PHYSICAL SECTION.

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The Contributions of H. F. E. Lenz to the Science of Electromagnetism.

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(*Concluded from p. 34.*)

PART II.

Heinrich Friedrich Emil Lenz was a voluminous writer as well as an indefatigable investigator, most of his experimental work having been done while he was a professor of physics at the University of St. Petersburg. The catalogue of the Royal Society contains a list of some fifty of his contributions. But little biographical information concerning him is available, probably owing to his residence having been so remote from the intellectual centers of Europe, and for the further reason that scientists, like other skilful artisans, scarcely leave any record but that of their experiments and papers; and probably there is an additional reason to be found from the fact that society at large, out of a requital for the scientist often having eschewed and neglected the humanities, forbears to consider his own life as a human document worthy of preservation. The author of the most insignificant literary work usually leaves enough of his life on record to show what the manner of the man was; but from the silence of social records, one must usually take for granted that the scientist was a man fulfilling at least the ordinary round of human life.

From brief encyclopædic notices in the French and German it is learned that Lenz was born February 12, 1804, at Dorpat, or the Russian Yurief. He seems to have studied theology in the earlier portion of his professional preparation; but, abandoning this subject, he devoted his attention to the natural sciences, and especially physics. What an

interesting chapter this portion of his life would furnish ! In 1823-26 he accompanied O. von Kotzebue, the son of the celebrated poet, on the second of his voyages around the world. He traveled on this journey in the capacity of a naturalist, and upon his return made a valuable report of his observations to the Imperial Academy of Sciences at St. Petersburg. In 1828 he was elected an adjunct of the Academy, and in 1834 was made a fellow (*Akademiker*). About this time he became Professor of Physics at the University of St. Petersburg, and also taught the subject of physics at the Pedagogical Seminary. In 1864 he published a "Handbook of Physics," in two volumes. He at one time was the rector of the University and also served as its counsellor. His health failing, he made a journey to Italy, where, on February 10, 1865, he died at Rome.

Among the brief notices of the life of Lenz, there is one which for singularity deserves to be quoted at some length.* It proceeds with "Lenz was a German physician, and was afterward Professor of Medicine at the University, and numbered among his pupils the imperial princes (sons of Nicholas I)." That the subservience of Lenz to a few royal children should be his leading claim to public notice, while not a word is awarded to his scientific achievements, is a suggestive reflection on the material which passes for learning in our country. But even this brief notice is seen to be ludicrous when it is observed that the German "*Physik*" and "*Physiker*" have been translated "medicine" and "physician."

In order to acquire some familiarity with the intellectual complexion of Lenz, the few contributions which he made prior to his classical papers may be examined with interest. His mind was evidently of an eager, inquiring character, and apt to be absorbed by the dominant ideas of his time. The first paper has to do with "Considerations on the Temperature and Salt Content of the Water of the Ocean at Different Depths."† His second was a "Report of a Journey to

* "*Lippincott's Biographical Dictionary*," 1895.

† *Pogg. Ann.*, XX, 1830, pages 73-130.

Bakou," and its contents were of a geological character. The third carries the pretentious title, "Physical Observations Made during a Voyage around the World in the Years 1823-26." These were followed by a second paper on the "Comparative Quantity of Salt Contained in the Waters of the Ocean,"* and in a fourth by some observations on the influence of temperature of the objects weighed on the movements of the beam of a balance. Finally, a sixth paper was devoted to "Variations that the Height of the Surface of the Caspian Sea Has Suffered to April (*sic*) of the Year 1830."

His first contribution of general scientific interest was the seventh in the list of his papers and was entitled, "On the Laws According to Which the Magnet Acts upon a Spiral When it is Suddenly Approached to, or Withdrawn from it; and on the Most Advantageous Method of Constructing Spirals for Magneto-electrical Purposes,"† which was read before the Scientific Academy at St. Petersburg, on November 7, 1832. It is significant to note the date of this paper in comparison with similar communications by Henry‡ and Faraday.§

In this paper Lenz frankly makes mention of Faraday's published experiments and states that he promptly repeated the principal ones. It will be seen from his own statements to what extent he verified the work of another, and how far he is entitled to be considered an original discoverer of the various phenomena of electricity induced from magnetism. In his own words from the English translation of his paper: "From the great interest which the late discoveries of Faraday in the field of electromagnetism must awaken in all the natural philosophers of Europe, it is to be expected that we shall soon receive many and various explanations. Up to the present moment we, here in the North, are only acquainted with the papers of Becquerel, Ampere, Nobili and

* Trans. in the *Edin. Jour. of Sci.*, VI, 1832, page 341.

† Eng. trans. by W. Francis, in Taylor's *Sci. Memoirs*, I, 1837, page 608; from *Mem. Imp. Acad. des Sci.*, St. Petersburg, 1833, Vol. II, page 427.

‡ Published in October, 1832.

§ Read February 17, 1832.

Antinori, and Pohl; and as none of these authors has occupied himself with that branch of the subject to which I have directed my particular attention, I hasten to make known, as quickly as possible, the following contributions to the science of electromagnetism."

After successfully repeating the experiments of Faraday, Lenz applied himself as an investigator to find out how the phenomena of the magnetic action on a spiral, suddenly approached or removed from the magnet, might be produced in the easiest and most powerful manner. For this purpose he foresaw he must determine in what respect the characteristics of the "electromotive" spiral, as he called it, influenced the phenomena. The characteristics which he studied were :

- I. The number of convolutions in the spiral.
- II. The breadth.
- III. The thickness.
- IV. The substance of the convolutions.

The galvanometer which he employed was constructed with Nobili's double, or astatic needle; and was wound with seventy-four turns of 25-mil wire. "I wound," Lenz states, "the electromotive wire about a soft iron cylinder, which served as an armature, and was filed smooth and flat at those places where it was laid on the poles of the magnet. As the removal of the armature can be performed in a more certain, prompt and uniform manner than the placing of it on the poles, I have, in all my following experiments, given the results which were obtained by pulling away the armature, or by the sudden removal of the magnetism of the iron." With these elaborate preparations, Lenz proposed to investigate the various factors in the induction of electrical currents by the magnet. In passing, it is noteworthy that Lenz in this paper refers to the laws which Ohm had established for the electrical circuit, and he intimates that he had discovered these laws and relations for himself.*

He expresses the results of his experiments in a number of generalizations. In the first of these he states: "The

* Reference cited, page 613.

electromotive power which the magnet produces in a spiral with convolutions of equal magnitude, and with a wire of equal thickness and like substance, is directly proportional to the number of its convolutions." In modern phraseology, if a coil of n turns is moved in a magnetic field of strength N , the electromotive force in volts is defined by

$$e = - \frac{dN}{dt} \times \frac{n}{108}$$

In this generalization, then, Lenz has established a principle which is of fundamental importance, though from lack of all knowledge of the magnitude of the magnetic field which he employed, the effect of the time-rate-of-change of the magnetic field escaped him.

With respect to his second series of experiments, he states: "I wound the copper wire in six convolutions around a wooden wheel 28 inches in diameter, and placed the wheel on the iron cylinder. After having completed the experiment, I wound six convolutions of the same wire about the same iron cylinder." The electromotive power in each case was nearly identical; hence he concluded that "The electromotive power which the magnetism produces in the surrounding spiral is the same for every magnitude of the convolutions."

In his third investigation he employed coils of ten convolutions or turns, in which the wires were of different diameters, while he made for his tests three separate coils. The length of the wire in each case was 33 feet, and as the copper wires were short and relatively of large section, their resistance seems to have been negligible. The coils were tested successively on the same iron cylinder with the result that the electromotive force induced was practically constant for the three coils. His conclusion was, "The electromotive power produced in the spirals by the magnet remains the same for every thickness of the wires, or is independent of it."

The final conclusion is perhaps the most interesting of the series and the most important in its consequences. He proved very rigidly that "The electromotive power which

the magnet produces in spirals of wire of different substances, under like conditions, is the same for all substances." From one point of view this conclusion is correct and rigid, but for ferro-magnetic substances, while it still holds true, the permeability of such conductors being greater than unity, the element dN is affected and masks the results, though this refinement he was seemingly unable to detect. To show how thoroughly Lenz had grasped the principles of the electrical resistance of conducting substances and circuits, his own remarks will be placed in evidence. In discussing the experiments leading to the fourth conclusion, he says: "Nobili and Antinori, in their first paper on the electrical phenomena produced by the magnet,* have already determined the order in which four different metals are adapted to produce the electric current from magnetism. They arrange these in the following order: copper, iron, antimony and bismuth." He then observes: "It is particularly striking that the order is the same as that which these metals occupy also in reference to their capacity of conducting electricity; and the idea suddenly occurred to me, whether the electromotive power of the spirals did not remain the same in all metals, and whether the stronger current in the one metal did not arise from its being a better conductor of electricity than the others. With this in view, I examined four metals: copper, iron, platinum and brass." His method of experiment was simple and conclusive; spirals identical in form were made of the several metals and these were tested, pairing two of them at a time by connecting them by series into a single circuit whose free ends were connected by copper lead wires to a galvanometer. He placed now one spiral and then the other on the soft iron armature of the magnet. There was thus no change of resistance in the experiment if the electromagnetic conditions for induction were constant; and he should thus have obtained an equality of inductive effect. Between the circuits containing the pairs of coils he made full allowance for the elements of their resistance,

* Pogg. Ann., No. 3, 1832.

and upon calculating the electromotive power in unit terms for each coil, he found the values agreed remarkably well for the entire series of tests. To show the care with which he proceeded, he took pains to avoid any thermo-electric action at the joints. Thereupon he derived a law which he thus phrases: "The electromotive power which the magnet produces in spirals of wires of different substances, but in every other respect placed in exactly the same conditions, is completely identical for all these substances."

From the present time, though deservedly we look back upon the work of the noted classical investigators and call it great, yet from our prevalent ignorance of the mental attitude of these men toward their work, it acquires in our eyes almost a reverent aspect, and we imagine these men to have been gigantic in their intellectual grasp, when often they were most puerile. To show how these investigators often worked in the dark, and how, as a result, they made great ado over nothing, Lenz may again be quoted in illustration. Still speaking of his experiments with his electromotive spirals, he adds: "The conducting wires were connected with the ends of this spiral only by a single twist of the wires; the result of four readings with the connection in circuit amounted to 36.8° ; upon this the same connection was made by twisting the ends of the wires ten times around one another as tightly as possible; the deviation again amounted to 36.8° . I finally pressed the last connections as tightly as possible with a pair of pincers, so that they were very much flattened; the deviation was 36.75° . We may therefore consider the connections made by tightly twisting the wires ten times around one another as quite sufficient."

In connection with the description of his experiments he, from his conception of the sine galvanometer, analytically investigated the magnitude of the currents produced. This work was done with some show of skill; but from a lack of full discrimination between ballistic and static deflections, the results obtained have considerable error, though this did not affect them since they were usually of similar magnitudes. It is indicative of the methods of Lenz that all his

results are corrected by least squares, a refinement far in excess of his possible instrumental accuracy.

In the final conclusion to his paper he proceeds to investigate the conditions for maximum electromotive power by deriving algebraical relations from his data. These interpretations of his experiments are rather formal and academical, and perhaps would be called crude in comparison with prevalent standards, and they would have been much more elegantly expressed by differential methods with which he shows himself to have been familiar by their introduction in later papers. Some of the quantities which he employs are based on bald assumptions; though by these means he arrives at some conclusions which appear to have been satisfactory to himself, they are devoid of interest to the present-day reader.

There have now been placed here, in their due order, the practically identical results of the leading scientists who laid the experimental foundations for the science of electromagnetism. Faraday and Henry are entitled to equal honors for the initiative work of discovery. The work of Lenz in comparison was to assign magnitudes and verify the phenomena, and later on to formulate a most important generalization. Of the three investigators, Faraday showed genius pre-eminently, for he sought after the causes of the phenomena, and developed the useful working hypothesis of tubes of force. Both Faraday and Henry neglected to attempt any mathematical statements and deductions from their experiments—Faraday from a lack of working knowledge of mathematics, and Henry because he evidently was not fully accustomed to the attitude of mathematical natural philosophy.

Again, of the three, the work of Lenz best stands comparison with modern methods, and he is pre-eminently the precise and analytical scientist seeking for relations and magnitudes. However, Lenz impresses one upon studying his work, as being singularly devoid of originality, and as being more nearly empirical, for he sets about his experiments largely in the spirit of the skilled workman who carefully examines every possible phase so that nothing may

escape him. Though this may be commendable, Lenz was seemingly not inspired by a high degree of the philosophical spirit and insight. One is impressed, however, upon reading the writings of Lenz, with the clear conception he displays of the momentary character of the induced currents. He undoubtedly realized that their action on the galvanometer-needle was ballistic, though he was in error in the estimation of the magnitudes of the current.

Following the first of what may be called the exact investigations of Lenz, in which he is undoubtedly entitled to precedence for determining the conditions upon which the magnitude of the electromotive force depended, he seems to have devoted himself to questions of electrical resistance. At first giving attention to the laws of divided circuits, he solved a number of intricate problems for the resistance of compound circuits.* However, it was in a paper read before the Academy at St. Petersburg, June 7, 1833, that he most clearly revealed his powers as an investigator. This paper was entitled, "On the Conductivity of Metals for Electricity under Varied Temperatures."† In it he states: "I had anticipated that there would be found a relation between the expansion of the metal under the action of heat and its lowered conductivity for electricity." He had examined copper, brass, iron and platinum, but by no means could he find any such temperature change of resistance as he anticipated, through the formulas which he employed for calculating the results of his experiments. But when he had developed his experiments on induced currents, he found through them a new means for further investigations of the supposed change of resistance; for he was thus enabled to put upon the circuit tested an electromotive force free from the uncertain element of the internal resistance of a battery which he had hitherto employed. Being able now to ascertain the resistance of all the elements of the circuit, he at once found and measured the temperature effect on the resistance of metals. To Lenz may be attrib-

* Dove's Reportorium, Bd. VIII.

† Pogg. Ann., Bd. XXXIV, page 418.

uted the priority in investigations of these phenomena and also their formulation; for he derived from his experimental data the expression

$$Y_n = X + Y_n + Zn^2$$

which may be recognized as the original for the now prevalent formula,

$$R_t = R_0 (1 + at + \beta t^2)$$

Usually only Matthiessen is mentioned as the authority for temperature changes of resistance, but the historical succession of authorities is Lenz,* Becquerel,† Arndsten‡ and Matthiessen§.

As a second result of the possession of the new and powerful means of investigation which the electromotive spirals had placed in the hands of Lenz, he promptly developed the necessity for some unit of resistance, and indeed employed this in terms of a unit length of copper wire of a definite section. The paper describing these experiments was read before the Academy, November 28, 1834, and was entitled, "On the Laws of the Conducting Powers of Wires of Different Lengths and Diameters for Electricity."¶ In this paper Lenz discusses Ritchie's observations on "conductibility"¶ and shows him to have been in error. He thereupon undertakes a lengthy discussion of the similar work of Ohm and Fechner, and in the course of his remarks he employs simple algebraic methods to phrase Ohm's law for simple and compound circuits, expressing his meaning through forms of analysis which are still accepted. Lenz, in his experiments, determined the resistance by the method of substitution, the current being obtained through electromotive spirals. His analysis begins with an expression of the familiar form,

$$J = \frac{E}{W} \quad (1)$$

* Pogg. Ann., Bd. XXXIV and XLV.

† Pogg. Ann., Bd. LXX.

‡ Pogg. Ann., Bd. CIV.

§ Pogg. Ann., Bd. CXV and CXXII.

¶ Taylor's Scientific Memoirs, Vol. I, page 311.

¶ Phil. Trans., 1833, page 313.

J being his symbol for current strength, and W the resistance of a simple circuit including the spiral, lead wires and the galvanometer. A standard resistance of copper wire was then inserted, whose length was l , and whose resistance in terms of his unit copper wire was $\frac{l}{c}$. Then it followed that

$$J' = \frac{E}{W \frac{l}{c}} \quad (2)$$

and by combination,

$$W = \frac{l}{c} \frac{J'}{J - J'} \quad (3)$$

from which W was determined in terms of $\frac{l}{c}$.

Then substituting for the standard resistance the wire whose resistance R he wished to ascertain, he found, by solution of an expression, its resistance. J'' being the current in this case,

$$R = W \frac{J - J''}{J''} = \frac{l}{c} \frac{J'}{J''} \frac{J - J''}{J - J'} \quad (4)$$

In this manner he obtained values for the conductivity of silver, copper, gold, iron, tin, lead, mercury, platinum, and many other conductors. Despite his crude standards for current and resistance, his methods are remarkably successful and the results are very close to the data which Matthiessen subsequently determined.

Throughout the discussion in this paper Lenz reveals a clear and concise grasp on his subject-matter, and exhibits a characteristically fine and well-trained mentality. He refers to Ohm's law as an axiom; and summing up his results, he states:

"The conductibility of wires of the same substance is inversely as their lengths and directly as their sections." Regarding this law as sufficiently proven, he continues, in explanation: "Still the method for determining the conductibility by the induced electrodynamic current offers so much facility and accuracy in observation that it appears to me worth while to apply this method." He had con-

ceived that some variations in the resistance of the battery employed as a source of electromotive force had been responsible for discrepancies in the results obtained by other investigators; and in contrast he considered his own source of electromotive force was, however, free from changes in internal resistance. At this time he had not yet grasped the conception which we now phrase under the term "impedance," though later on he developed this with much clearness. However, his circuits were low in reactance, and no doubt the small discrepancies, which at first he could not explain, were due to this effect; otherwise these methods were remarkably simple and effective. Probably nothing could more clearly illustrate that the first approximation of a scientific principle is often very simply obtained, and usually carries with it a degree of fame that is denied its elaborate and subsequent verification.

Though Lenz was not to receive wide recognition as one of the original discoverers of the phenomena of electricity induced from magnetism, yet his chief fame was to rest upon one terse and valuable generalization, which was to be known as Lenz's Law, and which was to serve for placing these phenomena under the broad generalization of the conservation of energy, soon to be developed and generally received, and which law should further prove one of the most practical for the application of the principles of electro-magnetic induction to electrical machinery. The enunciation of this law was first given in a paper read on November 29, 1833, before the Academy at St. Petersburg; it bore the caption, "Concerning the Direction of Galvanic Currents Excited by Electrodynamical Distribution." *

In its introduction Lenz takes exception to Faraday's rules,† and considers them insufficient, if not in error. He briefly summed up Faraday's statements to read: "(1) Be-

* Pogg. Ann., 1834, Bd. XXXI, page 483. The exact title of the paper is of interest; as it was first given scientific publication in the German, it reads, "Ueber die Bestimmung der Richtung der durch elektrodynamische Vertheilung erregten galvanischen Ströme."

† He had read these statements from Pogg. Ann., No. 5, 1832. Compare "Experimental Researches," Vol. I, pages 32-3.

tween parallel conductors, one of which carries a current, an opposing current is induced upon approach, and a current similarly directed upon withdrawal from the first conductor. (2) When a conductor is moved near a magnet the direction of the induced current depends upon the manner of cutting the 'magnetic curves.' " Lenz objected to this, and insisted that Faraday had here stated two wholly different laws for one and the same phenomenon. He based this singular objection upon what he calls "Ampere's beautiful theory," which regarded the magnet as a system of circularly directed galvanic currents. The objection, it must be confessed, appears trivial, and leaves Lenz open to the implication that he wholly failed to grasp the important significance of the magnetic curves or lines of force which Faraday had supposed constituted the magnetic field; and it further lays Lenz open to a suspicion that he was zealous for some opportunity to criticise the magnificent discoveries and work of Faraday.

This attitude of Lenz is all the more singular, since his first investigations proved conclusively that the cause of induction lay wholly apart from and without the circuit in which it took place; or, more briefly, in a medium surrounding it. Faraday clearly considered a magnet and a wire carrying a current as identical so far as they were both accompanied by magnetic curves; so his statements referring to two sets of conditions were very properly phrased into one general law. Again Lenz was correct in assuming that both the relations which he noted were aspects of one and the same phenomenon; his mistake originated wholly from adherence to Ampere's theory, and the failure to appreciate Faraday's conception of a magnetic field; though nearly all scientists and mathematicians at first were equally averse toward accepting this assumption of lines of force.

Since the processes by which Lenz finally arrived at his classical law are largely dominated by the criticism of Faraday's work, his objections will be given in some detail. In placing a stricture on the generality of Faraday's rules he instances the case of a conductor placed perpendicularly

to a second one in which a current is established. According to the interpretation which he placed on Faraday's rules, no current would be induced in this conductor when moved parallel with itself and with the inducing conductor. But this stricture is an obvious one since Lenz was inclined to be empirical rather than philosophical; and what should have led his thoughts to a conception of a field of force only in the end suggested to him an empirical generalization.

Faraday, in order to illustrate the sense of direction of the induced current relative to the polarity of the magnetic field inducing it, had resorted to the suggestion of a silver knife-blade, whose notched side was considered to be placed upward as it was moved along a bar, or cylindrical magnet, its edge cutting the lines of force. Lenz did not spare something of a sneer at the homely illustration, and considered it but an instance of the stricture he had placed on the supposed general law, since the knife-blade in fact was perpendicular to the axis of the inducing magnet, and should accordingly have had no current induced in it; a supposition which would have been true only for the position near the center of a very long straight magnet. The illustration, however, was a very apt one, and had in it something of the inspiration of genius on the part of Faraday, and its criticism showed the lack of this on the part of Lenz.

Upon the further study of Faraday's papers, and Nobili's comments upon them and his own experiments, the impression grew upon Lenz that all related electrodynamic distribution of currents might be simplified and brought together under the statement of a single, terse and comprehensive law; and guided by this idea, he entered upon a repetition, verification and extension of Faraday's experiments immediately following those by which he had established his discovery of the induced current. Lenz, through these experiments which he now instituted, was finally led to the elegant, though for him empirical, generalization which alone has made his name familiar to every student of electricity, and which serves more than any other detail to

make his investigations and papers classical. Stated in the language of its author, Lenz's law reads: *

"Wenn sich ein metallischer Leiter in der Nähe eines galvanischen Stromes oder eines Magneten bewegt, so wird in ihm ein galvanischer Strom erregt, der eine solche Richtung hat, dass er in dem ruhenden Drahte eine Bewegung hervorgebracht hätte, die der hier dem Drahte gegebenen gerade entgegengesetzt wäre; vorausgesetzt, dass der ruhende Draht beweglich nur in Richtung der Bewegung und entgegengesetzt wäre."

In a well-known and widely used text† the law is phrased in a form perhaps more familiar to the general reader, and is stated thus: "If the relative position of two conductors *A* and *B* be changed, of which *A* is traversed by a current, a current is induced in *B* in such a direction that by its electrodynamic action on the current in *A*, it would have imparted to the conductors a motion of the contrary kind to that by which the inducing action was produced."

The law expressed more tersely is: *The electrodynamic action of an induced current opposes equally the mechanical action inducing it.* When expressed in this form it is seen at once to be a corollary of the general law of the conservation of energy. Had Lenz expressly anticipated some such significance in it, his title to fame as a natural philosopher would have been established. However, the equivalence of the energy relations between the inducing and the induced currents did not seem to have occurred to him, his attention having been entirely absorbed by the mechanical relation detected in his experiments. It was not until some fourteen years later, when the principles of the conservation of energy were beginning to be grasped, that Helmholtz showed this law was a necessary corollary of the more general principle.

In order to obtain an idea of the working conceptions of induced currents which obtained among certain scientists in the early stages of the development of the science of

* Pogg. Ann., Bd. XXXI, page 483.

† Atkinson's Ganot's Physics.

electromagnetic induction, I translate a passage from the introductory discussion of Lenz's law, which Neumann gave in 1845.* It is to be recalled that Neumann gave mathematical expression and formulation to much of Lenz's work, as Maxwell did for that of Faraday. Neumann says :

"From the law of Lenz: the action which the inducing current or magnet exercises upon the induced conductor, if the induction results from the movement of the latter, is always in the nature of a check on its motion. And, further, the strength of the momentary induction is proportional to the velocity of the movement. From these considerations the general law of linear induction may be derived ; and

$$E. Ds = - \epsilon \nu C. Ds$$

In this formula, Ds is an element of the induced circuit, and $E. Ds$ is the electromotive force induced in the element Ds ; ν is the velocity with which Ds is moved, while, according to the direction in which Ds is moved, C denotes the magnitude of the resolved action of the induction upon Ds when unit current is considered to be flowing in this element. The magnitude of ϵ is independent of the activity of the induced conductor, and in the case of linear induction may be regarded as a constant ; but it is a function of the time, which decreases rapidly if its argument attains a finite value."

These views of Neumann are those of the pure analytical mathematician, and make no effort after a physical explanation of the phenomena or of their causation. They are based wholly on experimental results and are devoted to the establishment of relations between the various data. What is lacking in them is that physical aspect so finely expressed by Faraday in his conception of magnetic curves or lines of force. The pre-eminence of Faraday in this respect not only over Neumann, but Lenz more especially, is emphasized when it is considered that Lenz was so occupied with Ampere's theory of the magnet, that he did not

* Die math. Gesetzen der inducirten elektrischen Ströme ; 1845, Engelmann, page 4.

go beyond it; while Faraday, as fully conversant with "M. Ampere's beautiful theory," * as he calls it, found this inadequate and established the conception of the magnetic field.

Lenz, in order to make his law clearer, proceeded to phrase it somewhat differently, though again missing the perception of its greater significance: "To each phenomenon of movement by electromagnetism there must correspond an electrodynamic distribution. Consequently, it is only necessary to produce motion through other means in order to induce a current in the movable conductor which shall be opposed in direction to that so produced in the electromagnetic experiments."

His attack on the proof of his law is logically arranged and carried out experimentally where data were not otherwise at hand. As stated, the items were, the dynamic fact being stated first, and the reversed inductive action second:

A. By Ampere's rule for parallel currents, two similarly directed currents mutually attract; while if oppositely directed they repel each other.

a. From Faraday's experiment, if a current is flowing in one of two parallel conductors, when the other conductor is caused to approach, a current of opposite direction is induced in it; and conversely.

B. By what became in subsequent years the principle of the electro-dynamometer, if two circular currents are vertically placed with their planes at right-angles, having a common diametral axis of rotation, be the one fixed and the other free to move, the movable circuit will rotate until the two planes coincide and the currents have a common direction.

b. If two circuits are arranged as above, when the movable coil is quickly brought from a position of quadrature of its plane to one of coincidence with the fixed coil, a current is induced in the movable coil opposed in its direction to that in the inductor. This supposition was experimentally established by Lenz himself; and in it is recognized the principle of the earth inductor. In the apparatus used by

* "Experimental Researches," page 10, art. 38.

Lenz the circular frames were each wound with twenty turns of copper wire.

C. From an experiment of Nobili,* if from a fixed conductor, so long as to be considered as infinitely rectilinear, a short conductor be arranged at right-angles, and being free to move, be connected as a shunt from the fixed conductor, the direction of its current flow being from the fixed conductor, the shunt will move in the direction of the flow of the first current; and conversely.

c. If a shunt conductor, as above, be moved in the direction of the flow of current in the inductor, an induced current will be established, whose direction of flow is toward the inductor, or opposed to the direction in C; and conversely.

These, Lenz states, he considered the principal cases in which a galvanic current exercises an electrodynamic and an electro-inductive action upon an appropriate conductor. He then proceeded to examine the cases of mutual reaction between currents and magnets. These he prefaced with a discussion of Ampere's rule for finding the direction of an induced current by the friction of a man swimming in the circuit; and with something like perversity, proposed a modification derived from his own law. He gave as a rule, "If a conducting circuit is moved before the north pole of a magnet, an induced current results from the electrodynamic distribution, which streams through from the head to the feet, if one should be imagined to be in the circuit turned so as to view the north pole, and the motion of the conductor be toward the right hand." Just what conception Lenz himself had of this electrodynamic distribution (*elektrodynamische Vertheilung*) can not be obtained from his writings, if indeed he went so far as to establish a working conception for it. In his experiments he seems to have dealt with this electrodynamic distribution in the same sense that Faraday did with magnetic curves.

Proceeding to discuss the reactions between magnets and currents, Lenz resumes :

* Pogg. Ann., No. 3, 1833, page 407.

D. From Oersted's experiments, a galvanic current brought over a magnetic needle, the direction of the current being from the south toward the north pole, will deflect the north end of the needle to the right.

d. If a linear conductor is placed over a magnetic needle at rest, and the needle is suddenly deflected by some force, a current is induced whose relation of direction is opposed to that in *D*; or, if the north pole of the needle is deflected toward the right, the flow of current will be from the north pole toward the south; and conversely. To prove this experimentally, Lenz employed a frame 1 foot square, wound with many turns of fine silk-covered copper wire.

E. From De la Rive's experiment, if a circular current, free to move, surround a long, cylindrical magnet, and the direction of its current coincides with the resultant direction of the Amperean magnetic currents, the conductor will move toward the center of the magnet; while if the direction of the two currents be opposed the conductor will tend to push out over the nearer pole.

e. If a circular conductor be thrust over an end or pole of a bar magnet, a current will be induced whose direction will be opposed to that of the Amperean currents of the magnetic pole. Should the circular conductor be removed quickly from the magnet, the induced current will have the direction of the Amperean currents. This result Lenz takes from Faraday's experiments.

F. By the experiment of Barlow with a rotating wheel, if a bar magnet is placed diametrically over the wheel with the north pole toward the left, and a current flows from this point on the periphery toward the center, the wheel will rotate in a clockwise direction; and conversely by changing the relative direction between current and pole.

f. Faraday, varying the experiment, still keeping the axis of the wheel vertical, placed the north pole of a curved magnet over a point on the periphery of the wheel, and the south pole beneath. Upon turning the wheel in a clockwise sense, a current was induced from the center toward the periphery; and conversely.

G. By Ampere's experiment a cylindrical magnet, rota-

table about its axis, will rotate in a clockwise sense regarding its north pole, when a current passes from the north pole to the center.

g. Faraday showed when such a magnet is rotated in a clockwise sense, and a galvanometer is connected to its center and the upward-pointing north pole, a current is induced whose direction is from the center toward the north pole; and conversely.

The contributions which Lenz has made toward the establishment of the science governing the phenomena of magnetically induced electrical currents have here been presented, and the relation which his work bears to that of others, perhaps more widely known, has in a manner been pointed out. As an investigator, Lenz is no doubt entitled to the honor of being one of the foremost scientists who established the principles of electromagnetism. The sensationalism of discovery seems not to have been reserved for him; and there is much evidence that he lacked originality and that his work was largely shaped by the hints he obtained from other investigators, rather than that it sprang from his own initiative. Neither in his writings nor experiments can he be called brilliant; he perhaps did little that would not subsequently have been done; yet all his work was of that solid, enduring character which forms the foundation of all science. His work was painstaking and exhaustive; he verified, extended and formulated. His papers exercised a wide influence on the development of electromagnetics, especially in Germany and France, and in one respect at least they were the most noteworthy of the period; and this respect is most essential, for in all his work he seems to have been guided by the quantitative aspect of science. In this sense the writings of Lenz seem modern, especially when compared with those of Faraday and Henry, or of Ampere and such contemporaries.

The present intention has been to bring the work of Lenz into prominent notice only so far as it was contributory to the discovery and development of magnetically induced electricity. But this represents but a portion of

the scientific labors and contributions of Lenz. Much of his subsequent work was important, and all of it more or less influential, but it has less general interest than that here given in detail. A mere outline of his subsequent work, however, will be given.

Lenz investigated Grove's battery quantitatively,* and certain aspects of electrolytic polarization, and the internal resistance of batteries.† He made a notable contribution on the cooling effect of a current passed through the junction of a thermo-electric couple.‡ Soon after Joule published his law for the heating effect of the electrical current, Lenz proceeded to investigate the entire subject with characteristic thoroughness, and gave Joule's law perhaps its most rigid verification, conspicuous also for its completeness.§

Lenz seems to have been especially keen to have recognized in the electromotive spirals an instrument for investigation capable of wide and exact application. By use of these spirals, he conducted numerous tests and measurements, which in method and apparatus very closely resemble modern permeametry in its simpler forms. With the aid of Jacobi he found a parabolic relation between the strength of the magnetization of an iron rod and the magnetizing current employed; and they also measured the magnetic moment for various types of magnets.||

There was an additional line of investigation to which Lenz applied himself with the greatest enthusiasm and certainly with signal success; and this was a study of the properties and characteristics of the magneto-electric generators. He was led to establish experimentally that the plane of commutation does not coincide with the geometrical north-south plane; and in searching for the cause he found that the degree of shifting was in a sense a function

* Pogg. Ann., Bd. LXVII.

† Pogg. Ann., Bd. XC.

‡ Pogg. Ann., Bd. XLIV.

§ Pogg. Ann., Bd. LXI.

|| Pogg. Ann., Bd. XLVII and LXI.

of the current intensity; thus he recognized the existence of armature reaction.

Following the lead of Weber, he worked out with much thoroughness the relations for maximum current output for such machines; but perhaps the most important of all these later investigations was that series in which he studied the characteristics of the armature of the magneto-electric generator. As a result he was enabled to chart the sinusoidal electromotive wave form, the position and magnitude of a wave form due to counter-electromotive force, and the curve of magnetization as impressed and also as shifted by armature reaction.* In thus charting his data, he was one of the very earliest of the scientists who employed those graphical methods which are now so valuable and universally employed.

SWARTHMORE, PA., August 15, 1902.

THE BRUSH STORAGE-BATTERY PATENT EXPIRES.

The last barrier in the way of the general manufacture of electric-storage batteries was removed on March 3d by the expiration of the Brush patent on storage-battery electrodes. The *Electrical Review*, commenting on the fact, says that there may not be a great increase in the number of factories, but the magazine looks for improvement and extension of the use of power-batteries.

The electric motor-car manufacturers, it says, will profit more than anybody else by the new order of things. Lighter and better batteries for motor cars will appear, and the highly developed products of the European makers can be imported. In this way the prices can be reasonable, and the performance of electric motors greatly improved, with a resulting increase in their popularity and an augmenting business for manufacturers, both of machines and of batteries. Slight change is expected to occur in the power-station batteries.

The Brush patent, says the *Review*, was one of the most remarkable patents in the history of the electrical art. It covered completely the art of making plates by mechanically applied material, as a paste, powder, or in any other form. There have been repeated assaults on it in the Federal Courts, and enormous sums of money were spent in litigation to have the patent declared invalid, but in every instance it came forth victorious.

"To sum up," concludes the *Review*, "the result of the expiration of the Brush patent will be to improve and extend the use of power-batteries, though not markedly, and to increase greatly the quantity and quality of the cells for motor-car work."

* Pogg. Ann., Bd. XLVII and LXI.