics, although he preferred the title "natural philosopher."

The son of a blacksmith, Faraday was apprenticed to a bookseller, stationer, and bookbinder when he was thirteen years old. Thanks to the beneficence of a shop customer, young Faraday received a ticket to one of Humphry Davy's chemical lectures at the Royal Institution. Faraday was precisely the sort of "working man" for whom the Royal Institution had been founded in 1800, and he turned out to be its greatest triumph.

After writing out the text of four of Davy's lectures and employing his skills to bind them, Faraday presented himself to Davy and was fortunate in soon being offered a position as Davy's assistant. The following year, in 1813, Faraday accompanied Davy and his wife on a trip to the Continent during a period when England was at war with France. Despite the war—and despite his personal lack of gentility—Faraday found himself on a gentleman's tour; although he was in a subordinate capacity, he nonetheless met men of science who were Davy's peers. Among these were the Geneva natural philosopher Gaspard de La Rive (1770–1834) and his son Auguste-Arthur (1801–1873), who became Faraday's lifelong friends and correspondents.

On his return to England, Faraday became assistant to Davy's successor, William Brande (1788–1866), and continued to collaborate with Davy on projects. In 1825 Faraday, now a Fellow of the Royal Society, became director of the Royal Institution Laboratory, and in 1833 he was appointed the first Fullerian Professor of Chemistry. His laboratory—now a museum display—remains one of the showpieces of the Royal Institution.

Faraday's own research provided the subject for many of his public discourses, which included the Royal Institution's Friday Evening

Discourses and the Christmas-season "juvenile" lecture series largely created by him. The techniques used in lecture demonstrations and in the laboratory were discussed and illustrated in Faraday's *Chemical Manipulations* (1827). By 1827 he had many chemical investigations to his credit, from one published in 1816 on "caustic lime" to his isolation and identification of properties of "bicarburet of hydrogen" (benzene) in 1825.

Like Davy, Faraday was suspicious of Daltonian atoms and preferred to avoid the language of atoms; also like Davy, he inclined toward the view that the power of chemical affinity is associated with the power of electricity. As chairman of the chemistry section of the British Association for the Advancement of Science in the 1830s, Faraday was to direct much of the section's attention to studies in electricity. One of his greatest contributions to chemistry was the demonstration that a fixed, measurable quantity of electricity flowing from a voltaic battery characteristically releases from water 1 gram of hydrogen and 8 grams of oxygen, or, in general, the chemically established equivalent weights of elements decomposed from solution and deposited at the poles of the electrolytic cell. Here was independent evidence from chemical analysis for the concept of chemical equivalents.[4]

On the face of it, this result might seem supportive of Berzelius's theory of electrochemical dualism, discussed in chapter 2. In fact, Faraday undermined Berzelius's theory by demonstrating that the quantity of electricity in electrolytic decomposition did not depend at all on degree of "affinity." While Faraday conceded that the vocabulary of the atomic theory was consistent with his electrochemical results, and indeed that his experiments supported Dalton's numbers for atomic weights, he nonetheless concluded, "I must confess I am jealous of the term *atom;* for though it is very easy to talk of atoms, it is very difficult to form a clear idea of their nature."[5]

By the early 1830s, an increasing amount of Faraday's time was taken up with experimental studies of electrochemistry and electromagnetism. The electromagnetic experiments originated in an assignment Faraday accepted for the *Annals of Philosophy*. He was to write an account of Hans Christian Oersted's discovery that a magnetic needle twists circularly when placed above or below a platinum wire through which a current passes.

Both William Wollaston, who was then president of the Royal Society, and Davy were much interested in this discovery, for which Oersted received the Royal Society's Copley Medal in 1820. Wollaston tried an experiment with Davy to make a wire rotate on its axis when the wire carried a current in a magnetic field, but they found no positive result. Faraday successfully carried out a similar experiment a few months later, in the fall of 1821, without, as it happened, giving what some of Wollaston's friends thought should have been proper credit to him. In Faraday's "electromagnetic rotator," a pivoted bar magnet rotated around a wire-carrying current and a pivoted wire-carrying current, reciprocally, rotated around a bar magnet.

All through the 1820s experiments in electromagnetism were popular in London, as elsewhere, among both scientific amateurs and professionals. In lectures given by both George Birkbeck and William Sturgeon, a model of the earth's magnetic properties was exhibited in the form of a grooved wooden ball around which wires carrying electricity were wound. The point of the model was to show that magnetism could be caused by electric currents flowing in curves.

From 1831 on, Faraday hardly left the subject of electromagnetism. That year, he set himself the following problem: if magnetism could be produced from moving electrical currents, could electricity be produced from moving magnetic power? After a number of trials, recorded in notebooks that were later published, he found that when current flows intermittently from a battery through coils of wire wound around one side of a soft iron ring, with the wire insulated from the iron by calico cloth, electric current appears in a second coil wrapped around the other side of the ring and connected to a galvanometer. He soon found that the iron ring was unnecessary to produce the effect.

There followed experiments demonstrating that electricity is produced by moving a bar magnet in and out of a coil of 220 feet of copper wire wrapped around a paper cylinder and that electricity is generated in a copper disk or a copper coil rotated between the poles of a magnet.

Gradually, as Faraday carried out thousands of experiments (a total of sixteen thousand numbered entries in his published laboratory notes), he developed a full-blown theory of electromagnetism clearly distinct from Newtonian theory of action-at-a-distance forces. The forces that Faraday was studying acted along curved lines in a three-dimensional field, not in straight lines across the shortest distances between points. Newtonian forces of electrical attraction and repulsion had to be derived from the field; they did not constitute the field.

A crucial test for Faraday's notions came in experiments undertaken during 1845 and 1846—experiments he was urged to do by the

young William Thomson, whom Faraday met for the first time at the September 1845 meeting of the BAAS in Cambridge. The experiments resulted in the discovery of what came to be called the Faraday effect.

The Faraday Effect and Its Implications

Experiment had shown Faraday that electromagnetic effects are transmitted in curved lines and that a charged body can induce charge on a second body despite the obstacle of a nonconducting shield. Thus, he thought that either the ether or the medium of space itself must be filled with curves or lines of electric or magnetic force stretching like taut elastic threads from one charged surface to another or from one magnetic pole to another. These curves could be mapped with iron filings around a horseshoe or bar magnet (his first drawings of the lines were published in 1851). They are like lines of latitude and longitude, or the lines of electricity in Birkbeck and Sturgeon's sphere.

For Faraday, the wires along which current runs do not contain electricity but rather *conduct* it, so that the electricity, or electrification, is on the surface of the conductor. This he proved by entering a huge conducting cube, showing that the charge that is conferred on the cube has no influence inside the cube. The insulating substance (dielectric) between conductors is in a state of strain, so that, as he described it in the 1830s, the dielectric's particles are polarized like a series of small magnetic needles. Different dielectrics have different specific inductive capacities or powers. Any change in the tension of the "electrotonic" state of the medium in which the curves of force exist always gives rise to the production of electromotive force.

Faraday's theory seemed to presume an ether, the imponderable substance already at the heart of mathematical optics. Would a transparent dielectric—Thomson inquired of Faraday in 1845—have an effect on light? If the ether medium between electrical or magnetic poles is in a state of strain, would there not be an effect on a beam of polarized light, since optical theory predicts that an asymmetrical medium rotates polarized light?

This was not an entirely new idea to Faraday, who in 1833 had unsuccessfully sought an effect on a beam of polarized light as it passed through a solution undergoing electrolysis. He now repeated his earlier experiments, still not finding an effect. (It eventually was found in the mid-1870s by John Kerr, who used more sensitive apparatus.) After trying different arrangements for passing polarized light through various transparent materials (such as flint glass and rock crystal), Faraday finally discovered a positive effect with a piece of lead glass when the light was transmitted along the lines of magnetic force for a particular orientation of the magnetic poles.

The implications of this experiment were startling. For mathematical physicists, here was positive confirmation that the ether was subject to rotational stresses and strains in an electrical or magnetic "field," a term first used by Faraday in 1845 and first published in 1846. Here, along with the phenomena of dispersion, absorption, and stellar aberration, was another property of the ether that had to be taken into account in constructing a fluid or elastic-solid theory of the ether.

Indeed the need for an ether seemed all the more pressing as reports were published by the French experimentalists Hippolyte Fizeau (1819–1896) and Léon Foucault (1819–1868). During the period from 1849 to 1862, Fizeau and Foucault demonstrated that the speed of light is greater in air than in water, in exactly the ratio predicted by Fresnel. These experiments provided conclusive proof for the wave theory of light against the rival Newtonian particle theory.

Paradoxically, for Faraday the ether was becoming less of a reality. In an article on ray vibrations in 1846 he dismissed the distinction between ponderable matter and imponderable ether, saying that the difference between them could only be one resulting from the numbers of lines of force, not kinds of particles. In 1852 he published articles on lines of magnetic force in the *Philosophical Transactions of the Royal Society* and in the *Philosophical Magazine* in which he laid out how customary laws of action-at-a-distance may be derived from the lines.

According to Faraday, each line corresponds to a unit of magnetism or electric charge. The lines contract or expand, accounting for rectilinear attraction and repulsion phenomena, and they thin out as the square of the distance from the central axis running between opposite charges or magnetic poles. But he rejected the need for a special medium in which to embed the lines.

Now, as in his earlier "Speculation Touching Electric Conduction and the Nature of Matter" (1844), Faraday emphasized the notion that matter is known by its agency of power and action, and he deemphasized his own earlier notions of contiguous particles, material polarities, and imponderable ether. In identifying matter with power, he made reference to ideas put forward by the Serbo-Italian natural philosopher Ruggero Giuseppe Boscovich (1711–1787) in the late eighteenth century, but this reference may reflect convention rather than real debt.

Much has been written about the possible influence on Faraday of the philosophical traditions of *Naturphilosophie*, perhaps transmitted through Humphry Davy and the poet Samuel Taylor Coleridge, and of the religious views of the nonconformist Sandemanian (Church of Christ) sect to which Faraday belonged. Yet, as is well known among students of the history of nineteenth-century science, the notion of the interconvertibility of forces was a common topic that was "in the air" in the 1840s. As will be discussed in Chapter 4, this was true for Helmholtz and for J. R. von Mayer in Germany and for James Joule and William Thomson in England.

As Faraday put it in 1845, "the various forms under which the forces of matter are made manifest have one common origin; . . . they are convertible . . . one into another, and possess equivalents of power in their action."[6] The seriousness with which Faraday's younger colleagues were to take his ideas and integrate them into the mainstream of the Cambridge tradition of mathematical physics shows not only the power of his experimental demonstrations but the resonance of his non-Newtonian presumptions with similar notions in the intellectual milieu of the time.

The Cambridge Approach to Faraday's Natural Philosophy

As the historian of science Ole Knudsen has remarked, it was William Thomson who in the early 1840s discovered a mathematical equivalence of theories based on mutually exclusive physical concepts: Newton's concept of action at a distance and Faraday's concept of action propagated in a field. Thomson's presentation of this mathematical equivalence had at least two very important results. First, it made Faraday's experimentally-based principles respectable among mathematical physicists. Second, it demonstrated the usefulness of mathematics in the actual construction of physical theories as well as in expressing known physical laws. If two mathematical formulations could be demonstrated to be analogous in their structure or equivalent in their predictive outcomes, then new insight into the underlying physical phenomena represented by the two mathematical systems could be obtained.

In strong contrast to Faraday, Thomson was a member of a privileged academic family. His father, James Thomson, became professor of mathematics at Glasgow University in 1832. Educated at Glasgow

University and then at Saint Peter's College in Cambridge, William Thomson had mastered Joseph Lagrange's *Mécanique analytique* and Jean-Baptiste Fourier's *Théorie analytique de la chaleur* by the age of fifteen. When he was only eighteen and a recent arrival in Cambridge, Thomson published a paper (his third published paper) in the *Cambridge Mathematical Journal*. This paper, "On the Uniform Motion of Heat in Homogeneous Bodies, and Its Connection with the Mathematical Theory of Electricity" (1842) was a starting point for developing mathematical representations of Faraday's electrostatics and electrodynamics.

In Paris after he left Cambridge, the twenty-one-year-old Thomson made the acquaintance of French mathematicians including Joseph Liouville (1809–1882), the editor of the *Journal de mathématiques pures et appliquées*. The young Thomson's expertise inspired Liouville to ask him to write a paper on Faraday's electrostatics for a French audience, a paper that appeared in 1845.

At this time, the Continental approach to electricity lay largely in the tradition of French mathematical physics, especially the work of Poisson and Ampère, who along with Arago assimilated the phenomena of electromagnetism into an action-at-a-distance framework. Ampère, who like Faraday concerned himself with chemical as well as electrical phenomena, proposed the notion of an electrodynamic molecule in which magnetic effects result from circular electric currents within matter. Ampère's mathematical treatment of relations between two electric currents assumed that forces acting rectilinearly give the appearance of circular force.

Thomson's 1842 paper approached matters differently, however, developing an analogy between electrostatic phenomena and phenomena caused by the uniform flow of heat from one part of the solid body to other parts or to the body's surroundings. As J. C. Maxwell later put it, "The similarity is a similarity between relations, not a similarity between the things related."[7] The analogy is expressed in table 1.

Thomson's demonstration of how Faraday's curved lines of force correspond to lines of heat flux effectively correlated Faraday's forces with action-at-a-distance forces by means of mathematical representation. The differential equation that Thomson constructed could be used to represent equilibrium of temperature, attraction of bodies, or motion of a fluid.

The mathematical analogy was limited by the assumption in Fourier's theory of a steady flow of heat across an interface, while in Faraday's theory discontinuous fluxes occur from one medium to another. Thomson ignored this discrepancy, however. Thomson's approach supposes the conservation of heat and of electricity, like all the forces of nature. As was clear in both the 1842 and 1845 papers, he treated electricity as a substance (fluid) within the dielectric.

Table 1 William Thomson's analogy between electricity and heat.

Electrostatics	**Heat**
The electric field	An unequally heated body
A dielectric medium	A body that conducts heat
Electric potential at different points in the field	Temperature at different points in the body
EMF tending to move positively charged bodies from places of higher to lower potential	Flow of heat by conduction from places of higher to lower temperature
A conducting body	A perfect conductor of heat
Positively electrified surface of conductor	A surface through which heat flows into the body
Negatively electrified surface of a conductor	A surface through which heat escapes from the body
A positively electrified body	A sink of heat, i.e., a place at which heat disappears from the body
An equipotential surface	An isothermal surface
A line or tube of induction	A line or tube of flow of heat

In 1846, the year that Thomson, age twenty-two, took up the chair of natural philosophy at Glasgow University, he published another important paper. In order to represent the magneto-optic rotation confirmed by the "Faraday effect," Thomson sought a mechanical representation of electric, magnetic, and galvanic forces. In this paper Thomson introduced the operator *curl*, that is, the differential rotation of a volume element of a solid medium about the axis of a magnet:

$$\vec{F} = \mathrm{curl}\,\vec{A}$$

This work helped to establish in British electromagnetic theory the notation of "vector potential" for magnetic force.

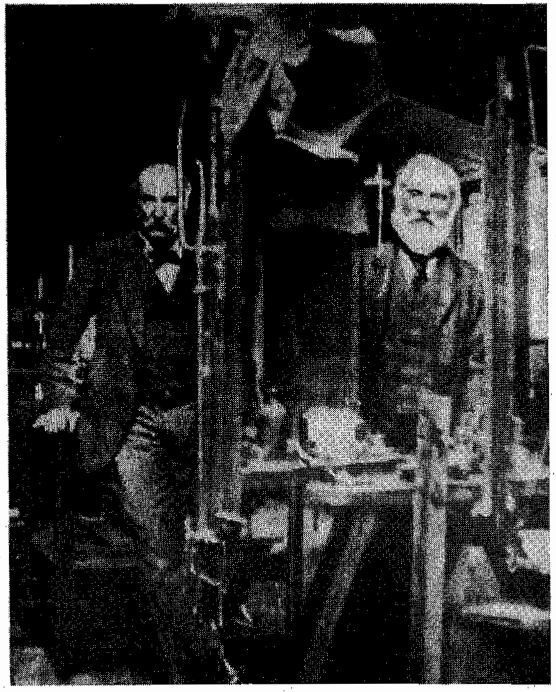
Thomson wrote to Faraday that this paper was only a "sketch" but that he thought that a detailed mathematical theory could be developed that would explain the effect of magnetism on polarized light, bringing together the phenomena of light, electricity, and magnetism. As he corresponded and collaborated with George Stokes, Thomson became increasingly interested in mathematical theories and visual models relating ether to matter, as in the statement on "vortex atoms" quoted at the beginning of this chapter.

Thomson's interest in vortex and hydrodynamics models was also stimulated by the Edinburgh engineer and physicist William Rankine (1820–1872), who proposed in 1850 that heat is the result of rotational motion of atmospheres about "motes," or molecules, of matter. Along with Stokes, Thomson began developing strongly visual, even tactile, mechanical models of the ether, or what he in the 1850s began calling the "air-ether" or "aer".

This use of mechanical models by Thomson and many of his British colleagues was based not on astronomical models, as was common on the Continent, but in experience of ordinary materials and engineering practice. Thomson, for example, spent much time as an engineering consultant for the laying of trans-Atlantic telegraph cables during the 1850s and 1860s. His demonstrations and research with students in his Glasgow laboratory were oriented as much toward resolving engineering and practical problems as toward solving theoretical problems.

In their biographical study of Lord Kelvin, Crosbie Smith and M. Norton Wise have called his method of modeling a "look-and-see" method that emphasized sensory perception—feeling and touching—to know cause and effect as a "potentially real thing." In lectures given in Baltimore in 1884, in order to help them think about the interaction of a molecule with the ether, Thomson encouraged students to embed a ball in a bowl of jelly; "Apply your hand," he said, and "produce vibrations in your jelly solid by taking hold of this ball and shoving it to and fro." To show coupled vibrations inside a molecule, Thomson constructed what he called a "wiggler," consisting of a set of weighted wooden bars attached to a piano wire and suspended from the ceiling. A box strung with cords was used to demonstrate stress and strain in the ether.[8]

These devices, like the many devices described in Oliver Lodge's *Modern Views of Electricity* (1889), comprised an imaginative physical "cabinet" of British natural philosophy— ridiculed by Pierre Duhem in a review of Lodge's book:



Lord Rayleigh (John William Strutt) and Lord Kelvin (William Thomson) in Lord Rayleigh's laboratory at his private residence at Terling in Essex in July 1900. In an aristocratic and gentlemanly tradition, Rayleigh and Kelvin helped establish standards for precise laboratory instrumentation and measurement through collaborations with researchers in their own private laboratories, as well as in laboratories associated with universities. From plate 53 in Robert Andrews Millikan, Duane Roller, and Earnest Charles Watson, *Mechanics, Molecular Physics, Heat, and Sound* (Cambridge, Mass.: MIT Press, 1937) reproduced from Robert John Strutt, *John William Strutt, Third Baron Rayleigh, O.M., F.R.S.* (London: Edward Arnold and Co., 1924; new ed., Madison: University of Wisconsin Press, 1968). *Courtesy of MIT Press and University of Wisconsin Press.*

> Here is a book intended to expound the modern theories of electricity and to expound a new theory. In it there are nothing but strings which move around pulleys, which roll around drums, which go through pearl beads, which carry weights; and tubes which pump water while others swell and contract; toothed wheels which are geared to one an-

other and engage hooks. We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory.[9]

Maxwell, Electromagnetism, and Methodology in Theoretical Physics

Equally alarming to Duhem was James Clerk Maxwell's 1873 treatise on electricity and magnetism, which Maxwell wrote as a chronological and experimentally-based account of his investigations and theories since 1856. The book seemed to many readers a badly organized, incoherent assemblage of experiments, derivations, equations, and theories—a far cry from the Continental fashion of laying everything out according to first principles.

Maxwell himself advised the reader to approach the four parts of the *Treatise* in parallel readings rather than in sequence. Further, his rejection of the notion of an "electrical fluid," his introduction of a "displacement current," and his long list of equations for the electromagnetic field, stated both in full Cartesian coordinates and in quaternions, provided for difficult and often incomprehensible reading.

The book appeared shortly after Maxwell had been appointed professor of experimental physics at Cambridge University and first director of the Cavendish Laboratory. By this time, Maxwell had a considerable reputation as a natural philosopher and mathematician. Maxwell was from a prominent Scottish family and entered the University of Edinburgh at sixteen, before going to Saint Peter's College in Cambridge. Another Scotsman, Peter Guthrie Tait (1831–1901), who was Thomson's coauthor for the *Treatise on Natural Philosophy* (1867), was then a senior student at "Peterhouse," as the college was called. Tait was to win out over Maxwell in 1859 in competition for a chair of natural philosophy at Edinburgh.

Following in his fellow Scotsman William Thomson's footsteps, Maxwell finished as second wrangler in the mathematical tripos at Cambridge. He triumphed on the 1854 Smith's Prize Examination, one of the questions being a proof of the "Stokes Theorem," which appeared for the first time in print on this exam. This theorem states the equality between the integral of a vector function around a closed curve and the integral of its curl over the enclosed surface. It was to have important applications in electromagnetic theory.

Maxwell returned to Scotland in 1856 in the chair of natural philosophy at Marischal College in Aberdeen before becoming professor of physics and astronomy at King's College in London from 1860 to 1865. The next years were spent at his family home in Glenlair with frequent trips to Cambridge, where he served as an external examiner. It was in these years that he wrote the *Treatise on Electricity and Magnetism.* His wife, Katherine Dewar Maxwell, was the daughter of the principal at Marischal College and worked with her husband during the London and Glenlair years in experiments on color vision and kinetic theory.

The appointment to the Cavendish Laboratory returned Maxwell to Cambridge. The laboratory was founded in 1870 through a generous gift from the seventh duke of Devonshire, who was chancellor of the University and a descendant of the eighteenth-century chemist and natural philosopher Henry Cavendish. Maxwell was the third choice for the directorship after Thomson and Helmholtz each declined to move to Cambridge. Maxwell's experimental and theoretical work fell off after 1871, with much of his time devoted to editing the electrical manuscripts of Henry Cavendish and to setting up the Cavendish as a laboratory of precision electrical measurement. Indeed, there was much hostility to the laboratory at the University of Cambridge because of its industrial appearance and its routinized training program for postgraduate students.

The Stokes theorem was one of many mathematical techniques that Maxwell applied to electricity and magnetism. His university studies, as well as his early correspondence with Thomson, led him in 1856, as he took up his youthful post in Aberdeen, to publish a paper that built on Faraday's and Thomson's work. Maxwell's paper "On Faraday's Lines of Force" had the purpose to "show how by the ideas and methods of Faraday, different types of phenomena which may be discovered may be made mathematical." The method was one of analogies: "In order to obtain physical ideas without adopting a physical theory, we must make ourselves familiar with physical analogies. . . . A partial similiarity between the laws of one science and those of another . . . makes each of them illustrate the other."[10]

Maxwell concerned himself with analogies between the formulas for heat, electricity, and gravitation. He proposed an imaginary fluid, "a collection of imaginary properties which may be employed for establishing certain theorems in pure mathematics." This fluid was incompressible, in steady motion, and arranged in tubes corresponding to Faraday's lines of force. Maxwell then developed analogies between electricity and magnetism.

In his formulation, the quantity of magnetism in a body is equivalent to the number of lines of magnetic force that pass through the body. The intensity of magnetism depends on the resisting power of a volume section as well as on the number of lines through the section. By the use of vectors corresponding to electric and magnetic "intensity," or force (E and H), and electric and magnetic "quantity," or flux (I and B), equations can be derived for induced electromotive force.

This force is proportional to the change in the number of lines of inductive magnetic action passing through a circuit and to the intensity and direction of change of state in the magnetic field. Faraday, Maxwell noted, referred to this state as the "electrotonic state": a state into which all bodies are thrown in the presence of magnets and currents.

The theory of 1856, he concluded, is a possible alternative to Wilhelm Weber's theory of positive and negative electrical masses moving through a conducting wire, although Weber's is a better *physical* theory. "[It] is a good thing to have two ways of looking at a subject and to admit that there *are* two ways of looking at it," Maxwell notes, adding "I hold that the chief merit of a temporary theory is, that it shall guide experiment, without impeding the progress of the true theory when it appears."[11] This statement by Maxwell was a powerful argument for the value of the heuristic approach in the construction of scientific theories. A hypothesis or theory that is not physically true might be used legitimately on the pathway to a better theory.

In 1861 Maxwell arrived at a theory that predicted novel experimental results. He proposed two new physical phenomena that were potentially testable: the "displacement current" and electric waves moving at the speed of light. The argument of the paper is clear and brilliant.

The distribution of iron filings in the vicinity of a magnet, begins Maxwell, makes us think that lines of force are real and exist even when there is no magnet present. Suppose that the phenomena of magnetism depend on tension in the direction of lines of force, combined with a kind of hydrostatic pressure—that is, a pressure greater in the equatorial than in the axial direction. What mechanical explanation can we give of this inequality of pressure in the fluid?

We may suppose that the mechanical origin lies in molecular vortices, with the axes of the vortices parallel to the lines of force. The vortices are presumed to be small in size in comparison with molecules (i.e., ordinary matter). We know that the lines of force are affected by electric currents and that they are distributed about a

current. But what is the physical connection between the vortices and the currents?

Continuing to draw on mechanical conceptions, Maxwell conceived of tiny idle wheels rotating in the medium between each pair of vortex cells, with the wheels rotating in place in the direction opposite to the rotation of the vortex cells. If the rotational velocity of a vortex cell changes with respect to an adjacent one because of strain in the medium, then translation of the idle wheels is caused, accounting for electric current.

The rotation of the idle wheels transmits the motions of the vortices from one part of the field to another, and the tangential pressures called into play constitute electromotive force. In a dielectric or insulator, the idle wheels do not translate, but are only slightly displaced because of strain in the medium. Thus, in a nonconductor, displacement causes electric polarization and a change in displacement causes an extra current (displacement current) in addition to the usual conduction current.

After making some assumptions about the elastic properties of the vortex medium, Maxwell calculated the velocity of transverse elastic waves that is caused by propagation of an electric displacement in the medium. In doing this, he concluded that the waves would move at a speed equal to a constant value: the ratio of the (electrostatic) force exerted by an electric charge on another charge to the (electrodynamic) force exerted by an electric charge on a neighboring magnetic pole when the electric charge flows through a conductor.

Gustav Kirchhoff had concluded in 1857 that the ratio of electrostatic to electrodynamic charge has the dimensions of a velocity and is of the same magnitude as the speed of light. In 1855 Wilhelm Weber and Rudolf Kohlrausch had published experimental results that this velocity is 3.11×10^{10} cm/sec, which is similar to Fizeau's value of 3.15×10^{10} cm/sec for the speed of light. However, they explicitly denied a similarity of origin. In contrast, Maxwell concluded,

> The velocity of transverse undulations in our hypothetical medium, calculated from the electromagnetic experiments of MM. Kohlrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena* .[12] [Emphasis original.]

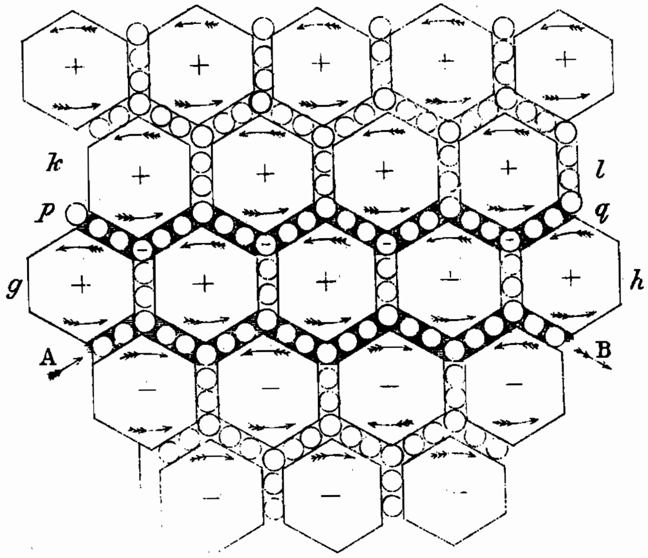
Maxwell viewed his mechanical theory of vortices as a temporary and provisory hypothesis, and, following up on the methods that Thomson and Tait were developing in their *Treatise on Natural Philosophy*, he moved within the next few years to free his electromagnetic theory from physical hypothesis and ground it in the dynamical formalism of Hamiltonian and Lagrangian functions, that is, principles of action and energy. His "Dynamical Model of the Electromagnetic Field" (1864) roots electromagnetic phenomena in the kinetic energy of motion of parts of the ether and in the potential energy residing in the structure ("elastic resilience") of the ether without specifying the motion or structure. The propagation of undulations in this medium, Maxwell argued, is the continual transformation of potential energy into kinetic energy.

Did Maxwell's route to his final equations of electromagnetic theory really mean that he relinquished the hypothesis of a material ether? Hardly so. In the 1870s he expressed confidence that there is a material medium for light and electricity, while still rejecting the notion of a material "electric fluid."[13] In an often-quoted article on the "Atom" in the *Encyclopaedia Britannica* of 1875, Maxwell praised the notion of the vortex atom and commended its mathematical solution as one that would bring great glory to its solver. In his *Encyclopaedia Britannica* article on "Ether" (1879), he suggested an earth-based method of detecting an ether wind by measuring variations in the velocity of two beams of light making journeys back and forth between two different mirrors, but he concluded that the effect would be to small to detect.

As for experimental confirmations of Maxwell's electromagnetic theory, there were several possibilities. One was a proof of electromagnetic radiation pressure, a prediction of the theory. As we will see in the last section of this chapter, William Crookes initially thought he had this proof in 1875. Another possibility was confirmation of the displacement current and of electromagnetic waves moving at the speed of light, as discussed in the next section of this chapter. A third possibility was discovery of phenomena further undermining the hypothesis of an electric fluid and consistent with Maxwellian principles.

As historian Jed Z. Buchwald has noted, this last proof was the considerable, but short-lived, achievement of two Americans, Edwin Hall (1855–1938) and Henry Rowland (1848–1901). In 1879, at the time he discovered what came to be called the Hall effect, Hall was studying Maxwell's *Treatise* under the direction of Rowland, the director of the new physics laboratory at the Johns Hopkins University in Baltimore. In Hall's experiment, an electric current was sent across the length of a metal (for example, copper) plate that was placed between the poles of an electromagnet, with the field normal to the plane of the plate. A galvanometer attached across the plate's width detected a current only while the field was turned on.

Fig: 2.



James Clerk Maxwell's mechanical model of electrical particles and molecular vortices. The motion of moveable particles (AB, *pq*) between neighboring vortices (*gh*, *kl*) is taken to be an electric current. As this current begins from left to right at AB, the row of vortices *gh* is set in motion in the opposite direction. Electric current then is induced in the layer of particles *pq* as the rotatory velocity of the vortices is communicated from one part of the field to another. From James Clerk Maxwell, "On Physical Lines of Force. Part II. The Theory of Molecular Vortices Applied to Electric Currents", pp. 467–88, plate 8, following p. 488 in *The Scientific Papers of James Clerk Maxwell*, edited by W. D. Niven, vol. 1 (Cambridge: Cambridge University Press, 1890). *Courtesy of Cambridge University Press.*

Hall and Rowland interpreted this phenomenon to mean that an electric current and a subsidiary electric field were produced in the magnetic field, and in 1880 Rowland incorporated Hall's new "field" into one of Maxwell's equations (the "Faraday law" for magneto-optic rotation). The new version of the equation led to a wave equation that nicely explained the Faraday effect. Richard T. Glazebrook (1854–1935) at Cambridge then took up Rowland's treatment and demonstrated that the Hall term that Rowland had introduced could in fact be derived from Maxwell's equations in the *Treatise*. Many, certainly Rowland, saw this as a vindication of Maxwell's theory, although the effect was later to be explained by the motion of negatively charged particles.

Hall and Rowland were by no means the only experimental physicists seeking positive confirmation of Maxwell's theory in the 1880s, and rival theories to Maxwell's, as well as reformulations of Maxwell's *Treatise*, were beginning to proliferate both in Great Britain and abroad. Maxwell's physical theory required an ether and denied the existence of an electrical fluid. The theory assumed that matter is different from ether, although perhaps only because of the size of its material molecular vortices. Maxwell's theory supposed that vibrations in molecules of matter produce light, which moves through the ether at a speed c. Maxwell's mathematical theory also predicted that waves created by alterations in electric current in the electromagnetic field travel at the speed c. How successful was Maxwell's original theory by the end of the century? And how had it changed?

Rivals and Revisions of "Maxwell's Theory"

Hermann von Helmholtz's physics laboratory in Berlin became a major testing-ground for rival theories of electrodynamics in the last third of the nineteenth century. Trained in medicine as well as in physics and physiology, Helmholtz made a formidable reputation for himself with his 1847 publication of the long essay "On the Conservation of Force." Along with that of J. Willard Gibbs (1839–1903) in the United States, Helmholtz's work in thermodynamics helped establish the theory of change in "free energy" as the motor of chemical reaction (see chapter 4). Having been successively professor of physiology at Königsberg, Bonn, and Heidelberg during the period from 1849 to 1871, Helmholtz returned to Berlin as professor of physics in 1871, and he became director of the newly established Physikalisch Technische Reichsanstalt in suburban Charlottenberg in 1887 (see chapter 1).

Familiarizing himself with rival theories of electrostatics and electrodynamics, Helmholtz developed a law of electric potential that could be used to derive different sets of electrodynamic equations by setting a constant $k = 1, 0,$ or -1. For Maxwell's equations, $k = 0$; whereas $k = 1$ or -1 for the rival action-at-a-distance formulations.

Helmholtz reiterated his continuing commitment to a hypothesis of electrical fluid in London in 1881, when he was invited to deliver the Faraday Lecture before members of the London Chemical Society. He expressed admiration for Maxwell's theory, which he said he was directing researchers in his laboratory to test. But the most famous part of the lecture became the brief Helmholtz argued in favor of "atoms of electricity" that attach themselves to corpuscles, or molecules, of matter, and he reminded his chemical colleagues of the early theories of Faraday that sought connections between chemical affinity and electrical force.

Helmholtz's laboratory was a center for students and researchers from the United States, Great Britain, and Japan as well as from Germany and central Europe. Rowland and Albert A. Michelson (1852–1931) were among the prominent Americans who studied there as young men. When Heinrich Hertz entered Helmholtz's laboratory at Berlin in 1878, Helmholtz directed him, like others, to work on testing the electrodynamic theories. One of Hertz's first investigations resulted in a demonstration that electricity does not have inertia, as predicted by Weber. Helmholtz suggested that Hertz look for electromagnetic effects that were predicted to result from dielectric displacement currents, but Hertz did not follow up this suggestion while in Berlin, thinking that effects from high-frequency oscillations would be impossible to detect.

In England, Oliver Lodge (1851–1940) was also concerning himself with possible ways to test Maxwell's theory. Lodge, the son of a clay merchant, turned to physics at the age of sixteen after hearing John Tyndall lecture at the Royal Institution. Lodge took an external degree at the University of London, became an assistant and advanced student with George Carey Foster at University College in London, and in 1881 became the first professor of physics at the new University College in Liverpool.

As an experimentalist, not a mathematician, Lodge was a fervent modeler of the ether, an enthusiast for the main points of Maxwell's theory, and a friend and correspondent of two other influential "Maxwellians," George F. Fitzgerald (1851–1901) and Oliver Heaviside (1850–1925).

Fitzgerald was professor of natural and experimental philosophy at Trinity College, London, from 1877 until his death in 1901, and he first met Lodge at the 1878 Dublin meeting of the BAAS. Heaviside, a nephew of Charles Wheatstone, the inventor of the telegraph, worked in submarine telegraphy from 1868 to 1874, publishing articles on telegraphy and electricity in the *English Mechanic* and the *Philosophical Magazine*. After illness in 1874 he worked independently on electrical researches at his family home in Camden Town in North London, and by 1888 he was publishing a series of articles on electromagnetic waves that brought him into correspondence and occasional visits with Fitzgerald and Lodge.

The historian Bruce J. Hunt has characterized these three—Lodge, Fitzgerald, and Heaviside—as an important group of "Maxwellians" with a rather different point of view from Cambridge-educated mathematical physicists William Thomson, Stokes, J. J. Thomson, and indeed Maxwell himself. For one thing, it was Heaviside who reduced Maxwell's equations in the *Treatise* to four equations often called Maxwell's equations. Heaviside dispensed with Maxwell's vector potentials, which still seemed to concede too much to action-at-a-distance, in favor of a vector calculus notation (see figure 1). These equations, which Maxwell had stated in words but not notation in a note of 1868, were also taken up by Hertz in his book on electric waves in 1892. They appeared, perhaps most influentially, in August Föppl's *Einfuhrung in die Maxwell'sche Theorie der Elektricität* in 1894. Albert Einstein was one of the many readers of Föppl.

The "Maxwellians" concerned themselves with the properties of the ether. Fitzgerald demonstrated the fundamental incompatibility

$$\text{div}\,\mathbf{D} = \rho$$

$$\text{div}\,\mathbf{B} = 0$$

$$\textbf{curl}\,\mathbf{E} = -\,d\mathbf{B}/dt$$

$$\textbf{curl}\,\mathbf{H} = \mathbf{J} + d\mathbf{D}/dt$$

Figure 1. Maxwell's four equations (modern notation). The mathematical operations *div* and *curl* specify directional aspects of forces and fields. The other symbols relate to electric and magnetic force and induction (**D, B, E, H**), to current density (**J**), and to resistivity (ρ).

between Maxwell's ether and the elastic-solid ether that was a mainstay of optical theory since the work of George Green in the 1830s. The Maxwellians ridiculed Stokes's notion of an ether that was "like" wax, pitch, or jelly, and they offered other interpretations. Fitzgerald, for example, suggested in 1898 that lines of electric force were long vortex filaments twisted into corkscrew spirals. A permanent kink in the spiral, with a change in its "handedness" on either side, would correspond to a discrete positive or negative electrical charge.

Lodge, whose conception of the ether included its role as a telepathic medium linking spirits and the living, not only conceived of mechanical and visual models for the ether but sought to test its effects. He, like Fitzgerald, had followed with interest the efforts of Michelson and Edward Morley (1838–1923) in the United States to take up Maxwell's suggestion for finding ether drag.

Albert Michelson carried out his first test for the ether wind in 1881, while he was spending time in Helmholtz's laboratory in Berlin. Michelson was a German-speaker whose family had emigrated to California from Prussia when he was a child. Experiments to test for an ether effect were resumed after Michelson returned to the United States, where he was appointed professor of physics at the Case School of Applied Science in Cleveland in 1883. During the rest of the 1880s he collaborated in these experiments with Edward Morley, a chemist who taught at Cleveland Medical College and Western Reserve College.

Michelson built an interferometer that was meant to detect a difference in the velocity, or wave fronts, of two beams of light traveling at right angles and returning to a common surface. The interferometer, mounted in a stone floating in a basin of mercury in order to minimize extraneous vibrations, could detect an effect of one part in 10 billion.

Michelson and Morley were successful in repeating the experiment by Fizeau that had confirmed Fresnel's theory of a stationary ether, amended by the assumption that transparent bodies have a partial dragging effect on light passing through them. But the failure to detect the earth's motion relative to the ether persisted, and Michelson began to incline to Stokes's view that the earth drags along with it the ether close to its surface.

During the years 1890 to 1893 Lodge was also carrying out experiments with an interferometer and a "whirling machine" to look for ether drag. Lodge later claimed that Fitzgerald's idea that bodies traveling through the ether might change in size or length by just the amount needed to account for Michelson and Morley's null result had grown out of discussions that he had had with Lodge. Fitzgerald, like Lodge and Heaviside, inclined to the view that forces between molecules are related in some way to electricity and to electromagnetic forces, all of these forces being propagated through the ether.

Using Heaviside's recently derived formula for the crowding together of electric and magnetic fields around the middle of a moving charge, Fitzgerald proposed in a letter to the American journal *Science* that matter contracts in the direction of the earth's motion through space. It was through Lodge's publications on the subject in 1892 and 1893 that many physicists, including Henrik Lorentz, learned of Fitzgerald's contraction hypothesis.

It was Fitzgerald, however, who had earlier (in 1879) discouraged Lodge from searching for light effects from the oscillating discharge of a Leyden jar or condenser on the grounds that light is produced by vibrations of atoms and molecules, not by electrical forces. In 1882 Fitzgerald read Lord Rayleigh's *Theory of Sound* (1877) and began to change his mind—coming to think of electromagnetic vibrations, heat, and light as part of one continuous spectrum of frequencies. But the task of detecting high-frequency vibrations that are not visible or heat-producing was still daunting. How could it be done?

While thumbing through an issue of Gustave Wiedemann's *Annalen der Physik* in 1888, Lodge discovered Hertz's paper reporting his recent experiments confirming Maxwell's theory. Its subject matter intrigued him, but his interest was further piqued by the fact that he had met Hertz in Germany in 1881. So Hertz had produced and detected electric waves traveling at the speed of light. How had he done it?

Heinrich Hertz, who originally prepared himself to become an engineer, had finished his physics education under Helmholtz in 1884. After two years as *Privatdozent* at Kiel, he moved to the Technische Hochschule in Karlsruhe, where there was a good laboratory. In 1886 he noticed that the oscillatory discharge of a Leyden jar or induction coil through a wire loop caused sparks to jump a gap in a similar loop a short distance away.

Using Helmholtz's theory of dielectric polarization, Hertz interpreted this effect as an induction phenomenon. He then turned to Maxwell's theory. The finite propagation of electric waves in space or air, independent of a wire, is a central point in Faraday's and

Maxwell's theory. As Hertz began trying to measure the velocity of what he now regarded as waves by reflecting them off the walls of his laboratory, his first results suggested that the velocity of the electric waves was greater than that of light, or perhaps infinitely large (instantaneous). This result favored action at a distance over Maxwell's theory, and it might be a crucial experiment.

Moving his apparatus to his lecture hall, the experimental decision soon turned in favor of Maxwell's theory. Hertz calculated a finite velocity for the electric waves at approximately the speed of light, although he also noticed what he took to be a discrepancy from Maxwell's theory in the electric waves' apparently slower velocity in wires than in air. If this were an accurate observation, then electromagnetic field theory would need some alterations.

Helmholtz announced Hertz's results to the Berlin Physical Society: "Gentlemen! I have to communicate to you today the most important physical discovery of the century." [14] And, indeed, electric waves, or radio waves as they came to be called, proved revolutionary in both their scientific and practical applications. In the next years, most physicists concentrated on reproducing the reflections of electric waves as initially described by Hertz. None replicated his wire guidance experiments, which remain difficult to explain, and Hertz himself turned to other problems.

Hertz later defined Maxwell's "theory" as Maxwell's set of equations, by which he meant the four equations as amended by Heaviside and himself. Hertz did not offer a visualizable description of Maxwell's theory. He knew, of course, that Helmholtz had been working on a theory to eliminate a priori assumptions about matter and force in favor of calculation of the energy of a system defined only by distance between volume elements in characteristic states. Hertz also was sensitive to recent criticisms by Kirchhoff and Ernst Mach (1838–1916) of the foundations of classical physics and of the mechanical world view.

The result was Hertz's publication in 1894 of *The Principles of Mechanics*. Here Hertz rejected the concept of force as a foundation for mechanics, charging that the term *force* lacked clarity. Like Henri Poincaré (1854–1912) and Pierre Duhem, Hertz argued that what is important is not the verification of particular entities or theorems but the verification of a system as a whole. Thus, he wrote, "I know of no shorter or more definite answer than the following: Maxwell's Theory is Maxwell's system of equations." [15]

Radiant Matter and the Etherial Electron

Hertz's studies in electricity in the 1880s included investigations with the electric-discharge tubes known as Geissler tubes in Germany and Crookes tubes in Great Britain. The study of phenomena associated with electrical discharge through gas was another area of investigation that had intrigued Faraday, who had investigated what he called the "glow phenomena" in 1833.

At ordinary room pressure (760 millimeters of mercury = 1 atmosphere of pressure), a spark passes through the air between electrified metallic plates when there is a potential difference of several hundred volts. In the eighteenth century, electrostatic machines could deliver long sparks because voltages were very high, sometimes as high as 30,000 volts. The lower voltage produced by voltaic piles depended on the number of units in the pile. Batteries at well-financed laboratories and institutions, such as the Royal Institution, delivered hundreds or even several thousand volts of electricity. In the last decades of the nineteenth century, the Ruhmkorff coil was invented to produce high potential differences and long sparks. It consisted of a primary coil made of thick wire with a few turns and a secondary coil of thin wire many miles—even hundreds of miles—long.

While Faraday could achieve high voltages in the 1830s, he could not produce the low pressures that were made possible around 1860 by use of the mercury pump, which allowed glass tubes to be evacuated of their gas, bubble-by-bubble, as mercury in a tube sank drop by drop. As air or gas was evacuated from the tube through which an electric discharge passed, a striking sequence of glow phenomena could be observed: first a spark between the positive and negative electrodes placed at right angles or opposite each other; then an elongated, luminous glow with color characteristic of the gas; then the breaking up of the glow into bands or striations with the appearance of a dark space near the anode (the so-called Faraday dark space); then the appearance of phosphorescence near the anode and a new dark space near the cathode first reported by William Crookes; and finally, complete darkness except for a bright, phosphorescent patch at the wall of the tube away from the cathode. The color of the phosphorescence varied with the kind of glass used to construct the tube. The initial part of the sequence occurs at about 20 millimeters of pressure (0.026 atmosphere) and the last phase at a pressure of about 0.000001 atmosphere.

In 1858, just before the introduction of the mercury pump, Julius Plücker (1801–1868) reported that the discharge in the vacuum tube was deflected by a magnet. Using a better vacuum, his student Johann Hittorf (1824–1914) reported a decade later that an object placed in front of the cathode cast a shadow opposite, indicating that the discharge originated in the cathode.

Eugen Goldstein (1850–1930) coined the term "cathode rays" in 1876, at about the same time that William Crookes began developing a theory that the discharge was matter thrown into a "fourth state" that was not solid, liquid, or gas. Crookes identified this state as one of "radiant matter," harking back to a term Faraday had in 1816 used for a "gradual resignation of properties" in matter, as matter "ascends in the scale of forms."[16]

William Crookes (1832–1919), an experimentalist and the editor of *Chemical News*, launched a series of improvements in the vacuum, coupled with ingenious and astonishing investigations in the discharge tubes. In 1875 he built a "radiometer" by mounting on a pivot in an evacuated glass bulb an arm or axle with vanes at either end. One surface of each vane was painted black, the other white. Crookes explained the continuous rotation of the arm and the vanes as the result of radiation pressure. Some scientists cited Crookes's work as confirmation of the radiation pressure predicted by Maxwell's electromagnetic theory. The explanation, however, turned out to be more complex, having to do with the gas still remaining in the not perfectly empty vacuum bulb.

While continuing to experiment with his radiometer, Crookes introduced similar techniques to study the "cathode rays," demonstrating, for example, that a paddlewheel mounted on a glass track within the electric discharge tube moves toward the anode under the "impact" of the rays on its mica vanes. He confirmed that a shadow was cast away from the cathode if an aluminum cross was placed in the tube and that the phosphorescent light at the end of the tube could be deflected by a magnet. He demonstrated that the rays could be focused by a concave or convex cathode. He concluded that the cathode rays were not radiations at all, but particles of "radiant matter" independent of the nature of the gas residue in the discharge tube and negatively charged, since repelled by the cathode:

> In studying this fourth state of matter we seem at length to have within our grasp . . . the little indivisible particles which with good warrant are supposed to constitute the physical basis of the universe. . . . We have actually touched the border land where Matter and Force seem to merge into one another.[17]

It is not surprising that some sober-minded German theoretical physicists rejected the spiritualist-sounding conclusions of Crookes. (Indeed, Crookes was a believer in spiritualist phenomena.) Hertz was among those who set out to disprove Crookes's "fourth state of matter."

In 1883 Hertz placed the discharge tube between electrostatically charged plates and reported that there was no deflection of the radiation. If Crookes were right about the negative charge of the rays, a deflection of the phosphorescent patch toward the positively charged plate would be expected. It was possible, of course, that enough gas was left in the tube such that polarized or ionized gas particles were attracted to the charged plates, insulating them from the rays, but this did not seem feasible to Hertz.

Hertz's student Philipp Lenard (1862–1947) demonstrated in 1892 that the cathode rays penetrate a thin aluminum window soldered into the discharge tube, which also seemed proof that they could not be particles of radiant matter. Further, the rays blackened photographic plates, like light. The Germans seemed to agree that cathode rays are an electromagnetic wave disturbance in the ether, and this is where the matter stood in the early 1890s.

As we have already seen, rival conceptions of the ether, its relation to matter, and the existence or nonexistence of electrical particles existing between lines of magnetic and electric force were numerous and much contested by the end of the nineteenth century. It can be misleading to describe differences along strictly national lines, but, on the whole, it can be said that German and Continental physicists tended to characterize the ether in terms that were more abstract and less realist than those used by British physicists (and chemists). Two concluding and contrasting examples are the theories of electromagnetism developed by Larmor and Lorentz in the late 1880s and early 1890s.

Joseph Larmor was born and educated in Belfast before going to Saint Johns College, Cambridge, where he finished as senior wrangler in the mathematical tripos in 1880, edging out J. J. Thomson. Like Thomson (to whom we shall return in chapter 6), Larmor in the 1880s interested himself in the properties of a fluid ether that was so endowed with latent rotational elasticity that it would allow the propagation of transverse waves but was sufficiently inertial in its properties that it could support the rotation of vortex rings.

After working with the idea that positive and negative electrification might be spread homogeneously over the core of an ether vortex, Larmor in 1893 broke the electrification apart into pointlike

charged nuclei of rotational strain, which he called "monads." The negatively charged cathode-rays, he suggested, might be streams of these monads.

In correspondence with George Fitzgerald in 1894, Larmor conceived of a better name than "monad"—namely, "electron," a term that Fitzgerald's uncle George Johnstone Stoney (1826–1911) had used for ionic or electrical charges. Larmor's *Aether and Matter,* which appeared in 1900, derived properties of matter, electromagnetism, and light from the mechanical ether, which was taken to be the primary material of the universe. So pervasive and persuasive was this approach that a few chemists, too, could be found speculating about the material ether at the end of the nineteenth century. Adolf von Baeyer, for example, proposed that the density of ether might be greater inside than outside the benzene ring.

Whereas Larmor derived most physical phenomena from the ether, Henrik Lorentz took the opposite tack by deriving the laws of ordinary mechanics, including inertial mass, from the electromagnetic condition of the ether. Lorentz, who held the first chair of theoretical physics at the University of Leiden from 1878 to 1923, was recognized by the turn of the century as one of the leading physicists on the continent, largely because of his work in electrodynamics. He was influential both because of his acumen as a physicist and his cosmopolitan charm as a colleague.

Like Larmor, Lorentz sought unifying principles through a physics of the ether and by 1900 he was confident that physical and chemical phenomena and perhaps even gravitational effects might be encompassed in an electron theory rooted in the ether. Emil Wiechert (1861–1928) in Germany and Paul Langevin (1872–1946) in France were working along similar lines.

For Lorentz, however, the ether had no mechanical connection with matter; rather, in the spirit of Maxwell, he drew a sharp distinction between ether and matter. The interaction between the two occurs through tiny, inertial, rigid bodies found in molecules and carrying positive or negative electrical charge. In 1895 Lorentz called these bodies "ions" and later, after 1899, "electrons." Thus electric flow is the flow of electrons. This hypothesis is, of course, contrary to Maxwell's argument that electricity is not material. For Lorentz, the motions of electrons create an electromagnetic field, the seat of which lies in the stationary ether.

Lorentz also concluded that electrons, and thus molecular matter, are affected by the speed of their motion, becoming shorter at speeds approaching the speed of light. This contraction would explain the failure of Michelson and Morley to detect the motion of matter through the ether. Lorentz soon realized that Fitzgerald had earlier come to the same conclusion about the relationship between the length and the speed of an electron as it moves through the ether.

A confirmation of Lorentz's theory came from experimental work by his younger Dutch protégé Pieter Zeeman (1865–1943) in 1896. Following up on Faraday's researches, Zeeman tried to repeat one of Faraday's last investigations, which had failed. In 1862 Faraday had looked for the effect of a magnetic field on the spectral lines emitted by sodium vapor. Maxwell, who believed that spectral lines were caused by the vibrations or oscillations of molecules independent from the ether and electromagnetic phenomena, had denied the existence of the effect sought by Faraday. Zeeman, who had at his disposal a diffraction grating far superior in resolving power to Faraday's prisms, observed a slight broadening of the spectral lines in the magnetic field. He found that he could produce spectral line triplets or doublets by varying the orientation of the direction of observation and the magnetic field.

This Zeeman effect gave Lorentz and Zeeman a tool to calculate the ratio of electron charge to electron mass (e/m) on the hypothesis that the light that is the spectral lines is emitted by the electrons of charge e and mass m moving about in regular periodic fashion within the atom. The charge for e was negative and the value of the ratio was approximately a thousand times larger than expected. Lorentz took this result to mean that the electron (or ion), if it carried a standard unit of charge, was very small.

The convergence of spectroscopic phenomena with electrical-discharge phenomena was to provide a fertile meeting ground for theories of matter, electricity, and light in the 1890s and the early twentieth century. Lorentz's results seemed to confirm the notion of "atoms of electricity" that Helmholtz had advanced in his Faraday Lecture in order to kindle "anew the interest of chemists in the electrochemical part of their science."[18]

As we shall see in later chapters, chemists in the nineteenth and early twentieth century were indeed to find their interest in electricity rekindled, first through Svante Arrhenius's ionic theory and then through J. J. Thomson's electron theory. By the 1920s, electrons were to provide explanatory mechanisms for chemical problems that were left unresolved in the theories of both structural organic chemistry and thermodynamical physical chemistry.

The Continental physicist Albert Einstein disposed of the ether in a relativistic physical theory that Faraday might well have liked (see chapter 7), no matter how much Larmor, Lodge, and William Thomson in fact disliked it. The direction in which the electrodynamics of the electron developed during the 1920s and 1930s was foreshadowed by Fitzgerald and Lorentz in the early 1890s, but hardly foreseen.

J. Norman Lockyer (1836–1920), the astronomer, spectroscopist, and editor of *Nature*, provided a striking metaphor for matter, electricity, and light that was to become outmoded by the 1920s:

> We believe that each molecular vibration disturbs the ether; that spectra are thus begotten; each wavelength of light resulting from a molecular tremor of corresponding wavelength. The molecule is, in fact, the sender, the ether the wire, and the eye the receiving instrument, in this new telegraphy.[19]

This vision of the natural world was a powerful one. It was a worldview that greatly complicated Newtonian principles or rejected them outright. The challenge of thinking about electricity and magnetism during the course of the nineteenth century brought into relief the difference in scientific explanation between realist visualization and abstract mathematics, even as it highlighted some differences in national customs of building scientific theories.