XV. *Experimental Researches in Electro-Magnetism and Magneto-Electricity. By the Rev.* William Ritchie, *LL.D. F.R.S., Professor of Natural Philosophy at the Royal Institution of Great Britain and in the University of London.*

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PART I.

ON ELECTRIC CONDUCTION.

According to the experiments of Professors Cumming and Barlow, the conducting power of a wire for voltaic electricity varies directly as its diameter, and inversely as the square root of its length. My own previous experiments on this subject, with all the conductors I then tried, led to the same result. According to the experiments of M. Becquerel, the conducting power varies directly as the square of the diameter or area of the section, and inversely as the length. M. Pouillet, from an extensive series of experiments, arrived at the conclusion that the conducting power was exactly proportional to the section of the wire, and inversely proportional to the length, increased by a constant quantity. Such discordant results, in establishing a fundamental law in electro-magnetism, obviously require a more careful examination than has yet been bestowed on them. Before we admit the accuracy of the conclusions, we must first examine the accuracy of the galvanometer employed, and the different modes of using it. The mode employed by Professors Cumming, Barlow, and Pouillet, was to observe the deflections of a compass needle placed over the conducting wire, and calculate the forces by assuming that the tangents of deflection were proportional to the deflecting forces. Now, when the conductor is indefinitely long, the wire very fine, the needle placed very near it, and the arcs of deflection small, the results obtained will not be very far from the truth. These conditions approach to the assumptions from which the mathematical law is deduced. But when the wire placed below the needle is short, when the diameter is considerable, and when the arcs of deflection rise to sixty, seventy, or eighty degrees, the results calculated in this way will be found to deviate very far from the truth. When the wire is formed into a short rectangular coil, as in the common galvanometer, no numerical results can be obtained from its indications; for all the conditions assumed in the mathematical investigation are here completely violated. A single experiment will prove the truth of this assertion.

Having placed four copper wires, about four inches long, parallel to one another, on a divided circle, I soldered the ends to those of four other wires about ten feet long, these wires being connected with an elementary battery, composed of two parallel plates of zinc and copper, each containing four square inches. The plates were immersed in diluted acid and the degree of deflection observed. An elementary battery, composed of two parallel plates, each one inch square, and having a single copper wire of the same diameter and length soldered to each, was connected with the ends of the four short wires, the battery immersed in the same acid, and the deflections observed. The tangents of these deflections, reckoning from the middle of the wires, were very nearly in the ratio of one to two, whereas the quantities of electricity were very nearly as one to four. When my torsion galvanometer (which is founded on no assumption,) was employed, the degrees of torsion were found to be nearly as one to four.

Since the tangents of deflections do not afford us accurate measures of the deflecting forces, it is obvious that any law deduced from this method must be fallacious. The mode employed by M. Becquerel in determining the law of conduction was the following. Two wires of different diameters being placed parallel to each other, had electricity in opposite directions induced on, and the length of one of the wires shortened till the needle remained stationary and parallel to the conductors. Instead of using a thick wire, the section of which was double that of the other, he employed three wires of the same diameter, and found that two of the wires having the same length, and conducting electricity in the same direction, neutralized the effect of one wire having half the length, and conducting electricity in the opposite direction. From this he concluded that the conducting powers were directly as the area of the conducting section, and inversely as the length. It is somewhat remarkable that the fallacy of this conclusion has never been observed, or at least pointed out.

He might as well have concluded that the conducting power was directly as the square root of the area of the section, and inversely as the square root of the length, or, in short, as the nth root of the area of the section, and inversely as the nth root of the length. The fact is, M. Becquerel has deduced the values of two unknown quantities from one equation.

Having shown that the laws of conduction, which we have examined, have been deduced either by false processes of reasoning or by employing galvanometers founded on false principles, these laws must be equally fallacious.

Let us examine the law, if any such exists, which connects the conducting powers of wires with the lengths when the diameters are the same. If two wires of the same diameter, but of unequal lengths, (for example, the one being four times the length of the other,) be connected with a single pair of zinc and copper plates of the same size, and immersed in diluted acid of the same strength, the short wire may be found by my torsion galvanometer to have twice the deflecting force of the other. The conducting powers of the wires might, from this experiment, seem to be inversely as the square root of the length. If the strength of the acid be increased, the ratio of the deflecting forces will have changed, the long wire having now more than half the deflecting force of the shorter one. If, on the contrary, the strength of the acid or the size of the battery be diminished, the ratio of the deflecting forces will also have changed in favour of the short wire. Again, if the diameter of the wires be altered, the lengths being the same, the ratio of the deflecting forces will also vary with the size and energy of the battery employed. This is indeed what we might expect, without experiment. The conducting power of a wire must be a function of all the quantities concerned in the experiment. These quantities are obviously the diameter of the wire, its length, the size of the battery, and the strength of the acid. It is not, therefore, to be wondered at, that those who have attempted to ascertain the law of conduction, have failed in their attempts, since all of them have overlooked one of the essential quantities concerned in the investigation, viz. the size and energy of the battery.

These deductions are in perfect accordance with the views of conduction which I have already published in the Transactions of the Royal Society. Let us suppose that there is no actual transfer of electricity along the wire, but that all the phenomena of deflection, &c., result from a definite arrangement of the electric fluid essentially belonging to the wire itself. Let us further suppose that a section of wire contains one hundred particles of electricity, and that the battery is capable of arranging one fourth of these, or twenty-five particles, then there will only remain seventy-five to be arranged by any increase of power. Let us now suppose we have another wire of the same length, whose section contains only twenty-five atoms; it is obvious that this battery will be able to arrange more than one fourth of this number, so that the ratio of the conducting powers cannot be as one to four, but will be found by actual experiment a very different ratio. If we increase the size of the battery, suppose the size of the plates to be doubled, then it is obvious we shall not double the deflecting power. For out of one hundred particles there are only seventy-five remaining, a part of which only can be arranged by the increased part of the battery. Hence the deflecting force increases very slowly with the increased size or energy of the battery.

We may conceive one of the conducting wires so diminished that the battery has arranged almost the whole of its electricity, in which case any increase in the size of the battery would scarcely produce any increase of deflecting force in the conductor. If these views be correct, it will obviously be in vain to look for a simple law of conduction involving only the lengths and diameters of the wires.

PART II.

ON CERTAIN PECULIAR PROPERTIES OF ELECTRO-MAGNETS.

Though the astonishing lifting powers of electro-magnets be sufficiently known, yet no attempt seems to have been made to investigate the law, if such exists, which connects this power with the length of the magnetic circuit. The subject appearing to me worth investigating, I procured two soft iron horse-shoe magnets (Plate VII. fig. 1.), with a short lifter, L, and having rolled the same quantity of covered wire about each, I had obviously the same inducing power when the ends were connected with the poles of the same battery. The lifter being suspended from the shorter end of a beam of light wood, and brought down on the poles of the magnet, the force by which the lifter was held could easily be ascertained by means of a sliding weight on the longer arm. The magnets, A and B, and lifter, L, were made from the same bar; the complete metallic

Fig. 1.

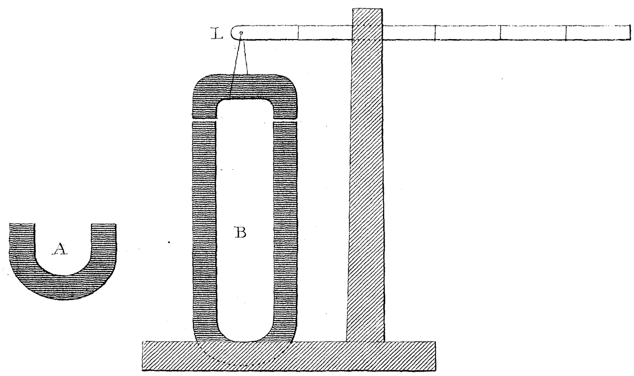


Fig. 2.

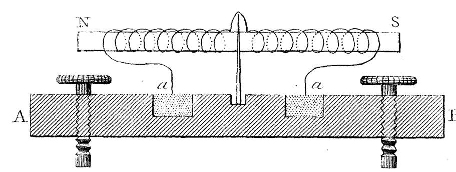
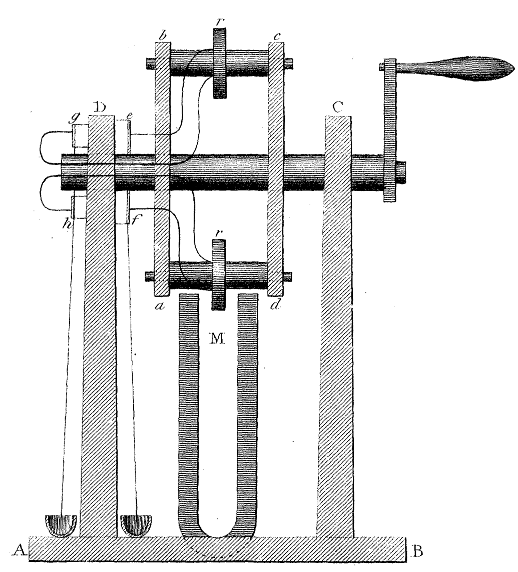


Fig. 3.



circuit in A being one foot, whilst that in B was four feet. By placing these magnets successively below the lifter, and connecting them with the poles of the same battery, the attraction of the short one was very nearly double that of the long one. This result seemed to lead to the conclusion that the lifting powers were inversely as the square roots of the length, which appeared to connect, in a remarkable degree, magnetic induction with voltaic conduction. Having discovered the fallacy of the generally received law of conduction, I began to suspect that no such simple law would be found to connect the lifting powers with the lengths.

Having substituted a more powerful battery, this simple ratio was immediately altered in favour of the long magnet, so that it now attracted the lifter with more than half the force of the smaller one: by diminishing the power of the battery, the ratio increased in favour of the short one. The reason of this variable law is obvious. When the battery is very powerful, it may be nearly able to arrange all the particles of electricity belonging to the soft iron, so as to give the short magnet nearly its greatest power. Any increase, therefore, in the size of the battery will produce very little increase of power in the short one, whilst the long one, not having more than half the power it is capable of receiving, will receive a considerable increase with every increase in the size or energy of the battery.

As a long magnet requires a large quantity of wire to cover it, and as the conducting power diminishes rapidly with the length, it is obvious the increase of lifting power which we gain by increasing the length of the magnet goes on very slowly, and that we must soon reach a limit beyond which no increase of power could be given. The truth of this observation will be rendered striking by the following experiment.

Having constructed, with great pains, an electro-magnet according to the American method, and connected it with a battery, I found it would carry about one hundred and forty pounds. I then rolled about twelve feet of copper ribbon about the middle of the lifter, which weighed about half a pound, and connected the ends of the coil with the same battery, the electro-magnet being now used as the lifter, and was surprised to find that the lifter was a more powerful magnet than that which had cost me so much labour to prepare. All that is necessary, then, in making a powerful electro-magnet, is simply to roll a ribbon of copper (metallic contact being prevented by a thin tape interposed) about a short bar of soft iron, and use a short-shoe lifter.

In constructing an electro-magnet, it is necessary to attend particularly to the quality of the iron. I have tried experiments with various kinds of iron, from the best mitre to the worst English iron, and have observed that the worst iron I could procure is best adapted for making an electro-magnet. When a piece of fine iron is broken, it appears fibrous like a piece of wood. When the worst English iron is broken, it appears of a crystalline texture, exceedingly porous, resembling cast iron. This structure appears peculiarly adapted to allow the particles of the electric fluid to arrange themselves round the crystalline particles in that mode which constitutes a magnet.

It is easy to ascertain, before making an electro-magnet, whether a certain kind of iron be well adapted for the purpose. All that is necessary, is to forge a small lifter, and try it with a common horse-shoe magnet. If it be powerfully attracted by the magnet, it is good for the purpose; if not, it should be rejected. Having made two lifters, one of them of the best iron I could procure and the other of the worst, I found that a horse-shoe magnet with the first would carry only fourteen pounds; with the second it carried no less than twenty-seven pounds.

These facts will enable us to obtain the most powerful electric state by the induction of magnets. A lifter made of the iron I have described will give a much larger spark than one made of good iron. Another circumstance to be attended to in obtaining a large spark, is to use a short lifter, with a magnet having its poles near one another. When the lifter is short, the recomposition of the electric fluid, on the return of the particles to their natural state, is almost instantaneous, and consequently induces, for an instant of time, a more powerful electric state on the coil surrounding it. When the deflection of the needle is the object, a longer lifter may be employed with advantage.

That the recomposition of the electric fluid goes on more slowly in a long than in a short magnet may be shown by the following experiment. Take a long horse-shoe magnet of soft iron and convert it into an electro-magnet. Change the poles of the battery, and the lifter will fall off by its own weight. With a short magnet the lifter will not fall off when the poles are rapidly changed; or if it does fall a little, it will be again attracted so rapidly as to bring it back to its former position.

In repeating these experiments, I was struck with a curious property of a long electro-magnet which had not been previously observed. When the wires were connected with the battery, and allowed to remain for a few seconds, and then removed, the lifter being disengaged, the soft iron scarcely retained any magnetic power. When the wires were again connected with the battery, it was rapidly converted into a magnet of considerable power. Having again removed it, and found the magnetic power almost destroyed, I connected the wires with the opposite poles of the battery, and was surprised to find that it required a long time to convert it into a magnet of much inferior power.

But the most beautiful result I have obtained from changing the poles of an electro-magnet, is the rapid rotation of such a magnet about its centre. The following short description of the first actually constructed will be sufficient to show how others of greater power may easily be formed.

Let AB, fig. 2., be a section of a circular sole of wood, having a circular groove, *a a*, turned in it for the purpose of holding mercury. The groove is divided into two compartments by thin slips of wood. These divisions are to be connected with the poles of the battery by means of cups, or in any other convenient way. NS is a piece of soft iron, having a copper wire rolled round it, the ends of the wires being made to touch the mercury in the two divisions of the groove. The electro-magnet is made to turn easily on a vertical axis, or on a fine point. The ends of the wire are adjusted so as to clear the two small divisions of wood, the surface of the mercury rising a very little above the divisions. If a horse-shoe magnet, having a considerable distance between its poles, be placed above the temporary magnet, the poles of the permanent magnet being directly above the slip of wood which divides the groove into two compartments, whilst the soft iron is converted into a magnet by means of the battery, a powerful and rapid rotation of the electro-magnet will take place; for the electro-magnet, being put in motion by the attraction of the poles of the other, will have its poles reversed the moment the wires pass the two divisions. At that moment attraction will be changed into repulsion, and the momentum thus acquired will be sufficient to carry the electro-magnet to that point where the poles will be again changed, and consequently attraction will now take place. A single magnet, with one of its poles opposite the point where the change of poles takes place, is quite sufficient to continue the rotation. By a slight modification of the apparatus, horse-shoe magnets may be made to revolve with considerable force. I have fitted a revolving apparatus of this kind, which has a power sufficient to raise several ounces over a pulley. When the apparatus is placed so that the change of poles of the electro-magnet may take place in the magnetic meridian, the action of the earth is sufficient to make the magnet revolve without the aid of exterior magnets. By fitting it up so as to revolve in the plane of the magnetic meridian, and to change its poles at the point to which the needle dips, a dipping needle might be made to revolve in a vertical plane.

PART III.

ON A MODE OF OBTAINING AN ALMOST CONTINUOUS CURRENT OF ELECTRICITY BY THE INDUCTION OF MAGNETS.

After the nature of magneto-electric induction had been developed in the splendid and ingenious researches of Mr. Faraday, and the mode of obtaining a spark from a common magnet by the method of SS. Nobili and Antinori pointed out, I clearly perceived the mode of obtaining a current of electricity, *almost* continuous, by the revolving apparatus which I am now to describe. Though the apparatus was partly constructed nine months ago, yet the laborious duties of my profession prevented me completing it till very lately. The following is a description of the best form of the instrument for answering the various purposes to which it may be applied.

In fig. 3, A B is a sole of wood, with two supports, B C, A D. Through the tops of the two supports, an axis passes, having two circular discs of wood, *a b*, *c d*, fixed on it for the purpose of holding four cylinders of soft iron, of which two of them, *b c*, *a d*, are seen in the section of the instrument. These cylinders have ribbons of copper, $r\,r'$, similar to those used in my apparatus for exploding the gases by the magneto-electric spark. Wires, proceeding from the corresponding ends of these ribbons, are made to press against a circular plate of copper, *e f*, well amalgamated. The other ends are made to pass through the axis, and being bent as represented in the figure, are made to press on a circular rim of copper, *g h*. This arc may be nearly a quadrant. The circular plate of copper and this rim have each strong copper wires soldered to them, and terminating in two cups for holding mercury. A horseshoe magnet, either permanent or electric, is placed perpendicularly on the sole, so that each of the cylinders, when made to revolve by turning the handle, may pass very near the poles of the magnet.

If the handle be now turned rapidly round, each cylinder, in passing the poles of the magnet, will become a temporary magnet, and in doing so will induce an electric state on the ribbon of copper, the two cups being connected either with a galvanometer or in any other way. After passing the poles, it returns rapidly to its neutral state, and in doing so would induce an opposite electric state on the coil if the wire did not leave the rim of copper at the proper time. When one of the wires is leaving the rim, another is just entering, so that whilst one current is ceasing to act, the other current is just beginning. We have thus a series of currents of a variable nature following each other in rapid succession, and all acting in the same direction. This current will keep the needle of a galvanometer almost steadily deflected, and will make a wire revolve about a magnet as in Mr. FARADAY's first experiment. By increasing the size of the apparatus, all the other rotations might of course be produced.

If a circular piece of copper be fixed on one of the supports on the outside of the rim formerly described, and having its circumference cut into teeth like a saw, and if the ends of the wires be made to revolve on these teeth, this plate, and that on which the other ends of the wires revolve, being connected, a series of magneto-electric sparks will follow each other, in rapid succession, for very nearly a fourth part of the circumference. If four magnets be placed opposite the four cylinders of soft iron, almost the whole circumference may be illuminated at the same instant, producing a very beautiful effect.