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(*b*. Erlangen, Bavaria, 16 March 1789; *d*. Munich, Bavaria, 6 July 1854)

physics.

Ohm was the oldest son of Johann Wolfgang Ohm, master locksmith, and Maria Elisabeth Beck, daughter of a master tailor. Of the Protestant couple’s seven children, only two others survived childhood: Martin the mathematician and Elisabeth Barbara. The father, a self-sacrificing autodidact, gave his sons a solid education in mathematics, physics, chemistry, and the philosophies of Kant and Fichte; their considerable mathematical ability was recognized in 1804 by the Erlangen professor Karl Christian von Langsdorf, who enthusiastically likened them to the Bernoullis. Of considerably less importance than his father’s tutoring was Ohm’s attendance (1800–1805) at the Erlangen Gymnasium, where the predominantly classical instruction stressed recitation, translation, and interpretation of texts. On 3 May 1805 he matriculated at the University of Erlangen, where he studied for three semesters until his father’s displeasure at his supposed overindulgence in dancing, billiards, and ice skating forced him to withdraw in virtual exile to rural Switzerland. In September 1806 Ohm began a two-and-a-half-year stint teaching mathematics at one Pfarrer Zehender’s *Erziehungsinstitut* in Gottstadt bei Nydau, Bern canton; in March 1809, he went to Neuchâtel for two years as a private tutor. Just before this move he had expressed to Langsdorf the desire to follow him to Heidelberg; but he was dissuaded with the advice that he would be better off studying Euler, Laplace, and Lacroix on his own.

By Easter of 1811 Ohm was back at the University of Erlangen, where on 25 October, after having passed the required examinations, he received the Ph.D. He subsequently taught mathematics for three semesters as a *Privatdozent*, his only university affiliation until near the end of his life. Lack of money and the poor prospects for advancement at Erlangen forced Ohm to seek other employment from the Bavarian government; but the best he could obtain was a post as a teacher of mathematics and physics at the low-prestige, poorly attended *Realschule* in Bamberg, where he worked with great dissatisfaction from January 1813 until the school’s dissolution on 17 February 1816. From 11 March 1816 until his release from Bavarian employ on 9 November 1817, he was assigned, in the capacity of an auxiliary instructor, to teach a section of mathematics at the overcrowded Bamberg *Oberprimärschule*.

On 11 September 1817 Ohm had been offered the position of *Oberlehrer* of mathematics and physics at the recently reformed Jesuit Gymnasium at Cologne, and he began work there (evidently) sometime before the end of the year. The ideals of *wissenschaftliche* Bildung had infused the school with enthusiasm for learning and teaching; and this atmosphere—which appears later to have waned—coupled with the requirement that he teach physics and the existence of a well-equipped laboratory, stimulated Ohm to concern himself for the first time avidly with physics. He studied the French classics—at first Lagrange, Legendre, Laplace, Biot, and Poisson, later Fourier and Fresnel —and, especially after Oersted’s discovery of electro-magnetism in 1820, did experimental work in electricity and magnetism. It was not until early in 1825, however, that he undertook research with an eye toward eventual publication. On 10 August 1826 Ohm was granted a year’s leave of absence, at half pay, to go to Berlin to continue this work. When his leave ended in September 1827, he had not yet attained his fervently sought goal of a university appointment.

Not wishing to return to Cologne, Ohm formally severed his connections there in March 1828 and accepted a temporary job to teach three recitation classes of mathematics a week at the Allgemeine Kriegsschule in Berlin. Sometime during 1832 he also took on a class at the Vereinigte Artillerie- und Ingenieurschule there. Continuing to find all higher academic doors closed to him in Prussia, Ohm hoped to have better luck in Bavaria; but although his ample qualifications were duly recognized, he could elicit no better offer (18 October 1833) than the professorship of physics at the Polytechnische Schule in Nuremberg, a job that brought him no improvement over his previous circumstances except the desirable title of professor.

Finally Ohm began to receive belated official recognition of the importance of his earlier work: he became a corresponding member of the Berlin (1839) and Turin (1841) academies, and on 30 November 1841 he received the Royal Society’s Copley Medal. He became a full member of the Bavarian Academy in 1845 and was called to Munich on 23 November 1849 to be curator of the Academy’s physical cabinet, with the obligation to lecture at the University of Munich as a full professor. He did not receive the chair of physics until I October 1852, less than two years before his death.

Ohm’s first work was an elementary geometry text, *Grundlinien zu einer zweckmässigen Behandlung der Geometrie als höheren Bildungsmittels an vorbereitenden Lehranstalten* (Erlangen, 1817), which embodied his ideas on the role of mathematics in education. The student, he believed, should learn mathematics as if it were the free product of his own mind, not as a finished product imposed from without. Ideally, by fostering the conviction that the highest life is that devoted to pure knowledge, education should create a self-reliance and self-respect capable of withstanding all vicissitudes in one's external circumstances. One detects in these sentiments the reflection not only of his own early education but also of the years of isolation in Switzerland and of personal and intellectual deprivation at Bamberg. The resulting inwardness of Ohm's character and the highly intellectualized nature of his ideals of personal worth were an essential aspect of the man who would bring the abstractness of mathematics into the hitherto physical and chemical domain of galvanic electricity.

Ohm's decision in 1825 to undertake, and publish, the original research that was to immortalize his name was made only after he had become convinced that his life had run into a dead end, that he must extricate himself from what had become a stultifying situation at Cologne. Overburdened with students, finding little appreciation for his conscientious efforts, and realizing that he would never marry, he turned to science both to prove himself to the world and to have something solid on which to base his petition for a position in a more stimulating environment. (Similarly, the occasion for the publication of his geometry book had been the desire to leave Bamberg.)

Ohm's first scientific paper was "Vorläufige Anzeige des Gesetzes, nach welchem Metalle die Contaktelektricität leiten" (May 1825).[1] In it he sought a functional relationship between the decrease in the electromagnetic force exerted by a current-carrying wire and the length of the wire. A brief discussion of his procedure is necessary to understand his results and their implications for his further work. From the zinc and copper poles of a voltaic pile he ran two wires, *A* and *B*, the free ends of which terminated in small mercury-filled cups, *M* and *N*; between *M* and another cup, *O*, he ran a third wire, *C*. Together *A, B,* and C formed what he called the "invariable conductor," to distinguish it from one of the seven wires of different lengths that, when placed in the circuit between *O* and *N*, constituted the "variable conductor." Among the latter was one "very thick" wire, four inches long, and six thinner ones, 0.3 line (.025″) in diameter, ranging in length from one foot to seventy-five feet. Finally, over wire C hung the magnetic needle of a Coulomb torsion balance, which served to measure the electromagnetic force exerted when one of the variable conductors completed the circuit.

Ohm referred all his force readings to the so-called normal force produced by the short, thick wire and chose as his variable the loss in force (*Kraftverlust*) brought about by one of the six longer and thinner test wires. This loss in force was equal to the difference between the normal force and the lesser force occasioned by one of the other wires, divided by the normal force. Tabulating these values against the lengths of the wires, he found that his data were well represented by the formula $v = 0.41 \log (1 + x)$, where v is the loss in force and x is the length of the wire in feet. (This seems to have been a purely empirical fit to his data.) Differentiating this equation—whereby he apparently forgot he was using common logarithms—to get $dv = m\, [dx/(1 + x)]$, Ohm then speculated that its general form might be $dv = m\, [dx/(a + x)]$; a would represent the equivalent length of the invariable conductor (which in the previous case by chance had been equal to 1). Hence the general equation, ignoring an additive constant, is $v = m \log (1 + x/a)$, which he found quite well confirmed by subsequent experiments and took as the sought-for law. Ohm believed that the coefficient m was a function of the normal force, the thickness of the wire, the value of a, and the "electric tension of the force." He seems actually to have believed that the loss in force would be total (that is, $v = 1$) for a sufficiently long conductor, as required by his formula. One of the striking features of this and Ohm's other early papers was their direct foundation on experiment. Indeed, several could be taken as models of inductive derivation of mathematical laws from empirical data. In his mature work of 1827, however, Ohm, under the influence of Fourier, adopted a highly abstract theoretical mode of presentation that obscured the theory's close relationship with experiment.

It is not obvious why Ohm chose to measure the loss in force and not the force itself. It should be noted, however, that he nowhere spoke of measuring the current; rather, he wanted to find out by what amount the electromagnetic force exerted by a given conductor was weakened when another, longer conductor was placed in the same circuit. From the beginning he sought a law that would elucidate the complex relationship between battery and conductor, and it is possible that he regarded the progressive attenuation of the battery's force by ever longer conductors as the central phenomenon to be explained. In this regard it is significant that three of Ohm's cryptic references to his formula's applicability were to the behavior of different forms of the pile; the other reference was to a series of experiments in which Poggendorff had shown that the magnifying effect of a multiplier eventually reached a limit as the number of turns—and thereby also the length of the conductor—was increased.[2]

In the same month that Ohm's first paper was published (May 1825) there appeared an extract in Férussac's *Bulletin des sciences mathématiques* of A.-C. Becquerel's and Barlow's work on the electric conductibility of metals.[3] Becquerel, like Davy before him. was primarily interested in comparing the "conducting powers" of different wires.[4] Their findings were similar: Becquerel said that to obtain the same conductibility with wires of the same metal, their lengths should be in the same ratio as their cross sections; Davy had said that the conducting powers of wires of the same metal varied directly with their mass (per unit length) and inversely with their length. Each also determined the relative conductibility of different metals, although their results differed markedly. Whereas neither Becquerel nor Davy actually measured anything like the current or the electromagnetic effect—both preferring an equilibrium or null-effect type of experiment —Barlow sought a direct relationship between current intensity, as measured by the deflection of a magnetic needle, and the length and diameter of the conductor. He found that this intensity varied roughly with the inverse square root of the length of the wire and that, for wires all of the same length, it increased with their diameters only up to a certain point, after which any further increase in the diameter of the wire had no effect on the intensity.

Additional experiments by both Barlow and Becquerel had corroborated that the electromagnetic effect did not vary sensibly at different points along the same wire, thereby proving that something having to do with the current remained constant throughout the circuit. Barlow had expected to find a steady diminution of effect either from the positive pole to the negative or from both poles toward the center, and thereby to be able to decide in favor of either the one-fluid or the two-fluid theory of electricity; hence the apparent inconclusiveness of this experiment puzzled him. Becquerel, however, used the same observation, in conjunction with his finding that conductibility decreased with length, in his explanation of the nature of the electric current. He conceived of it as a double stream, going in opposite directions, of positive and negative electricity, such that the intensity or quantity of each—Becquerel was not precise in his distinctions—decreased arithmetically from its pole of origin, resulting in a constant net current at all points. This conjecture, along with Becquerel's original observation that the electromagnetic effect did not vary over the length of the conductor, may have influenced Ohm's subsequent work. In it Ohm clarified with mathematical precision exactly what remained constant (the current) and what gradually decreased (the tension, or electroscopic force) along a conducting wire. At the least Ohm now took it upon himself to eliminate the discrepancies among these related findings. His suspicion, subsequently disproved, that conductibility varied with the strength of the current, made it all the more natural for him to incorporate the force into the relationship for conductibilities.

In February and April 1826, Ohm published two important papers that dealt separately with the two major aspects of his ultimately unified theory of galvanic electricity. The first, "Bestimmung des Gesetzes, nach welchem Metalle die Contaktelektricitä leiten, nebst einem Entwurfe zu einer Theorie des Voltaischen Apparates und des Schweiggerschen Multiplicators," announced a comprehensive law for electric current that brought order into the hitherto confused collection of phenomena pertaining to the closed circuit, including the solution to the problem of conductibility as he and others had conceived of it.[5] The second paper, "Versuch einer Theorie der durch galvanische Kräfte hervorgebrachten elektroskopischen Erscheinungen," broke new ground in associating an electric tension with both open and closed galvanic circuits.[6]

Ohm's experimental procedure in the first of these papers was analogous to that which he had used earlier but was modified in several significant ways. First, at Poggendorff's suggestion he now used a thermoelectric pile in order to eliminate the fluctuations in current strength accompanying the voltaic pile, fluctuations that Ohm attributed to changes produced by the current in the distribution *(Vertheilung)* of the components of the liquid conductor. Second, he sought a direct relationship between the electromagnetic force of the current and the entire length of the connecting wire. Although there is some evidence that Ohm may have been in possession of his new, correct law before he undertook this later series of experiments, he presented it as if it were a straightforward induction from his data and later consistently referred to it as having been derived from his experiments.

Be that as it may, in the paper in question Ohm simply observed that the data from each of his several series of experiments were very closely represented by the formula $X = a/(b + x)$, where X is the strength of the electromagnetic effect—which he took as a measure of the electric current—of a conductor of length x on the magnetic needle of a Coulomb torsion balance, and where a and h are constants the exact nature of which he proposed to determine from additional series of carefully controlled experiments. The observation that b remained constant for all series of experiments, whereas a varied with temperature, led Ohm to conclude that a depended solely on the electromotive force *(erregende Kraft)* of the pile and b solely on the resistance *(Leitungswiderstand* or, more commonly, *Widerstandslänge)* of the remaining portion of the circuit, in particular that of the pile itself. He also observed that the electromotive force of the thermoelectric pile appeared to be exactly proportional to the temperature difference at its end points. This process of reasoning back and forth between the experimental data and their mathematical representation, through which he was able to discover the physical significance of the terms, is a characteristic of Ohm's methodology.

After reconfirming the validity of his law by further series of experiments, Ohm exhibited its explanatory powers on some of the chief unsolved problems which had occupied scientists working on the pile; and he showed how it also cast light on a number of other previously reported but poorly understood experimental findings. For example, he was able to explain the apparent differences in behavior between voltaic and thermoelectric pile by pointing out that although both the electromotive force a and the resistance b are normally much greater in the voltaic pile than in the thermoelectric pile, the current in a circuit composed solely of a thermoelectric element bent back upon itself—for which $x = 0$ in the expression $a/(b + x)$ —could exert just as great an electromagnetic effect as the voltaic pile. According to Ohm's formula, however, the introduction of another conductor into each circuit would result in a relatively much greater diminution in the electromagnetic effect of the thermoelectric circuit than of the hydroelectric circuit, which was known to be the case. It had previously seemed anomalous that of two piles capable of registering the same electromagnetic action, one, the thermoelectric, should be incapable of producing either chemical actions or the ignition of fine wires. Such differences had either been attributed to a qualitative difference between electricities stemming from different sources or had been explained by saying that the electricity produced by the thermoelectric pile was greater in quantity but lower in intensity relative to that of the hydroelectric, or voltaic, pile. In addition, Ohm developed a simple mathematical theory of the multiplier that enabled him to say under exactly what conditions it would either amplify or diminish the electromagnetic effect, why this amplification eventually reached a maximum, and why the multiplier usually seemed to weaken the electromagnetic effect of a thermoelectric circuit, whereas it markedly strengthened that of a hydroelectric circuit. The fruitful application of Ohm's simple law to existing problems was an explanatory tour de force.

Ohm's second major paper of 1826 announced the beginnings of a comprehensive theory of galvanic electricity based, he said, on the fact that the contact of heterogeneous bodies produced and maintained a constant electric tension *(Spannung)*. He deferred the systematic exposition of this theory to a later work, however, and limited himself to stating without derivation the two equations that constituted its heart: $X = kw(a/l)$ and $u - c = \pm(x/l)a$, where X is the strength of the electric current in a conductor of length l, cross section w, and conductibility *(Leitungs-vermögen)* k produced by a difference in electric tension a at its end points; where u is the electroscopic force at a variable point x of the conductor; and where c is a constant independent of x. By means of the first equation one can, with respect to overall conducting power (or resistance), reduce the actual length of a wire of whatever cross section and conductibility to the equivalent length of one wire chosen arbitrarily as a standard. Letting l now be this equivalent length—called the reduced length *(reducirte Länge)* of the conductor—Ohm wrote his first law in the simpler form $X = a/l$, the expression which has become known as Ohm's law.

After pointing out briefly how this law, which corresponded to the one he had developed in his previous paper, embraced his and others' findings on the conductibility of different wires, Ohm devoted the rest of the paper to developing the implications of the second, electroscopic law and to comparing these implications with previously known facts. In this work he showed that his formula successfully explained those experiments which measured the electroscopic force at different points (especially the poles) of open and closed, and grounded and ungrounded, circuits. Here again the explanatory power of his law was impressive.

The fully developed presentation of his theory of electricity appeared in Ohm's great work, *Die galvanische kette, mathematisch bearbeitet* (Berlin, 1827). Hoping to make the book more accessible to the mathematically unsophisticated, he devoted the first third of it to an introduction in which he attempted an essentially geometric presentation of his theory. The introduction, which contained a discussion of the theory's success in explaining the property of conductibility, the phenomena of the pile, and the behavior of the electromagnetic multiplier, was virtually the only part of the book in which he referred explicitly to the theory's very close connections with experiment. But in neither the introduction nor in the body of the work, which contained the more rigorous development of the theory, did Ohm bring decisively home either the underlying unity of the whole or the connections between fundamental assumptions and major deductions. For example, although his theory was conceived as a strict deductive system based on three fundamental laws (*Grundgesetze*), he nowhere indicated precisely which of their several mathematical and verbal expressions he wished to be taken as the canonical form. The following exposition, although simplified by the omission of steps in the derivation and of the theory's more specialized developments, follows the letter of Ohm's work as it attempts to provide a clearer synopsis than is sometimes afforded by the book.

As a preliminary to the formulation of his fundamental laws, Ohm defined the electroscopic force operationally as that force the presence of which was detected by means of an electroscope, and the quantity of electricity of a body as the product of the magnitude of its electroscopic force times its volume. These definitions, in the context of the larger theory, gave the previously vague but universally used notions of intensity and quantity of electricity a precise interpretation.

Ohm's first *Grundgesetz* pertained to the communication of electricity from one body to another, and it involved the explicit assumption that the quantity of electricity communicated was proportional to the difference in the bodies' electroscopic force, an assumption the validity of which would be proved by the subsequent correspondence between theory and experiment. This hypothesis, coupled with the definition of conductibility as the quantity of electricity transferred per unit time across a unit distance, led directly to the expression

(1)

for the quantity of electricity communicated in time dt between two bodies of electroscopic force u' and u, separated by a distance s where k is the conductibility relative to these bodies. This may be taken as the mathematical expression of his first fundamental law.

Ohm's second *Grundgesetz*—which he based on the results of experiments Coulomb had done on the loss into the surrounding air of the electricity of a charged body—declared that, for an infinitesimal slice of thickness dx of a current-carrying conductor of circumference c, this loss across the surface in the time interval dt was proportional to that time, to the electroscopic force of the slice, and to its surface area, or to

(2) $bcudxdt$

where b is a constant dependent only on the condition of the air. As Ohm himself observed, this law has little or no applicability to galvanic phenomena; it was included for the sake of completeness and to maintain the desired parallelism between the fundamental equations of electricity and heat.

Ohm's third *Grungesetz* embodied the fundamental tenet of the contact theory of electricity by asserting that heterogeneous bodies in contact maintain a constant difference in electroscopic force (tension) across their common surface. Mathematically,

(3) $(u) - (u') = a,$

where the parentheses simply indicate that the quantities they enclose are to be evaluated at the common surface between the two conductors, and where a is the magnitude of the constant difference. This fact he considered to be the basis (*Grundlage*) of all galvanic phenomena.

Ohm derived several important results directly from the first fundamental law. Applying it to three infinitesimal slices M', M,and M, of a homogeneous prismatic current-carrying conductor, the quantities of electricity transferred from M' to M, and from M, to M, are

(4)

respectively, where u', u and u are the electroscopic force and $x+dx$, $x$and $x-dx$are the abscissas of M', M, and M,. Hence the total increase in the quantity of electricity of slice M is $[k(u' + u,-2u)dt]/dx$which, by means of the Taylor series expansions for u' and u,, can be written as

(5)

where the conductibility k has now been referred to unit cross section, ω being the cross section of the conductor. Furthermore, observing that each of the expressions in (4) is individually equal to $k\omega(du/dx)dt$, Ohm defined the electric current S as the quantity of electricity passing through a given cross section of the conductor in unit time, and wrote

(6)

which related the current directly to the (change in) electroscopic force. He then used this equation as the basis of the important condition for the continuity of current between two conductors,

(7)

where the parentheses have the same meaning as in (3).

The total change in the quantity of electricity of an infinitesimal slice of conductor is found by adding expressions (2) and (5). But, from the definition of quantity of electricity, this change is just equal to $\omega(du/dt)dxdt$—which quantity must, however, be multiplied by a factor γ, analogous to the coefficient for heat capacity, if equal changes in electroscopic force are not always accompanied by equal changes in the quantity of electricity. From these considerations Ohm derived the important general equation

(8)

Although Ohm solved this equation in its full generality, as well as for the steady-state case when $b \neq 0$ (that is, when the influence of the air may not be ignored), the only really useful solution was for the steady-state case when $b \neq 0$, Under these conditions the equation reduces to $0 = d^2u/dx^2$ the general solution of which is

(9) $u = fx + c$.

For the idealized case of a simple circuit composed of a conductor of length l, bent back upon itself so that the cross sections at $x = 0$ and $x = l$ are in contact, and of a single source of tension (*Erregungs-stelle*) located at this common point, equation (3), taken in conjunction with (9), implies that

$(u)_{x=1} - (u)_{x=0} = f \cdot l - f \cdot 0 = a.$

Hence $f = a/l$; and for this simple circuit

(10) $u = (a/l)x + c,$

where the constant c is determined whenever the electroscopic force at any one point is known—as, for example, by the circuit's being grounded.

In a derivation too lengthy to recapitulate here, Ohm showed that equation (10) can be generalized to circuits composed of any number of different conductors and sources of electromotive force, for which

(11) $u = (A/L)y - O + c,$

where A is the sum of the tensions of all sources of electromotive force; L is the total reduced length of the entire circuit; y is the so-called reduced abscissa, equal to the reduced length of that portion of the circuit between the origin and the point in question; and O is the sum of the tensions of all sources lying between the origin and that point.

Now from equations (6) and (11) one has

As Ohm showed from the (here omitted) derivation of equation (11), dy/dx, which simply relates the change in reduced length to the change in real length of the conductor, is just equal to $1/k\omega$. Hence

(12) $S = A/L$.

This equation—which is, again, Ohm's law as we know it—states that the current in a galvanic circuit is constant across all cross sections and is equal to the sum of all the tensions divided by the total reduced length of the circuit.

Equations (11) and (12) epitomize the theory as it pertains to the electroscopic and current manifestations of the galvanic circuit, respectively. Ohm's major conceptual originality lay in explicating the intrinsic relationship between tension and current, and in associating a varying electric tension, or electroscopic force, with each point of a current-carrying wire. The relationship between these two classes of phenomena had at best been obscure when, as was often the case, they were not regarded as mutually exclusive. This belief was, however, not without foundation, since in general one had been able to measure the electric tension of a pile only when no current flowed. Earlier experiments of Erman, Ritter, and C. C. F. Jäger, to which Ohm referred, had demonstrated not only the presence of an electroscopic force at the poles of a pile closed by means of a poor conductor (such as water) but also the progressive decrease in this force from the poles toward the center of the connecting conductor.[7] To the extent to which these experiments had not simply been forgotten, however, they were thought inapplicable to the case of metallic conduction because of the traditional classification of substances into perfect, imperfect, and nonconductors, each with its own peculiar characteristics. To Ohm, who had the mathematical physicist's tendency to regard properties less as an "either-or" of some quality than as a "more-or-less" of some quantity, such distinctions could have no intrinsic validity; and he did not hesitate to apply to metals findings originally restricted to imperfect conductors.

It was not a matter of casual importance that Ohm regarded the force arising at the contact surface of heterogeneous substances as the cardinal fact and starting point of his theory, for his acceptance of the contact theory of electricity was probably crucial to the genesis of his own theory. It was the contact theory that asserted the existence of an impulsive electromotive force, and it was this electromotive force (of the closed pile) which Ohm identified conceptually with the electroscopic force (of the open pile). Measurement of the electric tension of the open pile (while no current flowed and no chemical activity took place) by means of an electroscope was one of the foundation stones of the contact theory, as was the fact that this tension increased as the number of metallic couples was increased. Indeed, the very existence of such an additive electromotive force was an acute embarrassment to the defenders of the chemical theory of the pile, who consequently tended to play down the very phenomena from which Ohm borrowed one of his central concepts.

Ohm structured his theory in conscious imitation of Fourier's *Théorie analytique de la chaleur* (1822), a fact that may have induced him to deemphasize its experimental side in favor of an abstract deductive rigor, in striking contrast with the inductivist tone of his earliest papers. In particular his basic expressions for the conduction of electricity through a solid (1) and for the loss of electricity from the surface into the air (2), as well as his resulting general equation (8), are exactly analogous to Fourier's equations for the motion of heat. Although he did not spell out just how, Ohm wished the analogy between electricity and heat to be taken seriously, not as something merely coincidental but as revealing some underlying relationship. It is possible that Seebeck's thermoelectric pile had powerfully suggested the intimate relationship between the two phenomena that Ohm endeavored to exploit in his own theory.

Although Ohm's work was not immediately and universally appreciated even within Germany—largely because the majority of German physicists in 1827 represented a soon-to-be-superseded nonmathematical approach to physics—already by the early 1830's it was beginning to be used by all the younger physicists working in electricity: Gustav Theodor Fechner gave Ohm's theory a prominent place in his *Lehrbuch des Galvanismus und der Elektrochemie* (Leipzig, 1829) and subjected it to rigorous experimental testing (and confirmation) in his *Massbestimmungen über die galvanische Kette* (Leipzig, 1831); Heinrich Friedrich Emil Lenz used it in his first paper on electromagnetic induction, "Über die Gesetze nach welchen der Magnet auf eine Spirale einwirkt wenn er ihr plötzlich genahert oder von ihr entfernt wird und über die vortheilhafteste Construction der Spiralen zu magneto-electrischem Behufe," read on 7 November 1832;[8] Wilhelm Eduard Weber and Karl Friedrich Gauss used it from 1832–1833 in connection with their investigations on terrestrial magnetism and their construction of precision instruments; and Moritz Hermann Jacobi became familiar with it sometime after 1833 and used it in his first appreciable publication, *Mémoire sur l'application de l'Électro-Magnétisme au Mouvement des Machines* (Potsdam, 1835). On the other hand, the question of how fast Ohm's work became known and appreciated by the majority of scientists who were not particularly concerned with that branch of physics has still to be answered. One would like to know, for instance, how soon it entered the textbooks; suggesting its rather quick adoption was its inclusion in the *Supplementband* (Vienna, 1830–1831) to Andreas Baumgartner's *Naturlehre* (a popular text that went through eight editions between 1824 and 1845), although it remains to be seen whether this example was typical. English and French physicists seem not to have become aware of Ohm's work and its profound implications for electrical science until the late 1830's and early 1840's.[9]

It has been repeatedly asserted ever since the middle of the last century that Ohm's work had to await the recognition of foreign scientists around 1840 before it became well known in Germany. Insofar as his fame among the larger scientific and nonscientific community is concerned, there may be some truth to that assertion. However, by then his work had already been used by those working in electricity who should have appreciated it, at least among the scientists born after 1800. Nor does that traditional explanation gain plausibility from the observation that in the nineteenth century the notion had become a commonplace in Germany that Germans only esteemed what came from abroad, hence the uncritical commentator had a familiar and convenient dictum ready at hand to explain a complex situation.[10] The issue of the acceptance of Ohm's work by contemporary scientists has been further confounded with his lack of success in securing an academic appointment. In connection with the latter, to make matters worse, the fact that his chief adversaries in Berlin—Johannes Schulze, a powerful figure in the ministry of education, and Georg Friedrich Pohl, professor of physics at the Friedrich-Wilhelms-Gymnasium—were followers of Hegel and of *Naturphilosophie* has wrongly been taken as characteristic of the general situation in German physics. And even this confrontation was not simply a matter of ideologies: Martin Ohm, several years before, had incurred

Schulze’ dislike and had gained the reputation in Berlin of being a dangerous revolutionary because of his criticisms of the educational system; among his suggestions for reform had been the use of his brother’ geometry text, which did not find favor in Berlin.

NOTES

1. In Schweigger’s *Journal für Chemie und Physik*, **44** (1825), 110–118. Also in Poggendorff’ *Annalen der Physik und Chemie*,**4** (1825), 79–88.

2. J. C. Poggendorff, “Physisch-Chemische Untersuchungen zur nähern Kenntniss des Magnetismus der voltaischen Säule,” in *Isis von Oken* (1821), **2** (9 in the series), no. 8, cols. 687–710.

3. A.-C. Becquerel, “Du pouvior conducteur de l’électricité dans les métaux, et de l’intensité de la force électro-dynamique en un point quelconque d’un fil métallique qui joint les deux extrémités d’une pile lu è l’Académie royale des sciences le 31 Janvier 1825,” in *Annales de chimie et de physique*, **32** (Aug. 1826), 420–430; and Peter Barlow, “On the laws of Electro-Magnetic Action, as Depending on the Length and Dimensions of the Conducting Wire, and on the Question, Whether Electrical Phenomena Are Due to the Transmission of a Single or of a Compound Fluid?” in *Edinburgh Philosophical Journal*, **12** , no. 23 (Jan. 1825), 105–114. Extracts of these, which Ohm saw, appeared in *Bulletin des sciences mathématiques, astronomiques, physiques et chimiques*, **3** , no. 5 (May 1825), 293–296 and 296–298, respectively.

4. Humphry Davy, “Farther Researches on the Magnetic Phaenomena Produced by Electricity; With Some New Experiments on the Properties of Electrified Bodies in Their Relations to Conducting Powers and Temperature,” in *Philosophical Transactions of the Royal Society*, **111** (1821), 425–439. Ohm knew the German trans. in Gilbert’s *Annalen der Physik*, **71** (1822), 241–261.

5. In Schweigger’s *Journal für Chemie und Physik*, **46** (1826), 137–166.

6. In Poggendorff’s *Annalen der Physik und Chemie*, **6** (18260, 459–469; *ibid.*, 7(1826), 45–54, 117–118.

7. Paul Erman, “Ueber die electroskopischen Phänomene der Voltaischen Säule,” in Gilbert’ *Annalen der Physik*, **8** (1801), 197–209; and “Ueber die electroskopischen Phänomene des Gasapparats an der Voltaischen Säule,” *ibid.*, **10** (1802), 1–23; J. W. Ritter, “Versuche und Bemerkungen über den Galvanismus der Voltaischen Batterie.…Dritter Brief,” *ibid.*, **8** (1801), 385–473; C. C. F. Jäger, “Ueber die electroskopischen Aeusserungen der Voltaischen Ketten und Säulen,” *ibid.*, **13** (1803), 399–433. Even the recent experiment of Ampère and Becquerel had left open the question of whether tension was associated with complete conduction by metals, since they too detected a tension only at the poles of a pile closed by means of a so-called incomplete conductor; see “Note sur une Expérience relative à la nature du courant électrique, faite par MM. Ampére et Becquerel,” in *Annales de chimie et de physique*, **27** (Sept. 1824), 29–31.

8.*Mémoires de l’Acdémie impériale des sciences de*St.-pétersbourg, 6th ser. Sciences mathématiques, physiques et naturelles, **2** (1833), 427–457; repr. in Poggendorff’s *Annalen der Physik und Chemie*, **34** (1835), 385–418; and trans. in Taylor’s Scientific Memoirs, **1** (1837), 608–630.

9. The first exposition of Ohm’s work in French that I know of was Élie Wartmann, “Des travaux et des opinions des Allemands sur la pile voltaïque,” in *Archives de* l’électricité, **1** (1841), 31–66, followed by Auguste de la Rive, “Observations sur l’article de M. Wartmann …,” *ibid.*, 67–73.

10. See, for example, *Schweigger’s Journal für Chemie und Physik***10** (1814), 355; **23** (1818), 372; **33** (1821), 20; and Poggendorff’s *Annalen der Physik und Chemie*, **3** (1825), 191. Leibniz’ comment on his countrymen, “nil nisi aliena mirantur,” was often cited to support the generality of this supposed nationality trait.

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The 1st ed. of *Die galvanische Kette* has been reprinted in facs. (Brussels, 1966). It was translated into English by William Francis as "The Galvanic Circuit Investigated Mathematically," in R. Taylor, J. Tyndall, and W. Francis, eds., Scientific Memoirs, *Selected From the Transactions of Foreign Academies and Learned Societies and from Foreign Journals*, **II** (London, 1841), 401–506, and later reprinted (New York, 1891), no. 102 in the Van Nostrand Science Series. There is a French ed., *Théorie mathématique des courants électriques*,translated with preface and notes by Jean-Mothée Gaugain (Paris,1860); and an Italian one (not seen), "Teoria matematica del circuito galvanico," in *Cimento* (Pisa),**3** (1845), 311–348; **4** (1846), 85–96, 169–183, 246–266. A very useful and informative source is *Aus Georg Simon ohms handschriftlichem Nachlass. Briefe, Urkunden und Dokumente*, Ludwig Hartmann, ed. (Munich, 1927), which contains much of the MS material on Ohm in the Deutsches Muséum in Munich.

II. Secondary Literature.The fullest biography is Heinrich von Füchtbauer, *Georg Simon Ohm. Ein Forscher wächst aus seiner Väter Art* (Berlin, 1939), which contains extracts of letters not available elsewhere. Also very informative is the article by Carl Maximilian von Bauernfeind in *Allgemeine deutsche Biographie*, XXIV (Leipzig, 1887), 187–203. Useful for some aspects of his background and life is Ernst G. Deuerlein, *Georg Simon Ohm 1789–1854. Leben und Wirken des grossen Physikers* (Erlangen, 1939; 2nd ed., enl., 1954). Two contemporary eulogies are valuable: Friedrich von Thiersch, "Rede zur Feier des hohen Geburtsfestes Sr. Majestät des Königs Maximilian **II** . von Bayern," in *Gelehrte Anzeigen der k. bayerischen Akademie der Wissenschaften*, **40** (Jan.-June 1855), Bulletins der drei Classen, nos. 3–4 (Jan. 5–8), cols. 26–32, 33–35 (indicated here are only those portions of the speech dealing with Ohm; the bulk of the published articles is a long footnote on Ohm by Philipp Ludwig Seidel, cols. 29–35); and Johann von Lamont, *Denkrede auf die Akademiker Dr. Thaddäus Siber und Dr. Georg Simon Ohm*…(Munich, 1855).

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