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(*b*. Königsberg, Germany, 12 March 1824; *d*. Berlin, Germany, 17 October 1887)

physics.

Kirchhoff's major contribution to physics was his experimental discovery and theoretical analysis in 1859 of a fundamental law of electromagnetic radiation: for all material bodies, the ratio of absorptive and emissive power for such radiation is a universal function of wavelength and temperature. Kirchhoff made this discovery in the course of investigating the optical spectra of chemical elements, by which, in collaboration with Bunsen, he laid the foundation of the method of spectral analysis (1860). Outstanding among his other contributions were his early work on electrical currents (1845-1849) and on the propagation of electricity in conductors (1857). A master in the mathematical analysis of the phenomena, he insisted on the clear-cut logical formulation of physical concepts and relations, directly based on observation and leading to coherent systems free of hypothetical elements. His teaching had a considerable influence on the development in Germany of a flourishing school of theoretical physics during the first three decades of the twentieth century.

Kirchhoff's uneventful life and career afford a typical example of the somewhat parochial but substantial comfort which the academic profession enjoyed in Germany during a period of unprecedented economic expansion. Latecomers in the industrial revolution, the Germans, more than their wealthier English and French competitors, had to rely on scientific methods for the improvement of technology. The paradoxical result was that physics and chemistry found more favorable conditions of development under the multitude of petty feudal governments in Germany than in the progressive environments of prosperous manufacturing centers in England and France.

In Königsberg, Kirchhoff's birthplace, a nucleus of enterprising tradesmen and able officials had fostered a thriving intellectual circle. Kirchhoff's father, a law councillor (*Justizrat*), belonged to the strongly disciplined body of state functionaries which also included university professors. He regarded it as a matter of course that his sons keep up, according to their diverse talents, the family's allegiance to the service of the Prussian state. Gustav, the most gifted, upheld this tradition which still determined the careers of his own children. Yet, like other prominent figures of the German intelligentsia, he does not seem to have had difficulty in reconciling submission to authority in political matters with liberal opinions in other respects. The Manchester chemist Henry Roscoe, who knew both Kirchhoff and Bunsen well, relates an incident from a visit they paid him, which shows them taking quite a Voltairean view of the church.

Boltzmann described Kirchhoff, at the height of his powers, as being not easily drawn out but of a cheerful and obliging disposition. A disability from an accident, which compelled him to use crutches or a wheelchair, did not alter his cheerfulness, and he bore with patience the long illness of his last years.

At the university in his native city, Kirchhoff came under the influence of Franz Neumann; in the new science of electromagnetism, Neumann introduced and further developed in Germany the ideas and methods of the leading French school of mathematical physics. In 1847 Kirchhoff graduated from the university and married Clara Richelot, the daughter of another of his teachers—thus fulfilling the two prerequisites for a successful academic career. In 1848 he obtained in Berlin the *venia legendi* (the right to lecture privately in a university) and two years later became extraordinary professor in Breslau . In 1851 Bunsen, Kirchhoff's senior by thirteen years, came to Breslau, only to leave again the next year for Heidelberg. This brief period was sufficient to create a lasting friendship between the two men.

In 1854, on Bunsen's proposal, Kirchhoff was called to Heidelberg. He found there a congenial environment for his talents as teacher and investigator; and it was there that, partly in collaboration with Bunsen, he made his greatest contributions to science. This was the heyday of the university of Heidelberg, where the academic circle gathered around Helmholtz and, dominated by him, led a showy social life.

Kirchhoff's wife died in 1869, leaving him with two sons and two daughters; in 1872 he married Luise Brömmel, the superintendent in the ophthalmological clinic. On two occasions he turned down calls to other universities; only when his failing health hindered his experimental work did he accept a chair of theoretical physics offered him in Berlin (1875). He took up this new task with great devotion, untill illness forced him to give up his teaching activity in 1886. A year later, physically weak but intellectually alert he died peacefully, presumably of a cerebral congestion.

Kirchhoff's first scientific work dates from the time when he was studying under Neumann. One of the results he then arrived at has become, on account of its practical importance, a classical part of the theory of stationary electric currents: it is the formulation of the laws governing the distribution of tension and current intensity in networks of linear conductors (1845-1846). The derivation of these laws was essentially a simple application of Ohm's law, but generalizing it fully, as the twenty-one-year-old student did, demanded uncommon mathematical skill.

Ohm's theory of electric current (1828) was based on the hypothetical analogy between the flow and distribution of current in a conductor of any shape to which a "tension" is applied, and the flow of heat in a body at whose boundary some inequality of temperature is established. But apparently neither Ohm himself nor others had realized that the failure to follow up the analogy consistently had led to erroneous results. Thus Ohm thought that a uniform distribution of electricity could subsist at rest inside a conductor.

Kirchhoff's turn of mind was such that he was not long in discovering such a logical flaw and finding the way to mend it. In 1849 he was induced to look into the matter when confronted with some experiments by Kohlrausch on a closed circuit including a condenser, which involved both a static distribution and a flow of electricity. Kirchhoff pointed out that a consistent formulation of Ohm's theory required (at least for stationary currents) the identification of the tension with the electrostatic potential. Thus a correct mathematical unification of electrostatics and the theory of voltaic currents was achieved after more than twenty years of neglect.

The theory of variable currents raised more difficult problems. The law of dynamical interactions between currents had been formulated by Ampère (1826) in the spirit of the concept of action at a distance. The followers of the French school in Germany, Franz Neumann and Wilhelm Weber, concentrated their efforts on the search for an extension of the law of electrostatic interaction between charges, which would embody the new forces at play when the charges are in motion. Although their first attempts in this direction date form 1845-1846, progress was slow, owing above all to the technical difficulty of the experiments required for checking the validity of the necessarily speculative hypotheses on the nature of the electric current, from which the theoretical developments had to start.

The field was still open when Kirchhoff entered it in 1857 with his own general theory of the motion of electricity in conductors. His first paper, in which he treated linear conductors from the same premises as Weber, turned out to coincide in all essentials with an investigation carried out by Weber shortly before but delayed in publication. Both physicists noticed a remarkable implication of their theory: in a perfectly conducting circuit, oscillating currents could be propagated with a constant velocity, independent of the nature of the conductors, and numerically equal to the velocity of light. Both Kirchhoff and Weber, however, pointing to the extreme character of the condition of infinite conductivity, dismissed this result as a mere accidental coincidence.

In a second paper Kirchhoff presented a generalization of the theory to conductors of arbitrary shape. Although his equations purporting to give the local distribution of current and electromotive force were fundamentally wrong, they did yield for the total current the approximate equation already derived by William Thomson, and known as the "teleraphists' equation" on account of its application to the propagation of current in the transatlantic cable then being laid.

The element lacking in Kirchhoff's analysis was obviously the displacement current, or in equivalent terms, the introduction of retarded potentials. It is highly instructive to observe that this decisive step was indeed taken in 1866 by Ludvig Lorenz. Starting from kirchhoff's equations (modified in order to express the finite velocity of propagation of electromagnetic forces), Lorenz demonstrated the existence of purely transversal current waves which, in a perfectly transparent medium (a medium of vanishing conductivity), are propagated at the velocity of light. Lorenz was quite clear about the far-reaching consequences of his analysis: is spelled the end of the conception of action at a distance and opened the way to an identification of optical and electromagnetic waves.

Kirchhoff, aiming at a neat mathematical theory complete in itself, was operating with limited sets of concepts and relations directly suggested by experience. That he thus narrowly missed a great discovery illustrates the weakness inherent in his phenomenological method: emphasizing logical consistency entails the risk of closing the logical construction too soon and of overlooking possible connections between qualitatively different phenomena. In the case of voltaic currents, the closure of the theory demanded an extension of the scope of the potential concept, and the method led by good luck—to a unification of two hitherto separated domains. But in electrodynamics the opposite happened. The ideal program of a physics in which the various forces of nature would be ascribed to specific, sharply separated types of action at a distance blinded its adherents to the strong hint of a possible similarity between the dynamics underlying optical and electromagnetic phenomena. Lorenz' success, by contrast, resulted from his firm belief in the essential unity of all physical phenomena.

The events leading to the foundation and elaboration of the method of spectral analysis have been described by Bunsen (whose testimony is related by W. Ostwald in his edition of the classical paper by Bunsen and Kirchhoff). Bunsen was exploring the possibility of analyzing salts on the basis of the distinctive colors they gave to flames containing them; he had tried with some success to use colored pieces of glass or solutions to distinguish similarly colored flames. Kirchhoff pointed out that a much finer and surer distinction could be obtained from the characteristic spectra of such colored flames; unknown to him, the approach had been tried before, if only in a dilettantish way.

By rigorous experimentation, however, Bunsen and Kirchhoff soon put the method on a firm basis. The burner invented by Bunsen gave a flame of very high temperature and low luminosity, which emitted line spectra of great sharpness. The salts they investigated were prepared in a state of highest purity, and a spectroscope was specially designed to allow the positions of the lines to be accurately determined. By testing an extensive variety of chemical compounds, the ascription to each metal of its characteristic line spectrum was uniquely established (1860). The power and importance of spectral analysis became immediately apparent; its very first systematic application to alkali compounds led Bunsen to the discovery of two new alkaline elements, cesium and rubidium (1860).

In the course of his preparatory work in the autumn of 1859, Kirchhoff made an unexpected observation. It had long been known that the dark D lines, noticed in the solar spectrum by Fraunhofer (1814), coincided with the yellow lines emitted by flames containing sodium. (This effect could be accurately checked by allowing sunlight to reach the spectroscope after traversing sodium flame; if the sunlight was sufficiently dimmed, the dark Fraunhofer lines were replaced by the bright lines from the flame.) Kirchhoff's unexpected discovery was that if the intensity of the solar spectrum increased above a certain limit, the dark D lines were made much darker by the interposition of the sodium flame. He instantly felt that he had got hold of "something fundamental," even though he was at a loss to suggest an explanation.

On the day following the surprising observation, Kirchhoff found the correct interpretation, whcih was soon confirmed by new experiments; a substance capable of emitting a certain spectral line has a strong absorptive power for the same line. In particular, the interposition of a sodium flame of low temperature is sufficient to produce artificially the dark D lines in the spectrum of an intense light source which did not show them originally. The dark D lines in the solar spectrum could accordingly be ascribed to absorption by a solar atmosphere containing sodium. Immense prospects thus opened up of ascertaining the chemical composition of the sun and other stars from the study of their optical spectra.

A few more weeks sufficed for Kirchhoff to elaborate a quantitative theory of the relationship between emissive and absorptive power. He attacked the problem directly by a wonderfully simple and penetrating argument. He considered the balance of radiative exchanges between bodies with appropriately chosen properties of absorption and emission. From the sole condition of radiative equilibrium at a given temperature, he was able to conclude that the ratio of absorptive and emissive powers, for each wavelength, must be independent of the nature of the bodies, and hence that it was a universal function of wavelength and temperature. In a later elaboration of argument (1862), he introduced the conception of a "black body," which absorbs completely every radiation incident on it. Since by definition the absorptive power of such a body has its maximum value, unity, for all wavelengths, its emissive power directly represents the universal function whose existence is asserted by Kirchhoff's law. Hence, this function expresses the spectral distribution of the energy of radiation in equilibrium with a black body of given temperature; moreover, the empirical determination of this universal distribution is reduced to the practical problem of devising a material system with properties approximating those of a black body, and of measuring its emissive power.

Thus, Kirchhoff's law was the key to the whole thermodynamics of radiation. In the hands of Planck, Kirchhoff's successor to the Berlin chair, it proved to be the key to the new world of the quanta, well beyond Kirchhoff's conceptual horizon.

Kirchhoff's derivation of the fundamental law of radiative equilibrium is the triumph of his phenomenological method. He was fully aware of this methodological aspect and attached great importance to it. About ten years before the events just related, Stokes had commented to William Thomson on the coincidence of the Fraunhofer D lines and the bright lines of the sodium flame. Stokes suggested resonance as a mechanical explanation of this phenomenon: the sodium atom would have a proper frequency of vibration corresponding to that of the yellow light it emits and would accordingly absorb most intensively light of the same frequency. Now, Stokes's suggestion, which appears to us a striking anticipation of the atomic basis of Kirchhoff's law, did not appeal to Kirchhoff. When called upon to express an opinion on it (1862), Kirchhoff firmly asserted that the truth of the law had been established only by his own theoretical considerations and the supporting experiments; he thus implicitly denied Stokes's argument any demonstrative value.

Yet, Kirchhoff was not averse to atomistic ideas. Whenever he judged the atomic substratum of phenomena to be sufficiently accessible to analysis, as in the kinetic theory of gases, he readily adopted the proposed atomistic picture. Fully sharing the common ideal of a purely mechanical description of the universe, he realized that such a description could be achieved only on the atomic scale; but he thought — with some reason — that the time was not ripe for it. For him, arguments depending on detailed and unwarranted assumptions about the structure and properties of atoms were without cogency in spite of their suggestiveness. Kirchhoff's fidelity to the phenomenological point of view was thus dictated solely by methodological reasons; if this viewpoint sometimes proved too narrow, it nevertheless inspired not only his discoveries but his no less original attempt at a systematic exposition of the whole of physics. The historical importance of this attempt should not be underestimated.

In a period of expanding scientific horizons, the need soon arises for ordering and logical analysis of new knowledge. Among the leading physicists of the nineteenth century, it was Kirchhoff whose temperament was best suited to this task. In all his work he strove for clarity and rigor in the quantitative statement of experience, using a direct and straightforward approach and simple ideas. His mode of thinking is as conspicuous in his contributions of immediate practical value (the laws of electrical networks) as in those with wide implications (the method of spectral analysis). The excellence of Kirchhoff as a teacher can be inferred from the printed text of his lectures (he managed to publish only those on mechanics, the others being edited posthumously). They set a standard for the teaching of classical theoretical physics in German universities, at a time when they were taking a leading position in the development of science.

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