GEORG SIMON OHM AND THE FIRST COMPREHENSIVE THEORY OF ELECTRICAL CONDUCTIVITY IN METALS

This month's article focuses on the life and work of Georg Simon Ohm, an experimental physicist who is most well-known for establishing Ohm's law.

In the last decades of the 18th century and the early decades of the 19th century, electricity was a major preoccupation of physicists and men of science in general. The conduction of an electric charge traveling along a conductor had already been established by the English astronomer and physicist Stephen Gray (1666–1736) in 1729. Quantitative studies on electrical conductivity were initiated in 1747 by the Polish physicist Daniel Gralath (1708–1767) with the first trials for "weighing" the electric force with a sort of modified balance, and comparative measurements of conductivities of metallic materials including brass, copper, gold, iron, platinum, and tin were carried out since the 1770s by using instruments such as the portable quadrant electrometer devised by the Englishman William Henley (?–1779). The formal studies on current electricity were initiated after 1793 with the invention of the first primary cell by the Italian physicist Alessandro Volta (1745–1827). These were continued by others, for example, the German chemist, physicist, and philosopher Johann Wilhelm Ritter (1776–1810), who produced what can probably be considered the first dry pile and made progress in the study of the principles of electrical current distribution, which would be later perfected by his countryman Gustav Robert Kirchhoff (1824–1887).

The discovery of the magnetic effect of the electric current by Hans Christian Oersted (1777–1851) from Denmark in April 1820, the identification of the electrodynamic phenomena by the French physicist and mathematician André-Marie Ampere few months later, and the discovery of the thermoelectric effect by Thomas Johann Seebeck (1770–1831) from Estonia the following year added new ingredients to the subject. They also made it clear that a problem existed: the terms for describing current electricity were not well defined, universally agreed upon, or widely used, and there was a lack of methods of quantitative measurements. Factors playing in the galvanic circuit, such as the flow of current along the wire, the "contact force" at the terminals of the circuit, or the "electroscopic force" between any two points of the circuit, as well as the polarization of the electrodes, and the propensity of the electricity to break away into the air, had already been somehow identified, but their meaning could vary from one experimenter to another. The terms "potential" and "resistance" had not, by then, been applied to electricity, and other alternatives, such as "magnetic action of a driver" for the current, "conducting power" rather than resistance, or even sometimes "intensity" for the voltage, could indistinctly be used to represent similar concepts. Furthermore, there was no agreement among physicists about the nature of electric current: movement of intangible electric fluid, circulation of two fluids of opposite signs, or, even, step-by-step propagation of

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Fig. 1. *Georg Simon Ohm.*

a kind of polarization of particles within a conductor. Additionally, the electrometers used at that time to quantify the property were only able to evaluate, rather than to actually measure, the tendency to repulsion between the charges accumulated in the surface of a conductor.

The careful and systematic investigations of Georg Simon Ohm would contribute not only to the creation of order out of chaos, but also to providing, through the construction of a theory of circuits, answers to many questions that had puzzled earlier experimenters. In this way, he would profoundly influence the future study of electricity. This article deals with Ohm's achievements in the scientific context of his time.

I. SHORT BIOGRAPHICAL ACCOUNT

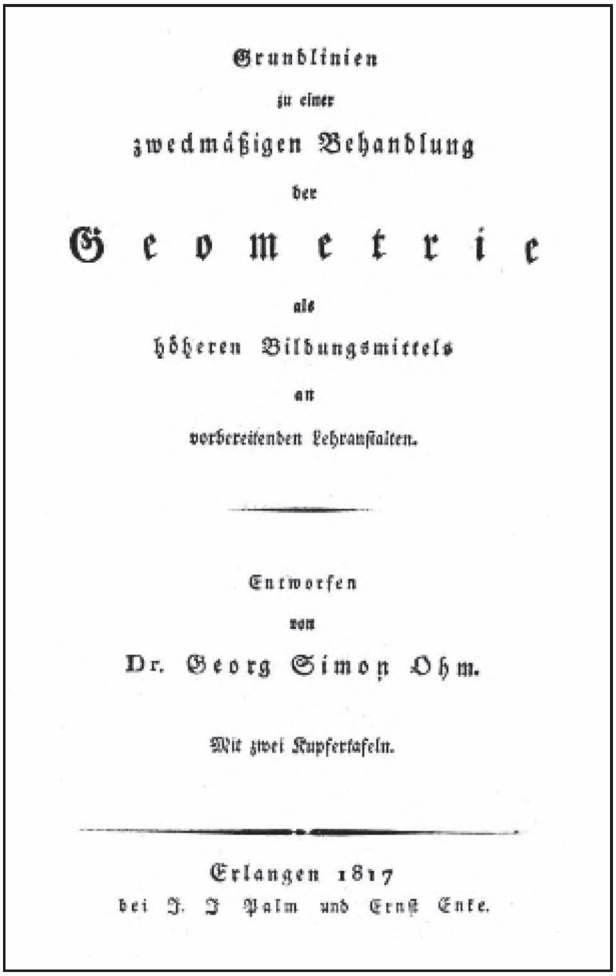
Georg Simon Ohm (christened Johann Simon) was born on March 16, 1789, in Erlangen, ten miles north of Nuremberg in Bavaria, Germany (Fig. 1). He was the oldest son of Johann Wolfgang Ohm, a master locksmith by trade, and his wife Maria Elisabeth (née Beck), a daughter of a master tailor. Of the protestant couple's seven children, only three (two boys and one girl) survived childhood. The father, a remarkable autodidact, gave his two sons, Georg and Martin (1792–1872), a solid education in mathematics, physics, and chemistry, as well as in the philosophical principles of their compatriots Immanuel Kant (1724–1804) and Johann Gottlieb Fichte (1762–1814). Martin became a mathematician and worked as a Professor of Mathematics at a military school in Berlin [1]–[3].

The outstanding abilities of young brothers became so seriously recognized that the mathematician and Erlangen Professor of Mechanics, Karl Christian von Langsdorff (1757–1834), compared them with the Bernoullis. After attending a gymnasium from 1800 to 1805, Georg entered the Erlangen University on May 3, 1805, enrolling in philosophy, but his studies were immediately directed to mathematics and physics. Lack of funds and the father's disapproval of his son's excessive involvement in dancing, billiards, and ice-skating forced Georg's withdrawal from school after just three semesters.

Two different jobs, the first one beginning at the end of September 1806, as a teacher of Latin and mathematics at a school in the village of Gottsdadt, canton of Bern in Switzerland, for two-and-half years, and the other as a private tutor at Neuchâtel for another two years, marked the initial steps of a very long road that only decades later would allow him to achieve his goal of becoming a university professor. Teaching activities were appropriately combined at that time with studies Ohm made on his own on the mathematical works of Leonhard Euler (1707–1783) from Germany and Sylvestre François Lacroix (1765–1843) from France. During Easter 1811, he returned to Erlangen, where, after having passed the required examinations, he obtained the degree of Doctor of Philosophy, on October 25 and, subsequently, joined the faculty as a mathematics lecturer. Because his new job was not well paid, Ohm was forced to use his abilities as fine draughtsman to supplement his income with other sources such as creating architectural plans for the university hospital and the library and other places.

With no possibility to direct a part of his academic activities to areas in which he was interested the most, such as physics, and particularly mechanics, light, and optics of color, and believing that he could not advance at Erlangen, Ohm left the lecturing post after three semesters and sought employment from the Bavarian government. During the next ten years he moved six times from one place to another, occupying minor posts at mediocre schools. The best posts he could obtain were as a teacher of mathematics and physics at the low-prestige and poorly attended *Realstudienanstalt* in Bamberg, where he worked with great dissatisfaction from December 16, 1812, until the school's dissolution on February 17, 1816, and as an auxiliary instructor of mathematics at the overcrowded Bamberg *Oberprimärschule* (Upper Primary School), until his release from Bavarian employment.

In spring 1817, Ohm published his first book *Grundlinien zu Einer Zweckmässigen Behand Lung der Geometrie als Höheren Bildungsmittels*



Grundlinien
zu einer
zweckmäßigen Behandlung
der
Geometrie
als
höheren Bildungsmittels
an
vorbereitenden Lehranſtalten.

Entworfen
von
Dr. Georg Simon Ohm.

Mit zwei Kupfertafeln.

Erlangen 1817
bei J. J. Palm und Ernſt Enke.

Fig. 2. *Cover page of the Ohm's text on geometry.*

an Vorbereitenden Lehranstalten (Groundwork of a Suitable Treatment of Geometry as a Means of Instruction for Preparatory Education) (Fig. 2), dedicated to the memory of his father, which was not successful. Copies were sent to the King of Bavaria and other reigning monarchs seeking possibilities of collaboration for a position at a university. King Friedrich Wilhelm III of Prussia answered favorably, and Ohm left Bavaria the next fall to accept a position as *Oberlehrer* (head teacher) in mathematics and physics at the recently reformed Jesuit Gymnasium (Royal Konsistorium) in Cologne.

The new enthusiastic atmosphere of learning, the possibility to teach physics, coupled with the existence of a well-equipped laboratory, stimulated Ohm to engage in investigations related to this area of science for the first time. The study of the French and Italian classics, such as those by Jean-Baptiste Biot (1774–1862), Joseph-Louis Lagrange (1736–1813), Pierre-Simon Laplace (1749–1827), Adrien-Marie Legendre (1752–1833), and Simeon Denis Poisson (1781–1840), followed by those by Jean-Baptiste Joseph Fourier (1768–1830) and Augustin-Jean Fresnel (1788–1827), and especially that of the discovery of electromagnetism by Oersted, influenced Ohm's first research in this last subject. His studies focused mainly on the characteristics of electric circuits, a virtually unexplored field at that time, and in which he thought he would meet less competition from other contemporaneous researchers than he would have with other topics [4].

II. FIRST PUBLICATIONS ON ELECTRICITY

At the growing and progressive Gymnasium of Cologne, Ohm's thoughts turned to research, and he was able to pursue his investigation in electricity. A fine collection of scientific instruments which the Gymnasium had built over the course of many years caught Ohm's attention. At last, he was doing the work that he felt was worthy of publication and that he hoped would gain him the recognition and the professorship he desired. In his spare time, he proceeded to experiment with current circuits containing electric batteries or, as they were called then, "galvanic chains." Very soon he began equipping his workshop to construct an apparatus not available or easy to find commercially that he required for the research he wanted to carry out. The detailed knowledge he had of his apparatuses and their capabilities and limitations very quickly complemented the knowledge he gained from regularly reading French and German journals, which informed him of what was being done in the field of electrical research.

In 1825, he published one experimental paper and two shorter notices. The initial objective was to determine the law according to which the metals conduct current electricity. The paper, simultaneously published in *Journal für Chemie und Physik* (also called the *Schweigger Journal*) and in *Annalen der Physik und Chemie* (also called *Poggendorff's Annalen*), became only the first step in his research and examined the decrease in the electromagnetic force produced by a wire as its length was increased [5], [50].

Ohm's paper was not illustrated. Fig. 3 was prepared from the description of the experimental setup in the text. The electromotive force was provided by a single chemical cell with a zinc electrode and a copper electrode in a trough 13 in high and 16 in long, being the electrolyte dilute

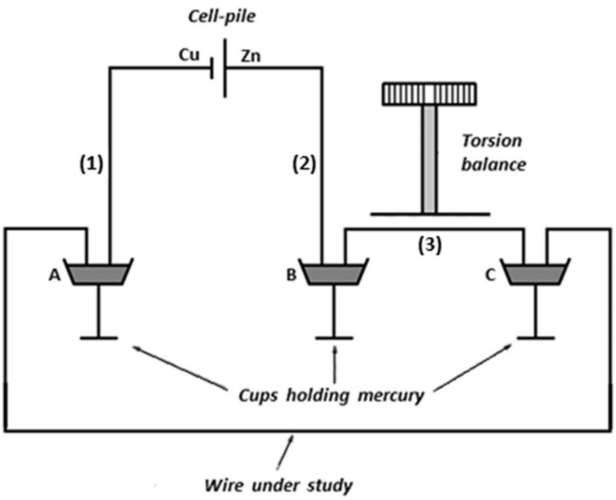


Fig. 3. *Schematic diagram of the equipment Ohm used to determine the relationship between the length of a wire and its corresponding electromotive force (adapted from [6] and [7]).*

sulfuric acid [6], [7]. The thickness of copper wires (1), (2), and (3), called "the invariable conductors," was one and one quarter lines thick (one line equaled one-twelfth of an inch) and their length totaled 4 ft. The wire to be studied, "the variable conductor," completed the circuit. Wires of six different lengths, 1/3, 1.3, 6, 10 1/3, and 25 ft, were tested.

A magnetized needle, suspended from a thin torsion wire over conductor (3) and parallel to it when no current was flowing, was used to measure the magnetic force of the current [8]. The device acted in this way as a sensitive galvanometer, following Coulomb's earlier examples of torsion balances. The current to be measured was allowed to pass through the wire, and a precision divided circle, to which the upper end of the filament was previously secured, turned so that the needle did not give deflection. The angle through which the wire must rotate measured the magnetic force acting on the needle. A magnifier helped him to set the needle in just the same parallel position every time.

Ohm found that his data could be fitted by the following logarithmic empirical relationship:

$$v = 0.41\ \log(1 + x)$$

which, after differentiation and reordering in order to obtain a better understanding of the physical meaning of its terms, became

$$v = m\ \log\left(1 + \frac{x}{a}\right)$$

where v is the "loss of force" (a term which has been interpreted differently by various historians as potential drop), x is the length of the wire in feet, and m and a are constants.

There is no explicit reference in Ohm's original papers to the employed procedure to find the equation of the line which provided the best fit to the available experimental data. The method of least squares, introduced independently by Legendre and the German mathematician Carl Friedrich Gauss (1777–1855) between 1805 and 1809 [9], dominated the theory of errors outside its field of origin (planetary mechanics) during the first quarter of the 19th century. It is very probable that Ohm, educated, as already mentioned, by his own reading of the texts of the leading French and German mathematicians, was aware of the technique and used it in the estimation of the coefficients of the equations he proposed.

Other information contained in the same paper was the preliminary announcement of his quantitative studies on the relative conductivity of brass and different pure metals such as copper, gold, iron, lead, platinum, silver, tin, and zinc, as well as the possibility he pointed out that wires of these metals having the same diameter used the same relationship, although with different constants [10].

III. A LAW IS EXPERIMENTALLY DERIVED

The experimental setup was not as stable as Ohm preferred and forced him to not make the measurements immediately and wait until the needle changed its position very slowly. There was not only a current surge every time he connected the circuit but also current reduction as the experiment proceeded due to the gas generated in the pile. He attributed the instabilities to the polarization effects on the behavior of the chemical cell. After showing that the equation failed for very long conductors, he realized the very limited range of his experiments and began to question his previously published results [11]. In addition, the equation also did not agree with conclusions based on the results of the experiments previously and simultaneously carried out by the physicists Peter Barlow (1776–1862) and Antoine César Becquerel (1788–1878) in England and France, respectively, on the same subject [12].

Johann Christian Poggendorff (1796–1967), the editor of the *Annalen der Physik und Chemie* since 1824, in a footnote appended to the Ohm's article suggested that the use of the Seebeck's recently discovered thermoelectric effect instead of the chemical electric cell could contribute to obviate these fluctuations in the force. Ohm welcomed the suggestion, making it clear that the equation must be replaced and, in December 1825, he began a new series of experiments with

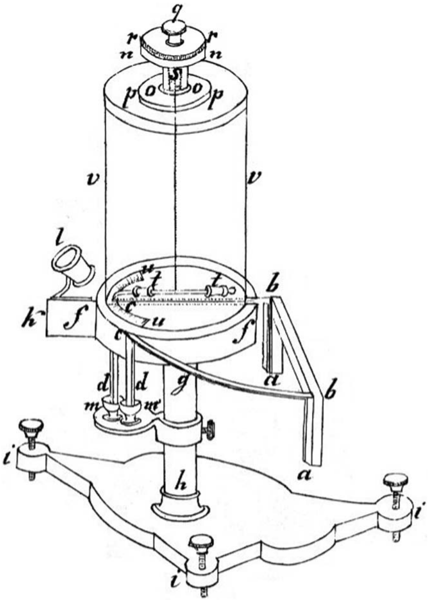


Fig. 4. *Ohm's improved apparatus.*

the steadier thermoelectric source of a copper–bismuth thermocouple, one end in ice and the other in boiling water (*aa* in Fig. 4). The potential difference was again measured by means of a Coulomb torsion balance.

Initially based on the invalid assumption that the current travels on the surface, which he did not publish in the article resulting from these experiments (and which he corrected one year later in his book on the mathematical theory of circuits), Ohm was able to derive the expression that he considered "a pure law of nature," which became the first presentation of the extremely simple law that bears his name in the rather unfamiliar form [13]

$$X = \frac{a}{b + x}$$

where X represents the intensity of the magnetic effect of the conductor wire under test whose length is x, and a and b are two constants depending upon the electromotive force and the resistance to conductivity of the other parts of the circuit, respectively (Fig. 5). While Ohm certainly did not equate a to the current electrostatic concept of potential difference, nor explicitly linked the strength of magnetic action to other variables, the above equation can be written in modern language

$$I = \frac{E}{r + R}$$

where I is current intensity, E is the battery's electromotive force, r is battery resistance, and R is circuit resistance.

The paper, 29 pages long, was published in 1826 and, even though not as well known as his book, became his most important work. It included not only the first formulation of the law, but also the data of the already mentioned relative conductivities of brass and eight pure metals. The results also helped to derive representative expressions for circuits consisting of parallel conductors and to invalidate the conclusions reached by Barlow about a supposed proportionality between the intensity of the current and the square root of length and the inverse of the area of cross section.

It has been speculated, after reviewing the above results, that scientists Henry Cavendish (1731–1810) and Humphry Davy, later Sir (1778–1829), from England, conducted experiments, many years before Ohm, where they came to a similar conclusion on which a complete discovery of Ohm's law was based. This fact, however, must not be taken seriously.

Eccentric and reclusive Cavendish devoted himself to scientific research which most results were not published and remained in his family's possession until 1879, when the papers were edited by his compatriot James Clerk Maxwell. Cavendish conducted his electrical experiments between 1771 and 1781 [14]. After demonstrating the inverse square law of electrostatic attraction, and thus anticipating Coulomb's experiment, Cavendish was responsible for carrying out the first studies on conductivity and the investigation on relating, around 1775, the "resistance" (potential difference in actual terminology) to "velocity" (or current) in a conductor. The relation of a power law he used seems to be his *a priori* assumption. By using the discharge of a Leyden jar as the source of current, condensers instead of batteries, his own body as an instrument to measure current (the galvanometer was not invented until ten years after his death), and a collection of wide and narrow glass tubes filled with a salt solution, he made four series of experiments in order to determine the index of power law. The experiment consisted in adjusting the length of the column of liquid in the tube under test until it allowed the passage of a discharge of the same strength as that through a second tube selected as a standard. With the body placed in circuit with the condenser and the test tube, the intensity of discharge was judged by his sensation of an electrical shock. The value of one found for the index of power law was only possible if the

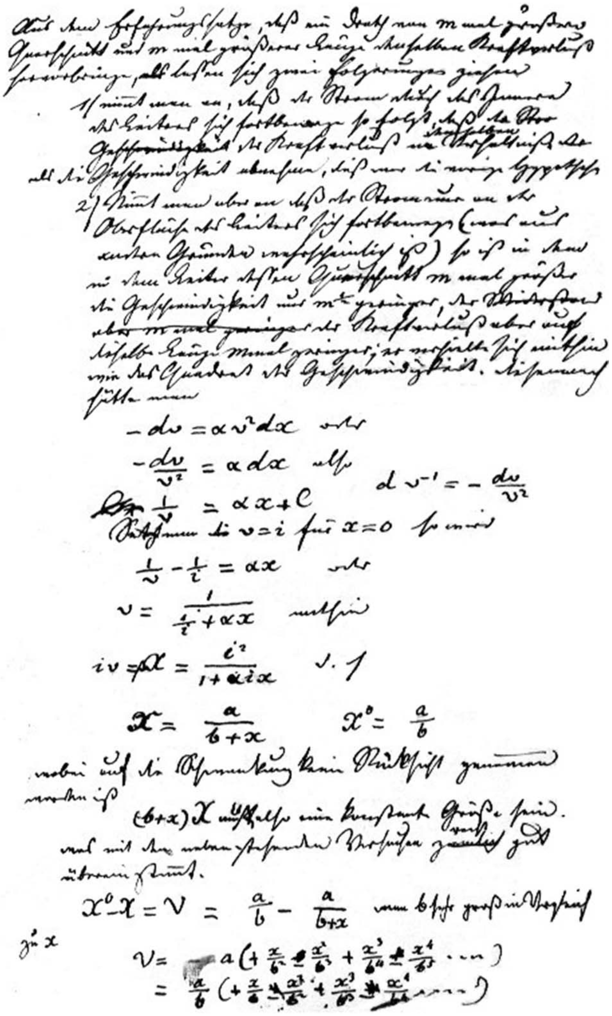


Fig. 5. *First formulation of Ohm's law in his own handwriting as it can be read in his notebooks. Credit: Archives Deutsches Museum, Munich, Germany.*

kinds of dependence of conductor length and diameter were known in advance, just like Cavendish seemed to have intuitively assumed. Cavendish did not publish these results during his lifetime, but, despite his discoveries, the absence of enough experimental support, the failure to expand the work to include conductors with sections of different shapes, and above all, the absence of the so-called steady currents provide sufficient reasons for not crediting him as the discoverer of the law.

Almost half a century later, in 1820, Davy, using for the first time steady currents, employed the technique of electrochemical decomposition to measure current by the number of cells it was capable of discharging "completely," that is, until there was no sign of gas coming out of water. He found that wires of different length discharged a different number of cells of the same pile, and he basically found the same results as Cavendish. It means that wires having the same ratio of length to cross section had the same resistance [15].

The mathematical description of conduction in circuits in Ohm's subsequent papers included the mathematical relations [16], [17], [51]

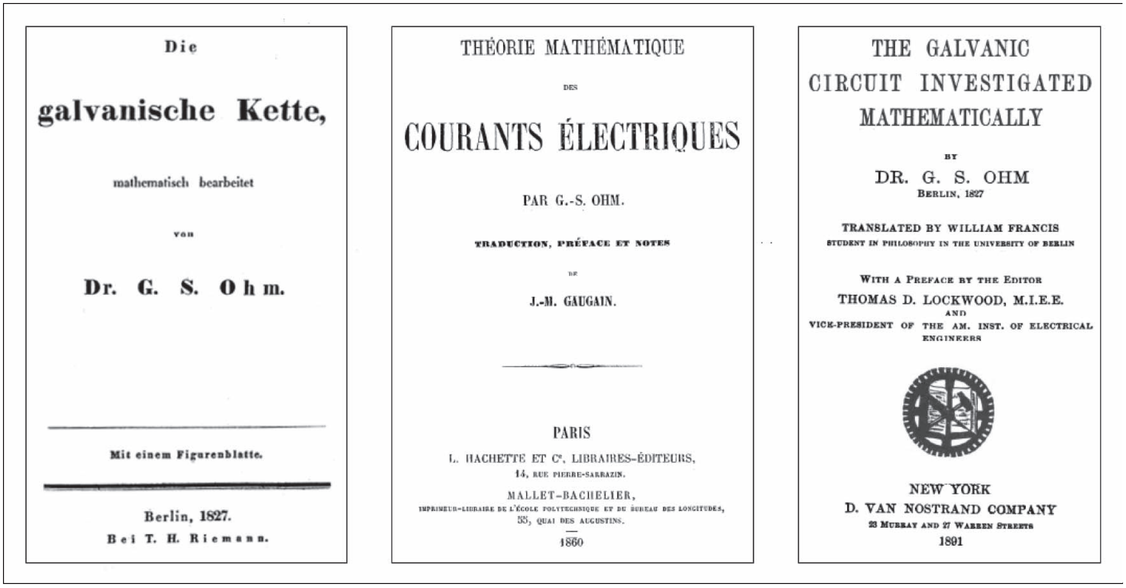
$$X = a\frac{kw}{l} \quad \text{and} \quad X = \frac{a}{L}$$

where X is again the magnetic effect of current, w and l are the-cross sectional area and the length of the wire under study, respectively, k is the conducting power of metal, and a is a constant depending, as with the other equation, upon the electromotive force. Ohm called L the reduced length (*Reduzirten Länge*) of the circuit (what is today known as resistance), which in turn was defined as the sum of *Reduzirten Länge* of all the individual parts of the circuit.

IV. A LAW IS THEORETICALLY DERIVED

Ohm feared that the purely experimental basis of his work would undermine the importance of his discovery and, in 1826, he turned to a theoretical derivation of his empirical results. A mind as his, trained and accustomed to analyzing the phenomena under study from a mathematical viewpoint, felt the necessity to show that what he had inductively recognized was deductively the consequence of simple concepts related to the flow of electricity and the behavior of conducting materials. He then applied for a year's leave of absence from the Jesuit Gymnasium in order to have sufficient time for writing. The leave was granted in summer of that year and, with one-half of his salary, Ohm moved to his brother's house in Berlin, where he had greater scientific activity and much better libraries at his disposal.

A year later, in 1827, Ohm's book, *Die Galvanische Kette, Mathematisch Bearbitet (The Galvanic Circuit Developed Mathematically)*, was published in Berlin (Fig. 6). The book presented Ohm's complete theory of electricity and highlighted the author's deep conviction of analogies and a close connection between the flow of electricity from higher to lower potentials and that of heat from high to low temperatures, the similarities between the "electroscopic force" that caused the motion of his electric fluid and temperature, as well as the



Die
galvanische Kette,
mathematisch bearbeitet
von
Dr. G. S. Ohm.

Mit einem Figurenblatte.

Berlin, 1827.
Bei T. H. Riemann.

THÉORIE MATHÉMATIQUE
DES
COURANTS ÉLECTRIQUES
PAR G.-S. OHM.
TRADUCTION, PRÉFACE ET NOTES
DE
J.-M. GAUGAIN.

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14, RUE PIERRE-SARRAZIN.
MALLET-BACHELIER,
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55, QUAI DES AUGUSTINS.
1860

THE GALVANIC
CIRCUIT INVESTIGATED
MATHEMATICALLY
BY
DR. G. S. OHM
BERLIN, 1827
TRANSLATED BY WILLIAM FRANCIS
STUDENT IN PHILOSOPHY IN THE UNIVERSITY OF BERLIN
WITH A PREFACE BY THE EDITOR
THOMAS D. LOCKWOOD, M.I.E.E.
AND
VICE-PRESIDENT OF THE AM. INST. OF ELECTRICAL ENGINEERS

NEW YORK
D. VAN NOSTRAND COMPANY
23 MURRAY AND 27 WARREN STREETS
1891

Fig. 6. *Cover pages of the Ohm's original book (in German) and its respective translations to French and English.*

decisive role of metal conductivities, electrical in one and thermal in the other, in the corresponding flows.

It was clear in the book that Ohm closely followed French mathematical physics [18]. More specifically, his mathematical description of conduction in filamentary circuits was modeled on Fourier's study on heat conduction. The fact that he was explicitly influenced by Fourier and based his own research patterns on Fourier's great mathematical classic *Théorie Analytique de la Chaleur*, published in 1822, is clearly recognized in his book: "The form and treatment of the differential equations so obtained [for conduction of electricity] is so similar to that given to us by Fourier and Poisson for the motion of heat that from this alone, even if no additional grounds existed, the conclusion might be drawn regarding an inner connection between the two natural phenomena . . ."

Taking an annulus as a good approximation to an electrical circuit, and applying Fourier's arguments, Ohm constructed a second-order, partial–differential equation for the diffusion of electricity in a conductor carrying a current. Following an approach regularly used by Fourier, Ohm divided the conductor mathematically into infinitely thin disks, and calculated the quantity of transferred electricity per unit time across the parallel surfaces and outward through the edges of the disks. The equation for the rate of change of potential with time at any point along the conductor

$$\gamma\frac{\partial u}{\partial t}=\chi\frac{\partial^2 u}{\partial x^2}-\frac{bc}{\omega}u$$

had the same form given by Fourier for heat diffusion in the same geometrically shaped thermal conductor, where several constants referred to electrical and geometrical properties of the conductor. By manipulating the solution as infinite series of sine and cosine functions with damping coefficients, Ohm was able to mathematically come to a conclusion that became his eponymous law.

One third of the 126 pages comprising the book, the "Introduction," included the mathematical background necessary for understanding the rest of the work (even for the contemporaneous leading German physicists, accustomed to the emphasis on a nonmathematical approach to physics at the time) and the exposition of the three basic postulates on which the theory was based: "the distribution of electricity within a body," and two other he called purely experimental, "the mode of dispersion of electricity in the surrounding air" and "the appearance of electricity at the contact of two heterogeneous bodies." The second part, entitled "The voltaic circuit," included a representation of the concepts supporting the essential mathematical results given previously. Finally, the third part, an appendix entitled "On the chemical power of the galvanic circuit," dealt with circuits in which current was accompanied by chemical changes.

By means of his book, Ohm considered to have presented the galvanic phenomena as a "unity of thought," in which the "torch of mathematics shines through physics, illuminating its dark places." According to his view, the mathematics possessed in this way a "new field of physics, from which it had hitherto remained almost totally excluded." "The main merit of mathematical analysis," Ohm wrote in his book, is that "it calls forth, by its never-vacillating expressions, a generality of ideas, which continually demands renewed experiments, and thus leads to a more profound knowledge of nature" [19].

V. DISAPPOINTMENT AND BELATED RECOGNITION

Copies of the book were sent to the Paris Academy of Science and to the Prussian Ministry of Education in Berlin. The latter copy was accompanied by a letter asking for a resignation from the Cologne Gymnasium, expecting the appointment to a university professorship. Instead, he was offered a position at *Allgemeine Kriegsschule* (General War School) in Berlin, teaching mathematics three days a week.

If it is true that very few scientists, such as his compatriot, philosopher, physicist, and experimental psychologist Gustav Theodor Fechner (1801–1887) and the Russian physicist and Professor at the University of Saint-Petersburg, Emil Khristianovich Lenz (Heinrich Friedrich Emil) (1804–1865), seemed to have begun to use Ohm's deductions soon after they had been published [20], the general rule was that Ohm's work failed to receive the acclaim of contemporary physicists. Ohm's theory was so unfavorably received in its first decades in Germany, that a contemporaneous journal named it "a web of naked fancies which could never find the semblance of support from even the most superficial observation of facts." "He who looks at the world," continued the writer, "with the eye of reverence must turn aside from this book as the result of an incurable delusion, whose sole effect is to detract from the dignity of nature" [21].

The different reasons proposed by historians to explain this fact range from the widespread faith in Hegelianism (*Naturphilosophie*) and its philosophical speculative postulates, much in vogue at the time, of scientific discoveries without the collaboration of matter and the corresponding experimental methods [22] to the then common impression that the law was exclusively the fruit of a theoretical deduction [23]. The radical contrast between the nature of his concepts of current and voltage and those existing in the contemporaneous structure in physics, together with the scarcity of good mathematical knowledge in Germany in the first decades of the 19th century also explained the poor reception of Ohm's work [24]. The book was in print for eight years. Its sales were so mediocre that Ohm paid his friends from outside the city to order the book in order to improve the print count.

Repeated failures to get a physics position at universities or academic institutions during the six years that followed turned Ohm into a bitter and disappointed man, but it did not stop his scientific production. In a series of articles, he revealed not only a fresh experimental proof of his law, but also the proof of Kirchhoff's law of branched currents, observations on the polarization of electrodes and the contact resistance, as well as alternative methods for determining electromotive force and electric resistances and explanations of the phenomena of unipolar conduction.

After unsuccessful attempts to receive a position in higher academics in Prussia, he returned to Bavaria, where, on July 3, 1833, King Ludwig I issued a decree by which he was finally given a professorship at the Polytechnic Institute of Nuremberg (currently the Nuremberg Institute of Technology Georg Simon Ohm). Ohm remained there for the next 15 years, alternating his teaching responsibilities and those occasional as a Rector there, with the corresponding services as Inspector of Scientific Education for the Bavarian State.

The recognition, although late, came gradually. Between 1831 and 1837, the French Professor of Physics at the Sorbonne and member of the French Academy of Science, Claude Servais Mathias Pouillet (1790–1868), experimentally confirmed Ohm's results and improved the law's accuracy by measuring weak currents with his tangent and sine galvanometers. Poulliet believed that Ohm had only deduced the famous relation mathematically from certain hypothetical premises, which led to a temporal confusion, mainly in France, about the real discoverer of the law. Some years later, in 1841, *Die galvanische Kette* would become the first work on an electrical subject to be translated into English under the auspices of a committee appointed by the British Association for the Advancement of Science to superintend the publication of foreign scientific memoirs. One of the members of the committee was Charles Wheatstone (1802–1875), inventor and then Professor of Physics at the University College London. Wheatstone, who had read Ohm's work, recognized that the non-yet then understood and accepted principles established by the German scientist were a key to solve his own research problem on electric telegraphy, which was finding the best circuit configuration for producing electrical effects over long distances [25]. The book was translated into Italian in 1847 and into French in 1860.

In November 30, 1841, the Royal Society, at its annual meeting, conferred Ohm the Copley Medal for his discovery in the domain of the exact investigation, and, particularly, for his research into the laws of electric currents. In granting this medal, the Council of the Royal Society pointed out not only the importance of the relationship Ohm established among three fundamental electric variables, irrespective of the nature of the source of the current, but also the clarification of the difference he made between current, or current intensity (term originated from the old French *intensité de courant*) and current density. One year later, Ohm was appointed Foreign Member of the Society, an honor received by only one German, Gauss, before that date. In 1839, he was elected a Corresponding Member of the Berlin Academy, and two years later a Corresponding Member of the Turin Academy in Italy.

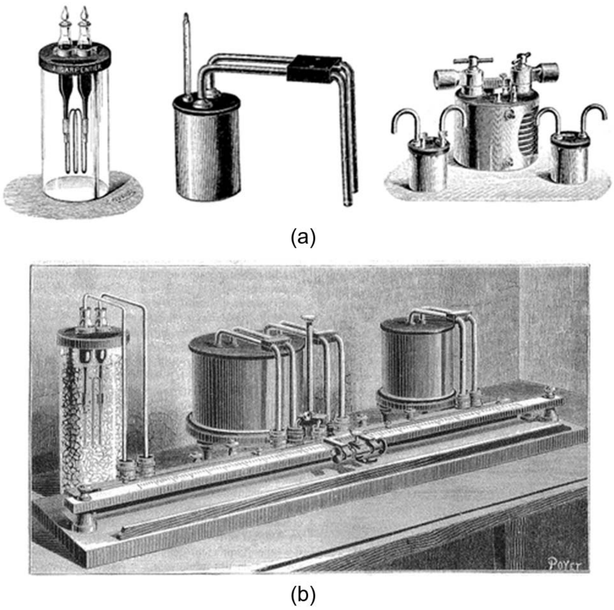

Fig. 7. *(a) Two models of Ohm's standards [28]. (b) Standards and measuring apparatus of electrical resistances (1885) [29].*

In 1849, just five years before his death, Ohm was called to be the curator of the physical cabinet at the Bavarian Academy in Munich, which later became a part of the Deutsches Museum. The new position carried an obligation to lecture at the University of Munich as a full Professor, receiving the corresponding Chair of Physics there, and realizing his lifelong dream, three years later.

Ohm died in Munich on July 7, 1854, at the age of 65, as result of a series of apoplectic episodes. At the end of his life, he experienced strong fatigue resulting from the production of a book in physics, which he considered indispensable in the class he taught. Toward the end of his life, he received different honors in his own country, such as the full Membership of the Bavarian Academy in 1845, the appointment as Technical Advisor to the State Telegraphy, Senator to the Royal Ludwig-Maximilian University from 1852 to 1853, and, just before he died, one of the first Memberships, by King Maximilian II, of the Bavarian Maximilian Order for Science and Art.

In 1881, the International Electrical Congress in Paris established "ohm" as the practical standard unit of electrical resistance (Fig. 7) [26], [27]. The "legal ohm" was provisionally adopted two years later by an international committee to which the congress had committed the subject as the resistance at 0 °C of a column of mercury 1 mm^2 in cross section and 106 cm long. The standard was approved at the Conference International Meeting of May 3, 1884.

VI. OTHER AREAS OF RESEARCH

Electricity was not the only topic on which Ohm undertook research. He also made contributions to several other subjects, mainly acoustics and molecular physics. The most significant was in the former. Acoustics was then a growing field of interest, and Ohm had entered upon it in 1839 with a brief note on the phenomena of beats and combination tones [30].

The instrument Ohm used to explore the physics of sound and its relation to human perception was an acoustical siren, an instrument originally invented by the Scottish physicist and mathematician, and Professor at the University of Edinburgh, John Robison (1739–1805), and subsequently improved in design in 1819 by the French engineer and physicist Charles Cagniard de la Tour (1777–1859) to test the entire range of human hearing. This version, the most accurate and commonly used siren of the early 19th century, consisted of a dish with equally spaced holes through which air blows as the disk rotates. Used to determine the frequency vibration of a sonorous body, it provided the frequency—pitch—of the sound emitted. Like his electrical law, Ohm structured his acoustical studies on Fourier's work and showed, in connection with the studies on heat transfer, that any function could be expressed as a sum of a series of simple sine or cosine terms. By applying this conviction to the phenomenon of sound, Ohm determined in 1843 that any motion of air, corresponding to a composite group of musical tones, was capable of being analyzed as a sum of harmonic vibrations of definite frequency, and that the particular quality of actual sounds was due to combinations of simple tones of commensurable frequencies. In other words, no matter how complicated the motion producing the sound may be, the total sound can be analyzed as consisting of many noninterfering sinusoidal waves, which act as if each wave is produced by itself [31].

According to Ohm's acoustical law, published in 1843, human ears perceived sound in terms of its individual frequency components [32]. In this way, the law provided the essential rationale for explaining the existence and nature of the combination tones. The law had little immediate impact on science during Ohm's lifetime. Except for August Ludwig Friedrich Wilhelm Seebeck (1805–1849), Director of the High School at Dresden, Germany, and son of the discoverer of the thermoelectricity, Thomas Johann Seebeck (1770–1831), no one seemed to have taken an interest in Ohm's paper. Seebeck was willing to admit that

Fourier's analysis of the siren impulse yielded a harmonic series of frequencies that the ear would actually hear as components of the siren's tone, but also claimed, in what was the beginning of a peaceful dispute, that, even in the most general assumptions, Ohm's theory failed in that it could not correctly predict the intensities of the various harmonics as they were actually heard as components of the siren's tone [33]. Ohm withdrew from the controversy after publishing the rejoinder to Seebeck [34], while the latter continued publishing on acoustics until 1849.

Fig. 8. *Ohm's law commemorative stamp.*

With a dispute without a clear winner, the law was relegated to a second level for eight years after Ohm's death. The theory was, however, successfully revived and overall exploited by the physician and physicist Hermann Ludwig Ferdinand von Helmholtz (1821–1894), who saw the significance of Ohm's paper more clearly than its author and used it to explain the relation of overtones to music, and revolutionize the field of acoustics in this way [35].

Regarding molecular physics, the studies on conductivities of metals seem to have aroused Ohm's interest in the behavior of the matter and its relation with its ultimate structure. He distinguished two types of properties in the bodies: some "filling" the matter and belonging to it, and others that he called "visitors" of the matter, which manifested themselves from time to time. He thought that the structure of bodies should be such that the knowledge of the properties of the first class allowed the determination of the others. Transport phenomena of entities such as light, heat, or electricity could be, in this way, fully determined from the only knowledge of basic properties such as nature, size, form, and atom's behavior. The plan, entitled "Contributions to Molecular Physics," to "create a work that should be for the microcosm of the world of atoms what Newton's 'Principia' had become for the microcosm of heavenly space" remained incomplete however [36]. Only one volume was published, while two more, originally proposed, were never written.

VII. CONCLUDING REMARKS

Georg Simon Ohm belonged to a generation of experimental physicists, which emerged in France and Germany in the first decades of the 19th century, that believed that measure and number become the true foundation of the exact scientific research which physics demanded [37]. The goal of these experimental physicists was perfectly stated years later by the British mathematical physicist William Thomson (later 1st Baron Kelvin) (1824–1907) as "systematic observations and experiments which have for their object the establishment of laws and formation of theories" [38]. This methodologically well-defined empiricist approach of the observation of nature regularly led, however, to intricate intertwining of theory and experiment, and Ohm's work proved it.

The fundamental value of experimental research for Ohm and several contemporaneous scientists derived from its capability to result in empirical laws. Without underestimating the value of theoretical analysis for purposes of experimentation, Ohm valued finding the new phenomena and the examination of the connection between several of them more, with the purpose of finding the corresponding governing empirical laws. He was firmly convinced that knowledge reached through generalizations and inductions would give a secure basis for physics.

By working painstakingly and patiently for several years, Ohm was able to rediscover different facts in the field of electricity but, above all, discover other of incalculable importance. The introduction of the cross-sectional area into one of the mathematical relations he derived showed his clarity in respecting the uniform flow of electricity throughout the volume of a metallic conductor and the difference with a static charge existing only on the surface of a conductor, instead of claiming results of previous researches. By taking much data, interpreting them, fitting curves, and drawing his conclusions, Ohm also rediscovered that the electric conductivity of metals is constant at constant temperature.

Ohm's law played a tremendous role in both the development of the telegraph and in the invention of the electric light bulb. The law's role continues to be important in many later and current practical applications of electricity and electronics. Although valid, as many of the fundamental laws, in basic situations (in this case, in all elemental conductors), it is however only an approximate law. While electrical science in the 19th century was dominated by materials which obeyed Ohm's law, the situation changed, and continues changing, in the 20th and 21st centuries. If it is true, for example, that in 1856 the German physicist Johann Wilhelm Hittorf (1824–1914) concluded that electrolytic conduction had nothing to do with chemical affinity and obeyed Ohm's law just as well as metallic conduction [39], [40], studies carried out only few decades later began to show deviations for solutions of weak electrolytes in water and other solvents [41–43]. If it is true that researchers have demonstrated that Ohm's law works for silicon wires as small as four atoms wide and one atom high [44], it is also true that deviations from Ohm's law for electronic conduction in semiconductors and materials used in the design of nanostructures in electronic and optoelectronic devices, to cite other examples, are almost the rule rather than the exception [45], [46]. Nevertheless, although deviations have been reported even for metallic materials under special circumstances [47], [48], the law is still applicable, without refinements or correction factors, in a remarkably wide range of situations.

The importance and validity of Ohm's contributions to the electrical science are indisputable (Fig. 8). They have become strongly established by the electrical engineer, industrialist, and historian of science and technology Bern Dibner (1897–1988) who referred to the scientist and his work with the following words: "The fame and name of Georg Simon Ohm is locked in perpetuity in a law and a term that will be used as long as electricity flows" [49]. ■

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