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> "Nec aranearum sane textus ideo melior quià ex se fila gignunt, nec noster vilior quia ex alienis libamus ut apes." Just. Lips. *Polit.* lib. i. cap. 1. Not.

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MAY 1852.

XLVI. *Reports on the Progress of the Physical Sciences.*

By JOHN TYNDALL, *Ph.D.*

[With a Plate.]

On the Electroscopic Properties of the Voltaic Circuit; being an experimental verification of the Theory of Ohm. *By* Dr. KOHLRAUSCH, Poggendorff's *Annalen*, vol. lxxv. p. 220; vol. lxxviii. p. 1; and vol. lxxxii. p. 1.

THE following quotation bears so pertinently upon the subject of the present report, that an apology for its introduction here is scarcely necessary. It is extracted from a discourse by Professor Dove, before the Berlin Society for Scientific Lectures.

"As the (then considered) essential portions of a galvanic circuit were two metals and a fluid, innumerable combinations were possible, from which the most suitable must be chosen. This gigantic task was undertaken by Ritter, an inhabitant of a village near Liegnitz, who almost sacrificed his senses to the investigation. He discovered the peculiar pile which bears his name, and opened that wonderful circle of actions and reactions which, through the subsequent discoveries of Œrsted, Faraday, Seebeck and Peltier, drew with ever-narrowing band the isolated forces of nature into an organic whole. But he died early, as Günther did before him, exhausted by restless labour, sorrow, and disordered living. It was soon found that many experiments succeeded better with a single pair of large plates than with several small ones; and, in short, that every apparatus exhibited certain actions better than all others. Here men of science long groped in darkness, when in the year 1827, the theory of galvanism by Ohm, then of Berlin, now of Nürnberg, rose like a pole-star to illumine the obscurity. He showed that, as the apparatus itself was composed solely of conductors, the electric current must proceed not only along the connecting wire from pole to pole, but also through the apparatus itself; that the resistance offered to the passage of the current consisted therefore of two portions, one exterior to the apparatus and one within it. At a stroke, the difficulties which up to this time had beset the subject, and which were thought insuperable by those who had confined their attention to the exterior resistance only, crumbled away.

"Ohm brought forward his discovery in the simple earnest language which distinguishes the true investigator of nature. A theory, he says, which lays claim to immortality must not depend upon the idle garniture of words for the proof of its noble origin, but must show in all its parts, by its simple and complete correspondence with facts, and without the aid of eloquence, its affinity to that spirit which animates nature. The manner in which this theory was received was different in different lands. Henry of Princeton, North America, who at once saw its infinitely practical importance, observes, 'When I first read Ohm's theory, a light arose within me like the sudden illumination of a dark room by lightning.' The Royal Society of London awarded him the Copley Medal, the highest prize given by the Society for physical investigation. In France also the discovery met with the greatest recognition which a foreign investigator could expect there. A physicist of that country thought it convenient to rediscover the same thing years afterwards. He thought, cette découverte n'est pas Française, mais elle est digne d'être Française. But what reward did Ohm reap in Germany? While the most laborious empirical inquiries were instituted, among which those of Fechner in Leipzic deserve especial mention, to bring the theory in all possible ways to the touchstone of experience, that science whose function it is to think the great thoughts of the Creator over again, glanced down with divine satisfaction from her Olympic throne upon these sublunary occupations; in the Berlin *Jahrbücher für wissenschaftliche Kritik*, Ohm's theory was named a web of naked fancies, which can never find the semblance of support from even the most superficial observation of facts; 'he who looks on nature,' proceeds the writer, 'with an eye of reverence, must turn aside from this book as the result of an incurable delusion, whose sole effort is to detract from the dignity of nature.'"

The investigations, of which we now purpose giving a review, occupy themselves with the experimental verification of the entire theory of Ohm. A portion of that theory has been already tested by physicists of all lands and found true: this portion, which on account of its superior importance is called the law of Ohm, forms, however, but one link in the chain of causation which the philosopher's speculations place before us. The comparative want of recognition which the other portions of the theory have experienced, is to be chiefly referred to the difficulty of procuring instruments sufficiently delicate to test them experimentally. By the invention and skilful application of suitable instruments, M. Kohlrausch has been able to travel side by side with the speculations of Ohm, and to convert them one after another into experimental facts.

The fundamental portions of Ohm's theory may be briefly sketched as follows:—Let the ring, Plate IX. fig. 1, represent a homogeneous conductor, and let a source of electricity be supposed to exist at A. To fix the ideas, let us suppose an electric machine placed there. The electricity from the machine will diffuse itself over both sides of the ring; the positive passing towards *a*, and the negative towards *b*, both fluids uniting at *c*. Now if the electricity be so distributed over the ring that a heaping up of the fluid nowhere occurs, then it follows that equal quantities of electricity pass through all cross sections of the ring in the same space of time. If it be assumed that the passage of the fluid from one cross section to another is solely due to the difference of the electric tension at both these points; and further, that the quantity which passes is proportional to this difference of tension, the consequence is, that the positive fluid proceeding from A right to *c*, and the negative fluid proceeding from A left to *c*, must decrease in tension the further they recede from A.

The tension of the electricity at every point in the circuit may be represented by a diagram. Let the above ring be supposed to be stretched out into a straight line AA′, fig. 2; let the ordinate AB represent the tension of the positive electricity, and A′B′ the tension of the negative electricity at the point of excitation, then the ring being homogeneous and of the same diameter throughout, the straight line BB′ will express the tension for all points of the circuit.

From these considerations, the law of Ohm expressed by the celebrated formula

$$S=\frac{E}{R},$$

where S represents the strength of the current, E the electromotive force of the battery, and R the resistance, naturally follows. If the electromotive force AB+A′B′ remain constant, then the greater the length of AA′ the less steep will be the inclination of the line BB′; that is to say, the less will be the difference of tension in two contiguous cross sections. But by the hypothesis, this difference is proportional to the quantity of fluid which passes from one cross section to the other; and hence it follows, that the greater the length of the circuit, the less will be the amount of electricity which passes through any cross section in a given space of time.

If the conductor AA′ be composed of material which offers a greater resistance to the passage of the electricity than that above supposed, as long as its length remains unaltered the distribution of the electricity will be the same. But inasmuch as the moving force, that is, the difference of tension between two neighbouring cross sections, is also the same as before, a less quantity of electricity must pass from section to section in a given time than in the case of the good conductor; that is to say, the current must be weaker. A greater length of the better conductor would produce precisely the same effect. These results find definite expression in the law, that *the strength of the current is inversely proportional to the resistance of the circuit.* Preserving the length and material of AA′ unchanged, and regarding the force AA′ + BB′ as variable, we deduce the law, that *the strength of the current is directly proportional to the electromotive force.*

One additional reference to the manner in which Ohm pictured to himself the electroscopic state of the circuit will suffice. Let the conductor AA′, fig. 3, consist of the same material throughout, but of two portions, possessing different cross sections. Let the cross section of A*d*, for example, be *m* times that of *d*A′; then if equal quantities pass through all sections in equal times, if through a unit of length of wire of *m* times the cross section no more fluid passes than through the thinner wire, the difference of tension at both ends of this unit of length in the former must be only $\frac{1}{m}$th of what it is in the latter. Thus the electric "fall," as Ohm terms it, that is, the decrease in the length of the ordinate for the unit of length of the abscissa, will be less in the case of the thick wire than of the thin, as shown by the line B*c* in the figure. The distribution of the electricity in such a circuit will be no longer represented by a continuous gradient, but can nevertheless be easily ascertained by calculation when the electromotive force of the circuit and the cross sections of its different portions are known. If, instead of one wire being thinner than the other, its specific resistance were greater, it would follow from the hypothesis of Ohm, that the greater the resistance of the metal the greater would be the electric fall. The result is summed up in the law, that *the "electric fall" is directly proportional to the specific resistances of the metals and inversely as their cross sections.*

Thus far we have travelled through a region of pure speculation. To test whether the actual distribution of electricity throughout a galvanic circuit bears any resemblance to that here supposed, an electrometer of surpassing delicacy was necessary. We shall give a brief description of the refined instrument made use of for this purpose by M. Kohlrausch.

A thin needle of silver wire, two inches in length, is suspended horizontally from a glass fibre of exceeding fineness; the fibre which passes in the usual manner through a glass tube is fastened to a torsion-head, the index of which being turned causes the little needle of silver wire at the other end to follow it. The needle lies across a thin strip of silver of its own length, through a slit in the centre of which the needle can descend; at the slit the strip is so bent right and left, that the needle, in following the index, can lay its entire length against the strip. This is the only portion of the instrument which requires a drawing to make it clear; it is represented in fig. 4. AB is the strip of silver, *cd* one-half of the needle crossing the strip in its centre, the other half is hidden by the strip. AB can be raised or lowered, so as to be in contact with the needle or detached from it. When the needle crosses the strip at right angles, the latter is raised so that the needle rests upon it, the apparatus thus forming a continuous cross of conducting material. Electricity, being communicated to the strip, distributes itself over the entire cross; when this is effected, the strip is lowered so that the needle again hangs free. The index above being turned, the needle will be solicited by the torsion of the fibre to approach the strip, but being charged with a like electricity, it will be repelled; by this play of torsion, on the one hand, and repulsion on the other, we arrive at a knowledge of the tension of the electricity communicated. The author has constructed tables from which the electric tension due to any observed amount of torsion can be instantly ascertained.

In connexion with the electrometer a condenser was made use of, the accuracy of which was carefully tested beforehand. For experiments with the galvanic circuit, both plates are of brass, suspended in a suitable frame by strings of silk, and separated from each other by three little patches of shell-lac placed at three different points near the periphery. When the poles of the battery are connected with these plates, the one becomes charged with positive, the other with negative electricity; and the strength of the charge is estimated by removing one of the plates to a certain fixed distance, and bringing the other, by means of an isolated copper wire, into connexion with the electrometer.

The electromotive force of a voltaic element, which Ohm expresses in his formula by the letter E, can be variously ascertained: the question suggested itself to M. Kohlrausch, whether any relation existed between this force and the tension of the electricity at the two poles of the element. The electromotive forces of various combinations were determined by Wheatstone's method. To ascertain the tension at the poles, the circuit, which had been permitted to remain in action for some time was suddenly broken, and the ends of the wires were brought into connexion with the plates of the condenser. The plates were then separated; one of them was immediately brought into connexion with the electrometer, and the strength of the charge was measured. The results derived from this process are contained in the following table:—

Description of element.	Electromotive force.	Tension at the ends of the broken circuit.
1. Zinc and platinum:—zinc in solution of sulphate of zinc, platinum in nitric acid of 1·357 specific gravity	28·22	28·22
2. Do. with nitric acid of 1·213 sp. gr...	28·43	27·71
3. Zinc and coal:—zinc in sulphate of zinc, coal in nitric acid of 1·213 sp. gr.	26·29	26·15
4. Zinc and copper:—zinc in sulphate of zinc, copper in solution of sulphate of copper	18·83	18·88
5. *a.* Silver and copper:—silver in cyanide of potassium or common salt, copper in solution of sulphate of copper	14·08	14·27
b. The same afterwards	13·67	13·94
c. The same some time afterwards...	12·35	12·36

This table establishes the important result, *that the electromotive force is proportional to the electric tension at the ends of the newly-broken circuit.*

The following experiments were instituted to ascertain the electroscopic properties of the active simple circuit. The author considers it practically impossible at present to construct an electrometer which shall directly declare the almost infinitesimal tension which obtains at the various points of the simple circuit, and hence the necessity of calling in the aid of the condenser: the manner in which the instrument was charged is as follows:—

From the lower condensing plate a wire of the same metal as the plate itself proceeded, and was buried in the earth. A branch was carried from this wire to a point *a* of the closed circuit. When another point, *b*, of the circuit was brought into metallic connexion with the upper plate of the condenser, it became charged to an amount which depends upon the tension existing at *b*, and on the condensing power of the plates. If several such points, *b*, be examined, the charges imparted to the condenser will be proportional to the electroscopic tension at the different points. Instead of connecting the lower plate with the earth, we might connect it and the point *a* directly, and bring the upper plate, as before, into connexion with *b*; experiment proves that the result obtained from this procedure is exactly the same as that obtained by the former method. The mode of observation first indicated is that pursued in the following experiments, the point *a* being deprived of all electric tension by its direct union with the earth.

Experiment 1.—The poles of the element were connected by a long fine wire, which was carried in a zigzag manner from side to side of a light wooden frame, and fastened to the latter by pins; the legs of the Vs thus formed were all of the same length.

a. Any point (*a*) being properly connected with the earth, when another point on that side of *a* from which the positive current proceeded was connected with the upper plate, the latter exhibited positive electricity; when, however, the point lay at the other side of *a*, a negative charge was obtained.

b. As long as the same length of wire existed between the point *a* and the point examined, exactly the same tension was shown by the electrometer, it mattered not in what portion of the circuit the examination took place.

c. When a series of points in the circuit at increasing distances from *a* were examined, the tension was observed to increase, the increase being exactly proportional to the length of wire intervening between *a* and the respective points. Calling to mind what has been said regarding the electric "fall," the case before us shows that, in a wire of uniform thickness, the "fall" is in all places the same.

Experiment 2.—The poles were united by two silver wires of equal lengths but of different diameters; the wires being smelted together in the flame of a spirit-lamp, so as to form one unbroken length: it was found,—

a. That in each of the wires the same electric fall existed throughout.

b. When one end of the thin wire was properly connected with the earth and the other end proved, the electrometer showed a charge of the strength E; when one end of the thick wire was connected with the earth and the other end examined, a charge *e* was obtained; the ratio of E : *e* was the same as that of the cross section of the thick wire to that of the thin.

Experiment 3.—The wire connecting the poles was formed of two wires, one of copper, the other of German silver; the former presenting very little resistance to the current, while the resistance of the latter was considerable. The total resistance of each wire was previously ascertained by means of a rheochord. It was found that the entire increase of tension from one end to the other of the copper wire was to the entire increase along the German-silver wire in the direct proportion of the resistances.

The above results may be summed up as follows:—*In wires of different materials and of unequal thicknesses, the electric fall is directly proportional to the specific resistances of the metals, and* *inversely as their cross sections;* which is a complete verification of the hypothesis of Ohm.

Experiment 4.—A rectangular wooden trough was constructed, and its interior was coated with wax. At one end was placed a porous cell containing a solution of sulphate of zinc, in which a plate of zinc was immersed; the rest of the trough was filled with a solution of sulphate of copper, and at the opposite end a plate of copper was immersed. The zinc and copper plates were connected by a wire. The edge of the trough was graduated; two copper wires dipped into the solution of sulphate of copper, and by means of the graduation their exact distance asunder could be readily ascertained. One of these wires was well connected with the earth, the other was connected with the upper plate of the condenser. The mode of experiment was, in fact, the same as that pursued with the metallic portion of the circuit. Here also it was found that the tension at the point connected with the discharging wire was zero; right and left from this point a regular increase of tension was observed; on that side from which the current proceeded the electricity was positive, on the other side negative. Further, according to the view of Ohm, who imagined the electricity to make its way through the *interior* of both metallic and fluid conductors, the tension at every point in any given cross section is the same. In the case of a metallic conductor it is, of course, impossible to test this experimentally; but in the fluid portion of the circuit, M. Kohlrausch found exactly the same tension throughout each transverse section, whether he raised or sunk the wire (which in these experiments was everywhere coated with shell-lac except at its extreme end) in the fluid, or pushed it more or less aside laterally*.

I trust the reader bears in mind what has been said regarding the electric "fall." The greater the resistance offered to the passage of the current, the greater the fall. In a thin wire, the line expressing the tension at every point will be a steeper gradient than in a thick wire; and in the fluid portion of the circuit the gradient may be expected to be steeper than in either of the former cases, for here the resistance is greatest. The simplest possible circuit must therefore exhibit a series of gradients expressive of the tension of its various parts. There is the fall along the connecting wire, the fall along the zinc and copper plates (which, however, is practically zero, as they offer almost no resistance), and the fall along the fluid. But let us suppose

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* Weber and Kirchhoff differ from Ohm here. They do not admit a motion of the fluid through the interior of the conductor, but solely along its surface. Their hypotheses, however, lead them to results which entirely agree with Ohm's.

the resistance in every portion of the circuit to be referred to a certain unit, and that the distances along the datum line from which the tensions are plotted are measured off with reference to this unit; that, for example, if an inch of the fluid portion exhibit a fall three times as great as an inch of the solid portion, the said fluid portion shall, on the datum line, be expressed by a distance three times as great as that which expresses an equal length of the solid portion; it is evident that when the resistances are thus referred to a common standard, the line which expresses the tension must be one uniform gradient from beginning to end. Ohm calls the length of a circuit referred to such a standard its *reduced length.*

It has already been stated, that when any point of the circuit is perfectly discharged, the tension at this point is null, and increases in tension right and left, showing positive electricity on that side of the point from which the current proceeds and negative electricity at the other side; the length of the circuit which shows the one fluid or the other will depend upon the position of the point; if exactly central, as at a'', fig. 5, the lengths will be alike. If the point be nearer to the zinc pole than to the copper pole of the arrangement, as at a', the length of wire exhibiting positive electricity will be greater than the length exhibiting negative electricity; and if the point be chosen contiguous to the zinc plate, as at a, the whole circuit will exhibit positive electricity.

Having the electromotive force bc, and the reduced length of the circuit, we are taught by the theory of Ohm to deduce by simple calculation the electroscopic state of every single point. Let the scheme in fig. 6 represent the state of things in a circuit where the discharged point a is contiguous to the zinc pole. The reduced length, ab, and the electromotive force, bc, being given, let d be any point whose tension, de, we wish to ascertain. Let $bc=a$, $de=u$, $ab=l$, $ad=\lambda$; then by similar triangles,

$$u:a=\lambda:l, \text{ or } u=\frac{\lambda}{l}.a;$$

or, expressed in words, if the reduced length of the circuit between the discharged point and the point whose tension is sought be divided by the reduced length of the entire circuit, the quotient, multiplied by the electromotive force, gives the tension at the required point.

In submitting this formula to an experimental test, M. Kohlrausch made use of the wooden trough before alluded to. The copper and zinc plates were united, as in one of the experiments already described, by a long fine wire, bent from side to side of a wooden frame in a zigzag manner. The tensions of the points described below were determined by direct experiment. The electromotive force was also determined, the reduced length of the circuit was found by measuring the resistances of its various parts, and from these two, the electromotive force and the reduced length, the tensions due to the same points were calculated by the foregoing formula.

Points examined.

a. The second lower angle of the zigzag.
b. The fourth lower angle of the zigzag.
c. The sixth lower angle of the zigzag.
d. The point where the zigzag joined the copper.
e. The solution of sulphate of copper 2·02 inches from the plate of copper.
f. The solution of sulphate of copper 4·02 inches from the plate of copper.
g. The solution of the sulphate of copper 6 inches from the plate of copper.
h. The solution of sulphate of copper 8 inches from the plate of copper.

In the following table the results obtained by calculation are compared with those obtained by direct experiment; the quantity λ is the same as that contained in the formula.

	λ.	u calculated.	u observed.
a	118·5	0·93	0·85
b	237	1·86	1·85
c	355·5	2·80	2·69
d	474	3·73	3·70
e	610·3	4·80	5·03
f	745·3	5·86	5·99
g	879	6·91	6·93
h	1014	7·98	7·96

The truth of Ohm's formula, which he derived from considerations purely theoretical, appears to be placed beyond the pale of doubt by these results. Hitherto the celebrated law which usually bears his name has rested upon a basis of conjecture merely; and to the extraordinary patience and refined experimental skill of M. Kohlrausch is due the credit of giving to this conjectural foundation the stability of fact.

It may be stated, in addition, that the same physicist has also examined the thermo-circuit, and has not only demonstrated the existence of electric tension at its poles, but also proved that the electricity obeys the same law of distribution as that true for the voltaic circuit.

Queenwood College, March 1852.

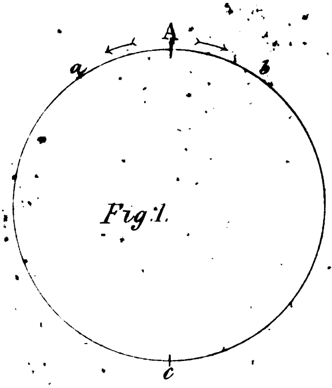

Fig. 1.

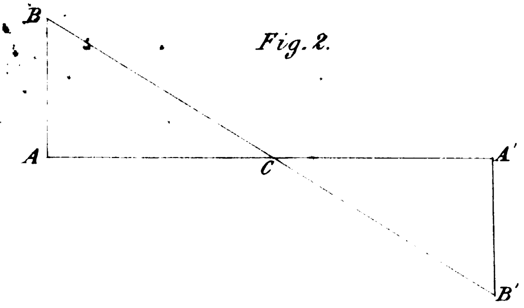

Fig. 2.

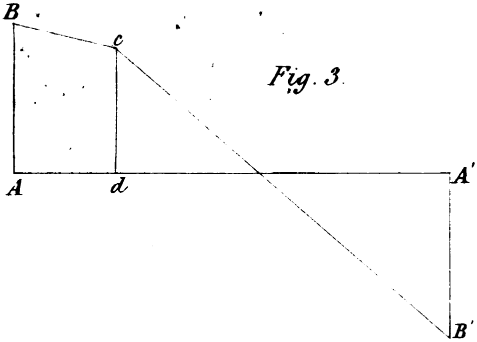

Fig. 3.

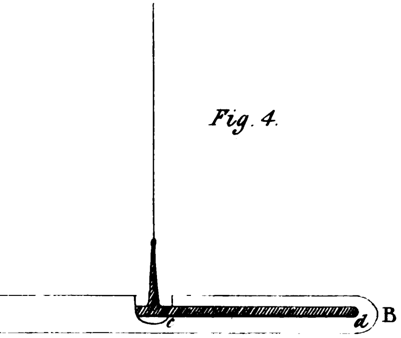

Fig. 4.

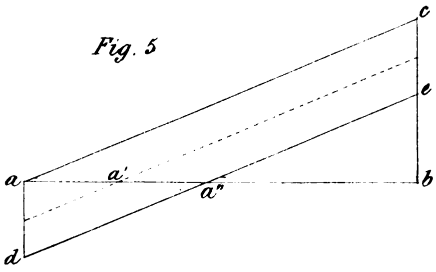

Fig. 5

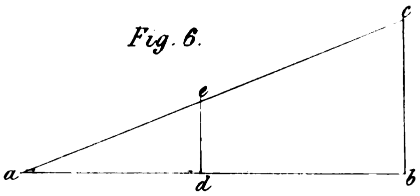

Fig. 6.

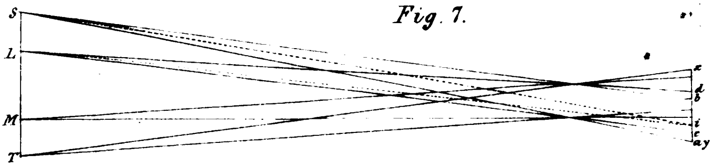

Fig. 7.