HISTORY OF PHYSICS

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CHAPTER V

Electricity and Magnetism

THE SCIENCE of electricity and magnetism is much younger than mechanics and optics. Antiquity contributed nothing beyond the word "magnet" and some elementary observations concerning rubbed amber. Besides the compass, which can be traced back to at least the second century A.D. in China and which was brought to Europe in the thirteenth century, the Middle Ages added only the discovery that every part of a magnet again constitutes a whole magnet. It is perhaps worth noting the horror with which Christopher Columbus, on his voyage of discovery in 1492, observed the change from the easterly compass declination, which then prevailed in South Europe, into a westerly one. Even the first century and a half of modern physics provides the history of physics with very little in this field, despite the unquestioned services of William Gilbert (1540-1603) who coined the word "electricity." He traced out the course of the lines of force by bringing a small compass needle near magnetized steel balls, thus demonstrating the complete analogy to the action of the earth on the compass. He put an end to all tales of great magnetic mountains at the North Pole or of a directing force coming from the lodestar. This condition was not altered much by the studies of Otto von Guericke, who noted the repulsion of like-charged particles, and constructed the first frictional electrical machine, and also discovered that iron filings can be magnetized merely by the action of the terrestrial magnetic field. In mechanics, optics, heat, and chemistry, there was available a fund of ancient pre-scientific experience, which had a certain value to the budding planned investigations, whereas the orderly study of electricity and magnetism had to pass through the corresponding "prehistoric" stage itself before it could lead to clear ideas. The investigators in the seventeenth and the first part of the eighteenth centuries were confronted by a confused collection of phenomena, such as frictional electricity, formation of sparks, and effect of atmospheric moisture, which they were unable to clarify because of the lack of fundamental electrostatic concepts.

Nevertheless, a number of important qualitative observations came from this period. In 1731, Stephen Gray (1670-1736) recognized the difference between conductors and insulators, and in 1759 Franz Ulrich Theodor Äpinus (1724-1802) went further by showing the existence of all stages of transition between them. They made the first observations of the influence exerted by charged bodies on insulated conductors. Both Ewald Georg von Kleist (born soon after 1700, died 1748) working in Kammin, Pomerania, and Pieter van Musschenbroek (1692-1761) in Leyden, Holland, were led by chance observation in 1745 to the Leyden jar, the original form of the electrical condenser, whose elucidation occupied not only Äpinus (Aepinus) but also Benjamin Franklin. (The latter was the author of the designations: positive and negative electricity.) In this connection, Johann Carl Wilcke (or Wilke) (1732-1796), in 1758 discovered the polarization of dielectrics, a typical instance of a premature and therefore quickly forgotten fact. Alessandro Count Volta (1745-1827) described in 1775 the electrophorus from which influence electrical machines were later developed. Great and deserved excitement was occasioned in 1752 when Franklin furnished the experimental proof of the electrical nature of thunder storms, a fact that had long been suspected.

The concept "quantity of electricity" seems to have been current since the seventeenth century, and without any real basis from the start was connected with the idea of the impossibility of creating or destroying electricity. The dispute as to whether there are two electrical "fluids," which compensate each other in their effects, or only one, which is present in an electrically neutral body in a certain normal quantity, could not be decided. The present concept is dualistic, in so far as it ascribes different carriers to positive and negative charges, and unitary, in so far as it accepts the most elemental carrier of positive charges, namely, the atomic nucleus, as also being the fundamental constituent of matter.

During the eighteenth century, there was really only one discovery concerning magnetism, and it too was premature and consequently ineffective. In 1778 Anton Brugmans (1732-1789) discovered diamagnetism, when he found that bismuth is repelled by a magnet.

Electricity did not attain the rank of a science until the announcement of Coulomb's law: The force between two charges is directly proportional to the charge on each and inversely proportional to the square of the distance between them. This law had a peculiar history. It began with suspicions related to the Newtonian law of attraction. However, in 1767 Joseph Priestley (1733-1804) found compelling evidence of it in the discovery by him and others, Henry Cavendish, for instance, that the charge of a conductor resides entirely on its surface, while the interior remains completely free of all electrical influences. However, this fact received no attention. In 1785 Augustin de Coulomb (1736-1806) made measurements with a torsion balance; he determined the force between charged spheres, partly by means of the static deflection of the balance, and partly through the vibration period, about its rest point, of a sphere suspended from the balance and set in motion by the action of the fixed sphere. However, in a subsequent (1786) communication, Coulomb reported that a conductor also shields its interior—he was not aware of his predecessors—and he saw in this also an indication of the force law. This portion of his communication, however, was so completely forgotten, that the shielding action is now commonly linked with Faraday's name. In fact, Coulomb's contemporaries remembered only the more obvious measurements secured with the torsion balance, and the law which bears Coulomb's name was derived from these data.

When Coulomb stated that the force between two charges is proportional to the quantities of electricity, he did so purely in analogy to the Newtonian law. He could offer no proof for his assertion, because means of measuring charges were not available. The idea of defining this quantity directly from Coulomb's law was contributed by Gauss.

Coulomb also extended his law to magnetism. In this case, however, the experiments were less convincing, because the accumulation of the magnetic "fluida" at the punctiform poles always remained somewhat in doubt, even though he had attempted to prove this by preparatory measurements. The valid portion of this extension finds its precise statement in the applicability of the Laplace differential equation to magnetism, as pointed out by George Green (1793-1841) in 1828. Coulomb's proof, by means of the torsion balance, that the earth's magnetic field exerts a moment of rotation on the compass needle proportional to the sine of the deflection from the meridian was important, because this finding constitutes the basis of the concept of magnetic moment.

The progress initiated by Coulomb's law was shown in 1811 when Siméon Denis Poisson carried over to it the theory of potential (see Chapter III) which was first developed for gravitation. In fact the whole of electrostatics, in so far as dielectrics are not involved in the phenomena, can be covered by means of the Coulomb law or the equivalent Laplace-Poisson differential equation and the knowledge that the potential on conductors is constant. The further elaboration of the theory of potential was due, in addition to Green, to Karl Friedrich Gauss, who published a famous work in 1839. This theory had an effect far beyond its own sphere, because it became the model for many other fields of mathematical physics.

Gauss contributed not only the definition of the quantity of electricity from the Coulomb law, as was mentioned above, but he also provided the first absolute measurement of magnetic moment of steel magnets, and of the strength of the earth's magnetic field. His mathematical theory of this field constitutes the direct and conclusive continuation of the work of W. Gilbert (page 42). He created with this the first rational electrical and magnetic system of units. In it, unit quantity of electricity is that quantity which, at a distance of one centimeter, repels an equal quantity with a force of one dyne.

The law of the conservation of electricity was first demonstrated in 1843 by Faraday. He brought a charged metal ball, suspended by a long silk thread, into an insulated "ice pail," which was electrically connected with an electrometer. The resulting deflection of the electrometer is a measure of the charge. He then showed that this deflection is independent of any other contents of the "ice pail" and also of what happens to the charge there. All or part of it can be transferred to other conductors; there is no effect. Only when additional charges are brought into the pail is there a change in the deflection in that the instrument now indicates the algebraic sum of charges that have been introduced. Other demonstrations of the law of the conservation of energy were being made around this time, and even though this experiment was not less important than the others, it did not receive the same recognition because the doctrine of the indestructibility of electrical fluids had already firmly established itself and hence needed no champion to do battle in its behalf.

The second and perhaps more fruitful advance was made by the science of electricity when Alessandro Count Volta transformed into a physical discovery the observations on frog legs reported by the physician Luigi Galvani (1737-1798), which had aroused much interest and had stimulated many successors. Seldom has a discovery posed so many difficulties to the human understanding as this one, but, in return it opened the way into utterly undreamed-of territory.

Galvani's first chance observations on the contraction of frog muscles connected with a metal loop in the neighborhood of electrical spark discharges at the approach of a thunderstorm were actually the earliest indication of electrical oscillation; the frog leg acted as a "detector." The physicists did not really accomplish anything with this observation until 100 years later. In 1792, however, conscientious experimentation and good fortune brought Galvani to the point at which he was able to make the muscle contract by simply applying to it a loop consisting of two different metals. This was the first galvanic element; the frog muscle was both its electrolyte and current indicator. Galvani himself, however, remained ignorant of these facts; he supposed, and perhaps not entirely erroneously, that these were manifestations of "animal electricity," which had been known for a long time in the case of electric eels and other fishes.

Volta also accepted this interpretation in 1792. However, long series of experiments brought him more and more to the conviction that the biological object, frog leg or human tongue, was only of secondary importance. In 1796 he eliminated it entirely and stated that an essential condition for the "circulation" of electricity in a conducting circuit was that the latter consist of two (or more) conductors of the "first" class and one of the "second" class. He originated these ideas, as well as the concept of the stationary electric current. On the basis of the new knowledge, he constructed in 1800 the voltaic pile, the prototype of the galvanic batteries, which in the succeeding years and decades sprang up like mushrooms from the ground. "Volta's fundamental experiment," which was designed to demonstrate the charging of two metals on contact, became famous. It has not stood the test of modern critical examination (Emil Warburg); invariably there is a layer of moisture between the metal plates and what is actually observed is the terminal voltage of an open galvanic cell. However, Volta's observation was correct and fundamental, because an electrical equilibrium, which excludes all current, is set up momentarily in a purely metallic circuit, no matter how many different metals are included in it. The fact that temperature differences also produce a current in such circuits (thermoelectricity) was first observed (1821) by Thomas Johann Seebeck (1770-1831).

Electrolytic decomposition, which is now regarded as the cause of the production of galvanic current, was described in

1797, i.e., before the voltaic pile, by Alexander von Humboldt (1769-1859), whose fame ordinarily is ascribed to his achievements in the descriptive natural sciences. His discovery was made with a cell consisting of a zinc and a silver electrode with a layer of water between. This finding was further utilized in 1799 by the gifted but visionary Johann Wilhelm Ritter who, for instance, separated copper electrolytically from a solution of cupric sulfate. He also recognized the identity of static and galvanic electricity in that he employed the discharge of a Leyden jar for electrolysis. He likewise was the first to bring forward the idea that chemical reaction in the galvanic cell is the cause of the production of the current. In 1800 Humphry Davy began his famous electrolysis researches, which, for example, led him to the discovery and separation of the alkali metals in 1807. His quantitative determinations of the amounts of the decomposition products opened a new field of investigation. This yielded: in 1834, the Faraday law of electrochemical equivalence; in 1853, the studies on the migration of ions by Johann Wilhelm Hittorf (1824-1914); also, in 1875, the recognition of the independence of ionic mobilities by Friedrich Kohlrausch (1840-1910); in 1887, the theory of electrolytic dissociation by Svante Arrhenius (1859-1927). The theory of electromotive forces of Walter Nernst brought this glorious series to a worthy close in 1889, and the theory of the galvanic production of current was thus completed. Of course, the idea that a sodium ion, for example, can move freely in a water solution without reacting chemically with its surroundings aroused considerable heated opposition at first; many refused to accept the distinction between the neutral atom and the ion. However, the Arrhenius theory received so many substantiations that the opposition was gradually silenced.

Volta's discovery opened still other lines of development. The galvanic cells produced electric currents of strengths and duration, quite different from those that had been obtained from the discharge of condensers and similar devices. For example, about 1811 Davy constructed the carbon arc with a battery of 2000 elements, and it served as a source of electric light until Thomas A. Edison (1847-1931) invented the incandescent bulb around 1880. Batteries also made the magnetic action of currents accessible to study. Surmises concerning the forces between the electrical and magnetic fluids were rather common at the beginning of the nineteenth century and had occasioned, for instance, the search for mutual actions between magnetic poles and open voltaic piles. Independent of such wrong turnings, and quite by chance, Hans Christian Oersted (1777-1851) in 1820 came upon the deflection of the compass needle by the electric current, and thereupon also discovered the corresponding directive force of a magnet on a rotatable electric circuit. Many others, especially French physicists, now entered the newly opened field, and the foundations of electromagnetism were laid in the short time up to 1822. First came the observation by Dominique François Arago and Joseph Louis Gay-Lussac (1778-1850) that a piece of iron is magnetized by a current flowing in a wire looped around it; this was the first electromagnet. Later, in this same year (1822), André Marie Ampère (1775-1836), who took no part in physics either before or after this period, set up his familiar swimmer rule for indicating the direction of the magnetic field of an electrical circuit and discovered that parallel currents passing in the same direction attract each other, and repel each other if their directions are contrary. He showed that a solenoid acts like a bar magnet. Jean Baptiste Biot and Feliz Savart (1791-1841) concurrently formulated from the experimental findings the law bearing their names, which deals with the magnetic action of a single line element of a linear current. In 1822 Faraday caused the movable part of a circuit to rotate by the action of permanent magnets and imparted rotatory motion to magnets through the action of currents. Thereupon, Ampère in 1822 demonstrated the rotational effects of two circuits and used this as the starting point for his fundamental law of "electrodynamics," a term that appears for the first time in his writings. However, more than a century elapsed before his explanation of magnetism became especially important; he abandoned the hypothesis of magnetic fluids, and (1821-22) ascribed magnetism to the action of his hypothetically assumed molecular currents.

These magnetic effects of currents now provided a means of measuring current strength. This was employed in 1826 by Georg Simon Ohm when, clearly separating the concepts of electromotive force, potential gradients, and current strength, he derived the (Ohm's) law of the proportionality between current strength and difference of potential, in which the proportionality factor represents the resistance of the conductor. He proved that in the case of a wire the resistance is proportional to its length and inversely proportional to its cross section and thus created the basis of the concept of the specific conductivity of materials. The latter, however, is one of the three constants which characterize the total behavior of every substance toward electricity and magnetism. In 1847 G. R. Kirchhoff solved the problem of branched circuits and set up the rules that now bear his name.

An application of these effects came when the telegraph was invented. The form devised in 1833 by Gauss and Wilhelm Weber (1804-1891) differed from its predecessors in that the current returned through the earth.

The development of electromagnetism halted after 1822, even though at first only half of this group of phenomena had been recognized. In 1831 Faraday wound two coils of wire around an iron ring and with this arrangement found that currents exert a back action which corresponds to their magnetic action. When he sent a current through the first coil, a pulse of current appeared in the second at the instant the circuit was closed, and again when it was opened, but in the reverse direction. In this way he discovered induction, and he clarified its various kinds in the years that followed. Faraday's somewhat scattered statements regarding the direction of the currents induced by movements were summarized in 1833 in the well-known (Lenz) law by Friedrich Emil Lenz (1804-1865). Induction machines soon followed, so that currents could be produced independently of galvanic batteries. However, their large-scale development did not come until after 1867, when

Werner von Siemens (1816-1892) substituted electromagnets, fed by the produced current itself, for the steel magnets previously used. This constitutes the dynamoelectrical principle.

Electrodynamics now made possible a second system of electrical units; it is independent of Coulomb's law. For example, the unit of current strength can be defined as the current which flows in two long parallel wires, one centimeter apart, when they exert on each other a force of two dynes per unit length. Since unit current strength must furnish unit quantity of electricity to a condenser, in unit time, an electromagnetic unit quantity of electricity has likewise been obtained. This necessarily raises the question as to the relation to the electrostatic unit as defined by the Coulomb law. An examination of the formulas shows that this relation has the dimension of a velocity. Wilhelm Weber determined its value in 1852 and the succeeding years, with the astounding result that it is equal to the velocity of light: 3×10^{10} cm/sec. As it was of fundamental importance to the electromagnetic theory of light, James Clerk Maxwell redetermined it in 1868-69 with greater accuracy. Subsequently, the comparison was perfected to such a degree that it is now included among the precision measurements of the velocity of light.

An international congress held at Paris in 1881 set up the electrical units (ampere, ohm, volt, etc.) now used in technical practice. These are based on the electromagnetic system of units. The prospects of any considerable technical development were so slight at that time that these authorities did not adopt the electromagnetic unit of current itself, because it seemed impractically large. They accordingly defined the ampere as one-tenth of this value.

All the measurements cited hitherto dealt with currents passing along metallic conductors. In 1872 Henry Rowland (1848-1901) showed that the convection currents of static charges exert the same effect on bodies in motion.

The discoveries of electrodynamics confronted theory with problems, which, in contrast to all those that had arisen previously, could no longer be solved solely by means of the central forces depending on the distances between mass points. Ampère and Franz Ernst Neumann, and, above all, W. Weber, attacked these problems. Weber's fundamental law (1846) assumed that the force between two charges depended not alone on the distance between them but also on the velocity and acceleration and that currents are moving charges. It covered electrostatic as well as electrodynamic forces including induction in closed circuits, in other words, everything that was known about electricity at the time. Consequently, this law played an important role in science until about 1890. However, all these theories contained the defect of assuming action at a distance and as soon as the finite speed of propagation of electrical actions was recognized, the ground was cut from under them. Today they merely illustrate the difficulty that beset the path of progress in this field, and show the extent of the great changes in the whole physical viewpoint that have transpired since their day.

Michael Faraday was the leader in acquiring the correct understanding of electrical and magnetic phenomena. In 1837 he discovered the influence of the dielectric on electrostatic processes and in 1846 and the following years the general distribution of the diamagnetic properties over all material to which, in contrast, paramagnetism appears as an exception. On this basis, he evolved the idea that electric and magnetic actions do not pass from body to body without a medium, but are transmitted through the dielectric which lies between and which accordingly becomes the seat of the electrical or magnetic "field." This latter thought also came from Faraday. As his experiments progressed, this idea developed. "The method which Faraday employed in his researches consisted in a constant appeal to experiment as a means of testing the truth of his ideas, and a constant cultivation of ideas under the direct influence of experiment. In his published researches we find these ideas expressed in language which is all the better fitted for a nascent science, because it is somewhat alien from the style of physicists who have been accustomed to established mathematical forms of thought." This judgment is by J. Clerk

Maxwell[1] who continues: "It was perhaps for the advantage of science that Faraday, though thoroughly conscious of the fundamental forms of space, time, and force, was not a professed mathematician. He was not tempted to enter into the many interesting researches in pure mathematics which his discoveries would have suggested if they had been exhibited in a mathematical form, and he did not feel called upon either to force his results into a shape acceptable to the mathematical taste of the time, or to express them in a form which mathematicians might attack. He was thus left at leisure to do his proper work, to coordinate his ideas with his facts, and to express them in natural, untechnical language." Concerning his own researches, Maxwell then adds: "It is mainly with the hope of making these [Faraday's] ideas the basis of a mathematical method that I have undertaken this treatise."

It was in this sense that Maxwell, in a first paper of 1855-56, provided the appropriate mathematics for the Faraday idea of lines of force. Particularly through his analysis of the course of the magnetic lines of force in the vicinity of an electric current, he arrived at the now familiar vector differential equation, according to which every current path produces a vortex line of the magnetic field, although with limitation to stationary fields. The achievement that was most particularly Maxwell's own, the step that was decisive for everything which came later, was first contained in a paper of 1862.[2] He added to the conducting current the displacement current, which occurs in every dielectric with varying electrical field strengths, and only in conjunction with this current, gives the total current which invariably is a closed whole. Actually, Maxwell came upon this through a hypothetical quasi-mechanical model. Nobody would regard this derivation as compelling truth, and it was not included in Maxwell's comprehensive textbook that was published in 1873. However, it is interesting to note that it was only by this roundabout way that he arrived at the decisive

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[1] J. Clerk Maxwell, *Treatise on Electricity and Magnetism,* Vol. 2, Oxford, 1873, pp. 162, 163.

[2] *Philosophical Magazine* [4], 23, 12 (1862). (See equation 112.)

step. The electromagnetic theory of light (Chapter IV), i.e., the recognition that there are electromagnetic waves possessing the velocity of light, then became no more than a necessary conclusion; Maxwell drew it in 1865.

The transmission of force through the electromagnetic field was ascribed by Maxwell to the stresses which bear his name. Entirely analogous to the elastic strains, analyzed by Cauchy (Chapter II), they differ from these only in that they are not associated with deformation of matter, rather, occasioned entirely by the field, they may reside entirely outside of all matter, even in empty space. According to this viewpoint, in a purely electrical or purely magnetic field, there is a stress along every line of force, and an equally strong pressure perpendicular to it. Only the Maxwellian stresses bring the ideas of close action to completion.

The bases of the present-day theory of electricity were thus laid down completely. Of course, it was not until 1890 that Heinrich Hertz put the Faraday induction law into the differential equation form in which it appears as a counterpart of the differential relation given by Maxwell. As a result, the system of Maxwell equations, in which modern physicists, along with Hertz, see the essence of the Maxwellian theory, was given that absolutely esthetically beautiful symmetrical form, which in view of its comprehensive physical content seems almost to have the character of a revelation. And yet this was only a matter of form. New physical knowledge was not added to it until 1884, when Poynting's theory of energy flowing was put forth (Chapter V), and by the demonstration, around 1900, by H. A. Lorentz and Henri Poincaré (1854-1912) that an electromagnetic impulse is associated with the electromagnetic energy current. However, this represents only a slight supplement to but no fundamental alteration of the basic theory.

Despite its inner completeness and the agreement with all experiment, Maxwell's theory was only gradually accepted by the physicists. Its ideas were too unconventional; even men of the caliber of Helmholtz and Boltzmann had to strive for years to secure an understanding of it. In 1879, the Berlin Academy offered as topic for prize competition the experimental proof of an effect of dielectrics on magnetic induction. Heinrich Hertz solved this problem in 1887 by means of rapid oscillations. Another result of such considerations was the experiment by W. C. Röntgen in 1888 to determine whether the motion of an electrically polarized dielectric has the magnetic effects of a current, as would correspond to Faraday's idea. The effect which he definitely demonstrated is called the Röntgen current. All doubts were conclusively removed by Hertz through his discovery in 1888 of electrical waves. He directly determined the velocity of propagation from the frequency and wavelength and found that it equals the velocity of light.

The previous history of this discovery goes back to the Helmholtz essay "The Conservation of Energy" (1847, Chapter VI). Various studies of the discharge of Leyden jars, especially the independence of the heat produced in the discharging wire of all special characteristics of the wire, led Helmholtz to conclude that the discharge is oscillatory in character. Likewise, in connection with the energy principle, William Thomson (Lord Kelvin) in 1853 gave the mathematical theory for it in a form to which practically nothing has needed to be added. Berend Wilhelm Feddersen (1832-1918), from 1858 to 1862, examined these oscillations in the image of the discharge spark in a rotating mirror. Friedrich Wilhelm von Bezold (1837-1907) definitely observed oscillations in wires with one free end and in wire circuits containing a spark gap. But it was only in the hands of Hertz that such wire circuits became the means of studying waves in free air, for revealing their polarization, reflection, and refraction, as well as their interferences, which then made it possible to measure the wavelength and so to determine the velocity of propagation.

The waves with which Hertz experimented were strongly damped. If his experiments can be repeated today with undamped waves, i.e., with greater nicety, it is because of technical advances. However, technology had to tread a toilsome path before it learned in 1913 and later how to produce, by means of vacuum tube transmitters based on feed back (Chapter I), the undamped waves needed for wireless teelgraphy and similar purposes.

Just as a period of mathematical development of mechanics followed Newton, a similar era of mathematical elaboration of the Maxwellian theory now set in. The vector potential had been introduced even earlier to represent the magnetic eddy fields in the vicinity of stationary currents. In opposition to this and the scalar potential of electrostatics Alfred Marie Liénard in 1898 and Emil Wiechert (1861-1928) in 1900 proposed the retarded potentials, in which the finite velocity of propagation of magnetic actions finds its most striking expression. The available space would by no means permit the enumeration of all the investigators who elucidated mathematically the scientific and soon also the technically important cases of electrical alternating fields. In its modern form the Maxwellian theory is an inspiring masterpiece, fully the peer of mechanics.

Thus, at the beginning of the twentieth century, the theory of electricity and magnetism seemed to be fairly complete, especially since atomistics had shortly before brought order and clarity into the confusion attending the phenomena of discharge through attenuated gases (Chapter X). And yet, a new and unexpected phenomenon appeared in its own most particular province, in the conduction of current. It had been known since 1835, from measurements by Heinrich Friedrich Emil Lentz, that the resistance of metals decreases when they are cooled. Heike Kammerlingh-Onnes (1853-1926) followed the decrease to below 10° absolute, when the attainment of such low temperatures became possible through his liquefaction of helium in 1908. Metals, e.g., gold, silver, and copper, were found to have a limiting value below which the resistance does not fall. However, in 1911 he observed, first with mercury and later with lead, tin, and several other metals, a sudden disappearance of all resistance as soon as the temperature fell below a transition point whose value is characteristic of the substance. Supraconductivity sets in; the current then flows without any potential gradient, and persists with undiminished strength and without any electromotive force as a permanent current for days in a supraconducting ring. This was demonstrated in 1914 by Kammerlingh-Onnes. He eventually also found that, without change in temperature, it is possible to annul supraconductivity by means of a magnetic field; Ohm's law then holds as usual. The field strength, which the supraconductor just withstands, the "threshold value," increases the lower the temperature is brought below the transition point. With pure metals it amounts to several hundred gauss.

Later investigators added a few more pure metals to the list of supraconductors and also a series of alloys and chemical compounds. W. J. de Haas and his associates observed further that the threshold value of a supraconducting wire seemed to depend on the direction of the magnetic field with respect to its axis. Max von Laue provided the explanation of this in 1932: a homogeneous magnetic field is deformed when a supraconductor is brought into it, because the lines of force avoid the conductor, in accordance with the Maxwellian theory, as Gabriel Lippmann (1845-1921) had previously concluded. The crowding together of the lines of force, however, brings about a strengthening of the field at certain points of the surface; the supraconductivity fails as soon as the threshold value is attained at even a single point. Subsequently, de Haas and his collaborators quantitatively verified this explanation with supraconductors of various forms.

A supraconductor is not a conductor in the usual sense of the Maxwellian theory that is merely distinguished from others by possessing an infinitely great conductivity. If this were so, a magnetic field that is entered above the threshold value must continue to exist inside the conductor when the temperature is lowered below this point. However, in 1933 W. Meissner and R. Ochsenfeld made measurements which showed that the field is forced out. It makes no difference whether the temperature is brought below the threshold value before activating the magnet, or vice versa. This Meissner effect requires a supplementation of the Maxwellian theory on a completely new foundation.

The relation of the electromagnetic field to its charges was subjected to remarkable fluctuations in the views of the physicist. Just as gravitation seemed to Newton and his successors to be the causal consequence of masses, every physicist at first conceived electrical forces as due to charges. Then the field concept came to the front with Faraday and Maxwell, and the charges were demoted to a kind of singular areas of the field. But the relation was again reversed when the rise of the electronic theory of optics and electrical discharge put the atomic carriers of the electrical elementary quanta in the forefront of interest. Neither of these viewpoints seems to fit the facts. Charges and field are so closely associated with each other that one cannot exist without the other. Precisely for this reason, science can just as well take the charges as the criterion for the knowledge of the field as to draw a conclusion from the course of the electrical lines of force. These are logical conclusions; they have nothing to do with the real relation of cause and effect. The same applies, of course, to the gravitational field and its masses.

The relations between the theory of electricity and mechanics are also of a special kind. As was mentioned, Maxwell around 1862 tried to construct for himself a mechanical picture of the magnetic field. Later, during the progressive acceptance of his theory, many sought in a more rational way to base it on a mechanics of the ether. To a certain degree, it is possible to subordinate the theory of linear, closed (quasi-stationary) currents to the theory of cycles, derived from mechanics, and developed especially by Helmholtz. This is little more than a mathematical analogy between different varieties of physical events. After all, it is indicative of the infiltration of electrodynamic views into wide circles that the present-day engineer frequently explains the mode of action of mechanical machines through a corresponding electrical connection. However, around 1900, it was gradually perceived that a general reduction of electrodynamics to mechanics is impossible.

Since 1880 the reverse idea has gradually taken shape, i.e., to refer mechanics back to electrodynamics. The fact that a moving charged body carries its electromagnetic field with it, and that an impulse resides in this, certainly was close to the idea of an electromagnetically inert mass. In fact many workers tried to conceive of every mass as electromagnetic mass. This found, for instance, its mathematical downfall (1902) in the theory of Max Abrahams (1875-1922), which deals with the impulse of the moving electron treated as a charged sphere. The mass proved to be dependent on the velocity, and the Abrahams formula covering this was in competition with the relativity formula for a long time (Chapter II).

Physics has discarded this idea also, since experiment has finally definitely decided in favor of the relativistic formula. In addition, the Abrahams theory produced a factor for the proportionality between energy and the mass at rest which differs from that appearing in the Einstein law of the inertia of energy. The latter has been fully confirmed through nuclear physics (Chapter XI). However, the Abrahams investigations had a permanent effect as preparation for relativistic dynamics.

Even though relativistic dynamics is completely independent of every concept concerning the nature of forces, i.e., also independent of electrodynamics, nevertheless the latter played a decisive role in the discovery of this dynamics. The findings which led to the Newtonian dynamics could never have sufficed to produce the Einstein relativity theory; they were not accurate enough. When electrodynamics compelled the relativity principle that is connected with the Lorentz transformation, it also compelled the change from Newtonian to relativistic dynamics. Therefore, in this purely historical sense, modern dynamics is based on electrodynamics.