XIII. *Experimental Researches in Voltaic Electricity and Electro-Magnetism.*

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THE splendid discoveries which have lately been made in magnetism and electro-magnetism have so much engaged the attention of philosophers, that the theory and laws of action of voltaic electricity, no longer possessing the charms of novelty, have been entirely neglected. The subject appearing to me full of interest, and lying at the very foundation of a large portion of physical science, induced me to undertake an experimental investigation of some of the most important points connected with it, the result of which I have the honour of laying before the Royal Society.

PART I.

ON THE LAWS OF ACTION OF AN ELEMENTARY BATTERY.

1. Volta was led to the invention of the pile by what he conceived to be the discovery of a new power in nature, viz. the development of electricity by the simple contact of dissimilar metals. Other philosophers have denied the existence of this power, and have substituted that of chemical action in its stead; whilst a third class still maintain that both powers are concerned in the production of voltaic effects. We have lately had a series of experiments by M. Matteucci to prove that motions could be excited in the limbs of a frog by carefully washing it in distilled water, and then acting on it with discs of copper and zinc. These experiments were intended to prove that galvanic action resulted from the simple contact of dissimilar metals, without the aid of chemical action, and that consequently the theory of Volta was well founded.

It is easy to neutralize the effects of these experiments by one much more striking, in which decided voltaic effects are produced by one metal and one liquid.

The best mode of proving this is by the following experiment:

Exp. I.—Form a galvanometer with a coil of copper wire, and leave the ends projecting about two feet. Roll one of the ends about a small rod so as to form a close spiral about a quarter of an inch in diameter. Roll the other end of the wire about a large rod or glass tube so as to form another spiral of half an inch in diameter. Place the small spiral within the larger one, and immerse them in water containing a quantity of nitric acid, and a very considerable electro-magnetic effect will be produced.

I have given this experiment to prove, in a manner free from every objection, that voltaic action may be produced without the contact of dissimilar metals, and consequently without the aid of that mysterious force, termed by Volta and his followers *electro-motive*.

2. Those who adopt the theory of Volta have taken it for granted, without a shadow of proof, that the free positive electricity which they conceived they had detected on the surface of the zinc, was that which circulated through the liquid and metallic conductors, and produced all the phenomena of voltaic electricity. M. Parrot of St. Petersburgh has examined the fundamental experiments of Volta with the most scrupulous regard to accuracy, and observed that sometimes a minute portion of free positive electricity was detected on the zinc and at other times on the copper. This minute portion was obviously developed by friction or simple pressure of the zinc and copper plates; for when the plates were soldered together, and the experiment repeated, as described by Volta, he could not detect the slightest sign of free electricity *. From the marked difference between the effects of free and voltaic electricity, it is extremely improbable that a minute portion of common electricity could ever acquire the characters of voltaic. Common electricity is diffused over the surface of the metal;—voltaic electricity exists within the metal. Free electricity is conducted over the surface of the thinnest gold-leaf, as effectually as over a mass of metal having the same surface;—voltaic electricity requires thickness of metal for its conduction.

3. A powerful argument against the theory of free electricity becoming com-

* Annales de Chimie, xlvi. 363.

bined or voltaic when connected plates are immersed in a conducting liquid, is derived from the experiments of M. Becquerel, combined with the following. M. Becquerel found that if one end of a metallic wire be heated by a spirit lamp, it becomes positive, whilst the cold end is negative. If a platina wire be placed on the cap of a gold-leaf electrometer, and the projecting end heated and then touched with a piece of heated glass or moistened paper so as to remove the positive electricity, the gold-leaves will immediately diverge by negative electricity. It becomes then an important question to ascertain if the free electricity thus developed, changes its character and becomes voltaic. This was accomplished by the next experiment.

Exp. II. Having connected two slips of platina by copper wires with the cups of a galvanometer, I heated the end of one of the pieces, and immersed both, parallel to one another, in diluted nitric acid, when only a slight effect was produced on the needle. I then substituted iron for platina, and repeated the experiment, when a powerful effect was produced. With copper, the effect was somewhat less. With zinc, the effect was considerable: but with antimony and bismuth scarcely any effect could be observed. But what is most remarkable is the fact, that in all the cases the cold metal is positive and the hot negative; or in other words, the cold metal has the same relation to the hot, that zinc has to copper in an ordinary voltaic arrangement. This experiment demonstrates that the free electricity developed by heat has no connexion with that developed by voltaic action: since the effects of heat in developing free electricity in platina is much greater than in iron; whereas the voltaic electricity developed in iron is much greater than that developed in platina, and both of an opposite character. Since this portion of free electricity developed by heat does not become voltaic, it is exceedingly improbable that the electricity developed by the contact or pressure of metals should by immersion in a liquid acquire this character.

4. In both theories of voltaic electricity it is admitted that the zinc is positive, and the copper negative. The analogy between common and voltaic electricity seems to me to have been pushed too far. I have carefully sought for the proof of this principle, but have been unable to find any. We have already shown that the experiments of M. Parrot are quite conclusive against the truth of the experiments of Volta. Again: in the dry pile of De Luc, free posi-

tive electricity is developed at the zinc end, and negative at the copper end. But the electricity developed in the dry pile has not one character in common with voltaic. It makes gold-leaves diverge;—voltaic does not. It is most energetic with an imperfect conductor between the plates;—voltaic on the contrary increases with the conducting power of the fluid interposed. This electricity will not decompose water;—a slight development of voltaic does so, energetically. This pile is only in action when the poles are not connected;—voltaic action does not exist unless the poles be connected. The experiment of Dr. Wollaston in which he decomposed water by common electricity might seem at variance with this reasoning. But this decomposition is totally unlike that produced by voltaic electricity; for, as Dr. Wollaston remarks, a mixture of oxygen and hydrogen rose from each of the fine metallic points, a fact which shows that the decomposition was produced in a manner essentially different. The decomposition in this experiment seems to have been effected by the mechanical agency of the electric fluid. The fine electric dart shooting out from the invisible gold points may have actually cleaved a molecule of water which happened to be favourably situated, and thus its oxygen and hydrogen were disengaged at the point where the mechanical cleavage took place *.

5. It does not appear to me at all necessary that zinc and copper should be thrown into opposite electric states to produce voltaic action. I shall make no suppositions with regard to those states, but ground my views of voltaic action on well established facts. Zinc has a much more powerful attraction for oxygen than copper; and yet copper has also a decided attraction for it, otherwise there could be no salts of this metal. Let us now suppose, merely for the sake of illustration, that a molecule of water is composed of an atom of oxygen united to an atom of hydrogen. In the Plate VIII. (fig. 1.) let the oxygen be represented by the white circle, and the hydrogen by the black. The zinc plate *z*, having a greater attraction for the oxygen than for the hydrogen, will turn round the molecule of water in contact with it, till its oxygen side be towards the zinc, and its opposite side towards the copper plate *c*, which is connected with the zinc by the wire *w*. The same thing will take place with

* The same remarks apply to Mr. Barry's experiments on decomposition by atmospheric electricity. Decomposition was never effected by common electricity in which the component parts of the substance were liberated at opposite poles.

Fig. 1.

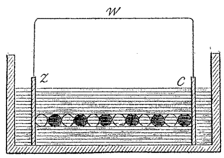


Fig. 2.

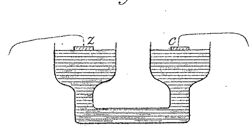


Fig 3.

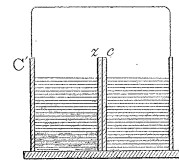


Fig. 5.

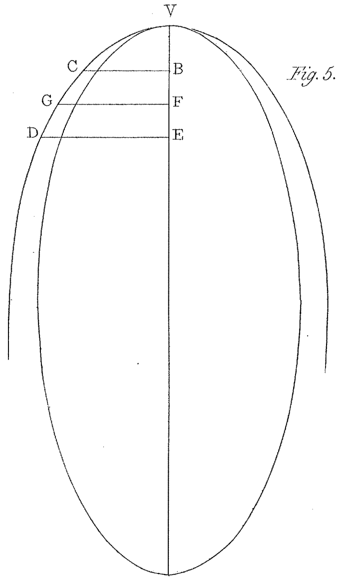


Fig. 6.

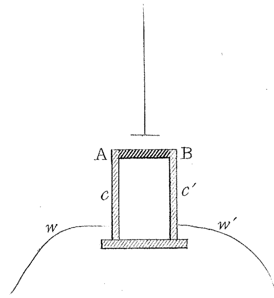


Fig. 4.

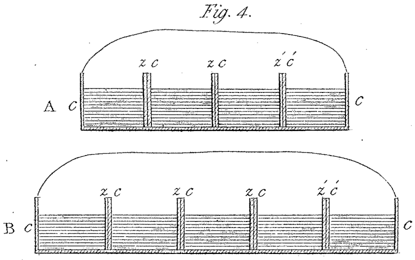


Fig. 8.

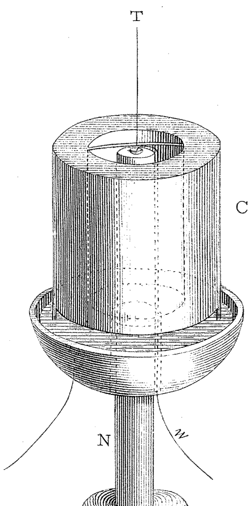


Fig. 7.

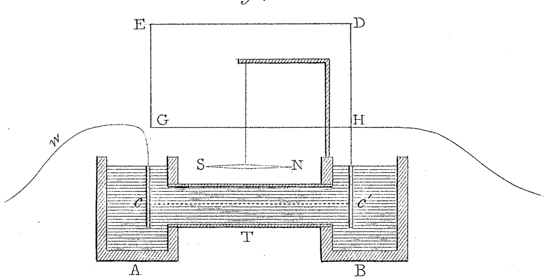


Fig. 9.

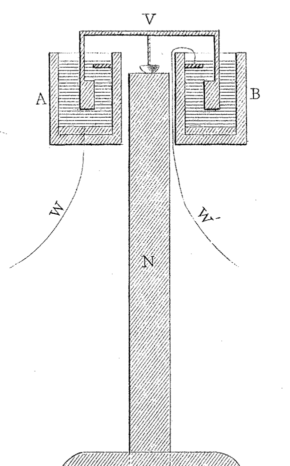
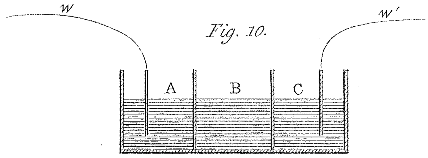


Fig. 10.



the other molecules, till the whole chain of aqueous particles be arranged in this definite order. The component parts of the electric fluid naturally belonging to the oxygen and hydrogen will also assume a definite arrangement. The component parts of the electric fluid, thus arranged, will act by induction on the neutral electricity belonging to the metallic plates and connecting wire, and thus produce a definite arrangement of the molecules of the electric fluid along the whole metallic circuit *.

If the attraction of the oxygen for the hydrogen be stronger than the attraction of one of the metals for the oxygen, the water cannot be decomposed; and yet this definite arrangement may take place, and consequently there may be decided electro-magnetic effects without chemical decomposition. Hence diluted alcohol when placed between the copper and zinc plates, develops voltaic electricity without the slightest trace of decomposition.

If the attraction of the zinc for the oxygen be greater than that of the oxygen for the hydrogen, the oxygen will combine with the zinc, and the hydrogen will be set at liberty. This hydrogen must therefore either be transported through the liquid to the copper, or attach itself to the oxygen of the next molecule of water, and set its hydrogen at liberty; and so on, till the last atom of hydrogen in contact with the copper plate, having nothing to combine with, escapes in its gaseous state. It is difficult to conceive how hydrogen could be dragged through the intervening mass of liquid with equal facility in every direction, and even when the plates are separated by a moistened diaphragm of bladder. The view we have taken of voltaic action, without any actual transfer of hydrogen, appears the most simple and natural; and striking illustrations of its truth will be given in future experiments.

When an atom of oxygen is separated from the hydrogen at the surface of

* Since this paper was written, these views have received a striking confirmation from the splendid discoveries of Mr. FARADAY. That ingenious philosopher has proved, by the clearest evidence, that the neutral electric fluid, essentially belonging to a metallic wire, may be *decomposed* by the inductive power of a common magnet, and has even obtained an electric spark from a temporary magnet, *the only magnet from which a spark has been obtained;* for, in the experiments of NOBILI, in which a common magnet is used, it is still from a *temporary* magnet that the spark is ultimately obtained. To render the analogy more striking, I have succeeded in exploding a mixture of oxygen and hydrogen gases by the spark obtained from the induction of a common magnet, without any actual transfer of electricity from the magnet to the conductor.

the zinc plate, the molecules of water must turn round their axes till the definite arrangement of the particles again take place. This revolution of the particles of water must obviously produce, by induction, a similar revolution of the molecules of the electric fluid round the distinct elementary particles of which the metallic conductor is composed, agreeably to the ingenious theory of M. AMPÈRE.

From this view of the subject, it is obvious that whatever will render the water more easily decomposed will also increase the power of the voltaic arrangement. If the temperature of water be raised, the attraction between its molecules will be diminished; it will therefore become more fluid, its molecules will be turned round with a smaller force, and arrange themselves in the definite order which seems essential to voltaic action. Again: strong sulphuric acid is an imperfect conductor; pure water is also a bad conductor; but if they be mixed together, we get a liquid of high conducting powers. Now, according to the theory of an actual transfer of electric fluid, this is exceedingly mysterious; but is a necessary consequence of the view now given. When water is mixed with sulphuric acid, the attraction between its own molecules must be diminished, and consequently acidulated water will be more easily decomposed than pure water, and will consequently produce more powerful effects when placed between the copper and zinc plates in a voltaic arrangement.

6. If this view of the subject be correct, it follows that all liquids whose component parts go to the same pole, are non-conductors of voltaic electricity. Oils, resinous substances, melted camphor, caoutchouc, &c. are hence non-conductors. The liquified gases, examined by Mr. KEMP, submit to the same law. Liquified sulphurous acid is a good conductor, because oxygen and sulphur, its component parts, go to opposite poles. Liquified ammoniacal gas is doubtful as to its conducting power. Hydrogen goes decidedly to the negative pole, but nitrogen seems doubtful to which pole it belongs; and hence Mr. KEMP, without any view of supporting a favourite theory, could not determine with certainty whether this substance was a conductor, or not. It obviously follows from this view of conduction, that all simple substances (except the metals,) in a fluid state are essentially non-conductors. When liquified chlorine was submitted to the same test, it was found to be a perfect non-conductor. This affords another beautiful illustration of the simple nature of chlorine.

7. In examining the conducting power of alcohol when placed between platina discs connected with a powerful battery, I was at first surprised to find a gas given off at the negative pole, without the slightest appearance of anything being separated at the positive pole. After collecting a small portion of the gas, I found it to be pure olefiant gas.

Now, alcohol being composed of oxygen, hydrogen and carbon, in the proportions which constitute water and olefiant gas, it is obvious that water, without suffering decomposition, must have been separated at the positive pole. This is indeed what might have been expected. Water, being composed of oxygen and hydrogen, must have a greater tendency to the positive pole than olefiant gas, the component parts of which have both a decided tendency to the negative pole. When the alcohol is diluted, it becomes a better conductor, in consequence of its becoming more easily decomposed. The water with which it has been diluted does not suffer decomposition, but performs the same office with regard to alcohol that sulphuric does when mixed with water.

8. It obviously follows from this view of conduction, that a liquid has a very confined limit to its conducting power, or, in other words, that a section of a liquid will only conduct a given quantity of electric influence. This was established by the following experiment.

Exp. III. Having drawn out a glass tube in the middle, by means of a blowpipe, and bent it into the shape of the letter U, as in fig. 2, I filled it with diluted acid.

Discs of copper and zinc of the same diameter with the narrow part of the tube, and connected with the torsion galvanometer, were immersed at *z* and *c*, and the deflecting force ascertained. Having removed these plates, and substituted others several times larger, very little increase of effect was observed. It appears from this experiment, that the water in the narrow part of the tube had been arranged in the definite order, and that an increase of metallic surface had very little effect in modifying the arrangement.

9. If this view of conduction be correct, there can be no actual transfer of electricity along those substances which are called conductors, as in the case of common electricity; the whole of the effects depending on the definite arrangement of the molecules of the electric fluid, essentially belonging to the conducting substance. Let us suppose, for the sake of illustration, that the

atoms of the vitreous and resinous elements possess polarity, or have the strongest tendency to unite at opposite points. These poles will obviously be arranged facing each other in a copper and zinc plate, forming an elementary battery. This arrangement will re-act on the chain of aqueous molecules, till the maximum of effect take place. The electric fluid thus arranged in the zinc and copper plates will be partially retained by the coercitive force of the metal. Hence it follows that the electric molecules might be so arranged as to have opposite poles turned to opposite sides of a thin plate of metal; or, to use the usual mode of expression, a thin plate of metal might have one side rendered positive and the other negative. The best mode of exhibiting this property, which seems first to have been observed by Ritter, is the following.

Exp. IV. Cement three very thin copper plates, about two inches square, in a wooden trough, at the distance of half an inch from each other, having copper wires soldered to each. Connect the extreme plates with the ends of a powerful battery, the spaces between them being previously filled with diluted acid, and allow decomposition to go on for a few minutes. Remove the battery, and connect one of the extreme plates and the middle one with a galvanometer, and very decided electro-magnetic effects will be observed. Connect the other extreme plate and the middle one with the galvanometer, and the needle will be powerfully deflected in the opposite direction.

This appears to offer the true explanation of the secondary piles of Ritter, and the more recent experiments of M. De la Rive.

10. When diluted sulphuric acid is employed in an elementary battery, the water is rapidly decomposed, and hydrogen is copiously evolved at the surface of the copper plate, even when a diaphragm of moistened bladder is interposed between the plates. With this acid the electro-magnetic effects are proportioned to the quantity of hydrogen liberated at the copper plate, without any regard to the immense quantities which may be liberated at the surface of the zinc plate. When nitric acid is employed, a much greater electro-magnetic effect is produced, though a much less quantity of hydrogen be now liberated at the surface of the copper plate. This acid seems to favour the facility of the definite arrangement of the molecules of water, without rendering it so easily decomposed. When the surfaces of the zinc and copper plates are covered with bubbles of hydrogen, the effect must be much diminished, as

the gases are non-conductors of voltaic electricity. The increase of effect, then, which is gained by the addition of nitric acid, seems to result from this circumstance, whilst the sulphuric acid, by dissolving the oxide, keeps the surface comparatively clean. When diluted sulphuric acid alone is used, and the plates in an elementary battery placed at different distances from one another, the quantities of hydrogen disengaged at the surface of the copper plate are within certain limits inversely proportional to the square roots of the distance between the plates; a law which has been found to connect the distances of the plates with the electro-magnetic effects *.

If the plates be removed to a very great distance, they will be unable to arrange the molecules of the fluid in the definite order which seems essential to the development of voltaic electricity, when all action will, of course, cease. As we approach this limit, the diminution of effect goes on more rapidly than the square root of the distance. When the plates, on the other hand, are brought very near each other, the increase of effect goes on more slowly than the square root of the distance, probably on account of the small space being partially filled with gaseous matter. Had these exceptions to the general law not taken place, there would have been no limit to the increase of effect till the plates had been brought into actual contact; nor would there have been a complete destruction of voltaic effect till the plates had been removed to an infinite distance.

PART II.

INVESTIGATION OF THE FUNDAMENTAL PRINCIPLE AND LAWS OF ACTION OF THE VOLTAIC BATTERY.

11. In every theory of the battery which has yet been proposed, an actual transfer of electricity is supposed to take place, and a continued circulation kept up through the entire circuit. According to the two theories, the battery is supposed to be charged before the poles are connected, and the electricity thus accumulated is ready to rush along the connecting wire the moment the poles are brought in contact. I can find no proof either for this accumulation or actual transfer, nor have we any proof that voltaic action takes place till the circuit be completed. Nor does any theory of the battery which has yet

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been proposed take into view the law which connects the voltaic action of an elementary battery (or that consisting of a single pair of plates,) with the distance between them; a law essentially connected, not only with the action of the battery, but with its very existence. It is curious to remark that VOLTA, by reasoning from false principles and on very imperfect data, arrived at the invention of one of the most powerful instruments of research which genius has bequeathed to the philosopher.

I would not be understood, by this remark, to detract from the merit of the Italian philosopher. I have ventured this observation to encourage the young philosopher in his pursuit of physical truth, even when his views are imperfect and obscure.

From these observations it is obvious that the theory of the battery is incomplete, if not absolutely false. It is entirely from possessing the most perfect measurer of voltaic electricity,—namely, the torsion galvanometer,—that I have been enabled to give a more complete analysis of the principles of the battery, and the laws which regulate the accumulation of voltaic power.

12. In analysing the compound effect of the battery, we must first examine what takes place, when a single pair of zinc and copper plates are soldered together, and diluted acid placed in cells on their opposite sides, instead of being placed between them as in the elementary battery.

Let *z c* (fig. 3.) represent a zinc and copper plate soldered together, and let C′, C″ be two copper plates of the same size connected together, and cemented in a trough having the cells filled with diluted acid. The acid in the left-hand cell, between the two copper plates, can act only as a conductor, and hence the action of the compound plate *z c* will be exactly the same as what would take place if C″ and C′ were connected by a fine metallic wire having the same conducting power as the mass of fluid contained in that cell. In order to ascertain the effect of this arrangement, let wires proceeding from the copper plates C′, C″ be connected with a very delicate torsion galvanometer having astatic needles. Let another compound plate of zinc and copper be cemented between the extreme copper plates, and let copper wires from these plates be connected with the galvanometer as before, and the deflecting force will be found to be doubled. If three plates be introduced, the effect will be tripled; and so on in proportion to the number of plates. Hence the voltaic

effects of two batteries of the same length, and having the same size of plates, will be directly proportional to the number of plates. Hence it follows that each pair of plates produces an equal effect in whatever part of the battery it is placed. This is one of the fundamental principles on which the true theory of the battery is founded.

13. Since each pair of plates, then, produces an equal effect, let us now examine what will take place with regard to batteries of unequal lengths, when the plates are of the same size, and placed at the same distance from one another.

Let A, B be two batteries, having the same size of plates, and placed at the same distance from one another, and let n be the number of plates in A, and N the number in B. Let the voltaic effect of the extreme pair of plates in the first battery be denoted by F, and that of the extreme pair in the second by f.

Two equal plates of copper c, c are placed at the ends of each, and the extreme cells filled with the same diluted acid as that used in the other cells. The extreme pair in the battery A which produce the effect F, are $z' \; c'$; and those in the second battery which produce the effect f, are $z' \; c'$.

Now, since the effects of the extreme plates are inversely as the square roots of their distances, they will be inversely as the square roots of the number of plates. Hence $F : f : : \frac{1}{n^{\frac{1}{2}}} : \frac{1}{N^{\frac{1}{2}}}$. Multiplying the terms of this proportion by those of the identical proportion

$$n : N : : n : N,$$

we have $$n F : N f : : \frac{n}{n^{\frac{1}{2}}} : \frac{N}{N^{\frac{1}{2}}}$$

or $$n F : N f : : n^{\frac{1}{2}} : N^{\frac{1}{2}}$$

But n F being the accumulated energy of the battery A, and Nf that of the battery B, we have, within certain limits, the voltaic energies of two batteries, very nearly proportional to the square roots of the number of plates.

14. Had the conducting power of acid solutions in an elementary combination been in the simple inverse ratio of the distance, there could have been no accumulation of voltaic effect; or, in other words, the battery could never have existed.

For in that case we should have had

$$F : f : : N : n$$

and $$n : N : : n : N$$

Hence $$nF : Nf : : nN : nN : : 1 : 1.$$

That is, the effects of batteries of any number of plates would always have been to each other in a ratio of equality.

15. Had the law of diminution followed the square of the distance instead of the square root, there would obviously have been a loss of power by an increase in the number of plates. It is obvious, then, that any theory which does not take in the law of conduction must be founded on very imperfect data.

16. I was now anxious to ascertain whether the preceding reasoning was borne out by direct experiment, which must always be considered as the criterion of the truth of any theory in physical science. By the following experiments this theory of the battery must either stand or fall.

Exp. V. Having fixed two pieces of copper, an inch broad and two inches high, in the bottom of a box separated into two compartments by a diaphragm of bladder, and inverted a funnel-mouthed tube over one of them, (the box being previously filled with water slightly acidulated,) I connected the plates with the ends of a battery of thirty pair of plates. The hydrogen disengaged in three minutes was found to occupy about two inches and a half of the tube. The plates were now connected with one hundred and twenty plates of the same battery, and the decomposition allowed to go on for the same time; when it was found that the hydrogen collected was scarcely double that in the first experiment. Now the number of plates being as one to four, and the quantity of hydrogen nearly as one to two, we have the effects nearly as the square roots of the number of plates. By increasing the number of plates to a great extent, we should find, agreeably to a remark in § 10 of Part First, that the increase of effect would not go on so rapidly as the square root of the number of plates. This fact, which follows from theory, is strikingly confirmed by direct experiment.

17. The theoretical views now unfolded are strikingly confirmed by the application of the torsion galvanometer in the following experiment.

Exp. VI. Two copper plates four inches square, having copper wires soldered

to them, were immersed in the extreme cells of a battery of thirty, four-inch plates; metallic contact between the copper plates and the ends of the battery being carefully avoided. The connexion being made with the cups of the galvanometer, the deflecting force was found to be equal to 90 degrees of torsion of the glass thread. The copper plates were then immersed in the extreme cells of the same battery, containing one hundred and twenty pair of plates, when it was found that the degrees of torsion were somewhat less than 180. Hence the electro-magnetic effects of the two batteries were nearly as the square root of the number of plates. Hence the electro-magnetic effects of two batteries are within certain limits proportional to the quantities of water decomposed.

18. These principles will enable us to account for a fact in electro-magnetism which has never been explained in a satisfactory manner. Since the discoveries in electro-magnetism, it was observed that no increase of electro-magnetic power is gained by increasing the number of plates in a battery, when the extreme plates were connected by metallic contact with the ends of the battery. This unexpected result has been accounted for by supposing that voltaic electricity, having tension like common electricity, acts feebly on a magnetic needle. Not feeling satisfied with this vague explanation, I had again recourse to experiment.

Exp. VII. Having soldered copper wires to several plates in a common galvanic trough, I connected a single pair with the galvanometer, and observed the deflecting force. By connecting the extreme plate and the others in succession with the galvanometer, the effect, within certain limits, was observed to be nearly constant. When the number of plates was increased to forty or fifty, a slight diminution of power was observed.

Since the deflecting force of a single pair is inversely as the square root of the distance between them, which is the whole length of the battery, and since the effects of all the other plates are directly as the square root of their number, it follows that within narrow limits the compound effect must be constant *.

* The supposed analogy between common and voltaic electricity, which was so eagerly traced after the invention of the pile, completely fails in this case, which was thought to afford the most striking resemblance.

19. The law now established may be exhibited to the eye by the co-ordinates of a parabola. Let V B (fig. 5.) represent the length of a battery, and the ordinate B C its voltaic power; and let V E be the length of another battery, the plates being equal and placed at equal distances, and let D E be its voltaic power; then will F G represent the power of a battery whose length is V F. When the length of the battery becomes great, the length of the ordinates diminishes more rapidly than in the parabola, or the curve approaches more to the nature of an ellipse. For want of a battery of a sufficient number of plates, I have been unable to determine the real nature of the voltaic curve. It appears exceedingly probable that the curve returns into itself, or, in other words, that the battery after gaining a certain power gradually loses its energy by any further increase of the number of plates. I should have scarcely any hesitation in touching the ends of a battery a mile long, and still less if it were extended to the length of ten miles.

PART III.

APPLICATION OF THE PRECEDING PRINCIPLES TO FURTHER DEVELOPMENTS IN VOLTAIC ELECTRICITY.

20. There are only three substances which can be regarded as good conductors of voltaic electricity: viz. the metals, charcoal, and acidulated water. The metals when employed as conductors seem to have been the only substances whose deflecting energy on the needle has been carefully examined. It appeared to me worth an experiment to ascertain if charcoal deflected the needle, and that, too, with the same energy as metal conducting an equal quantity of voltaic electricity. This was ascertained by the following arrangement.

Exp. VIII. A piece of charcoal about an inch and a half long was placed between two slips of copper fixed perpendicularly in a piece of wood, and an astatic needle, suspended by a fibre of silk, brought over the middle of the charcoal. Fig. 6. will exhibit this arrangement, in which A B is the charcoal, c, c' the slips of copper, w, w' wires soldered to the copper slips. When the wires were connected with an elementary or with a compound battery, the needle was deflected in the same manner as by a metallic wire. When one of the slips of copper was placed below the needle and at the same distance as

before, the needle was equally deflected. The needle is therefore deflected by the quantity of electricity conducted, without any regard to the nature of the conducting substance.

Since charcoal therefore deflects the needle, it might be made to rotate about a magnet, agreeably to the laws first established by the ingenious experiments of Mr. FARADAY. This was accomplished as follows:

EXP. IX. A thin slip of copper, having a small cup soldered on the middle, and two short tubes on the ends to hold pieces of charcoal, was placed on the point of a needle on the pole of a horse-shoe magnet, the points of charcoal being made to dip into the mercury contained in a wooden cup, as in the experiment for the rotation of a wire. The charcoal was now made to conduct voltaic electricity from a battery of a hundred pair of plates, when it revolved rapidly, as a metallic wire would have done in similar circumstances.

21. The French philosophers have introduced a distinction between the current of voltaic electricity passing along a metallic conductor, and that transmitted by a liquid conductor, which seems to me entirely groundless. This distinction may be given in the words of Mr. CUMMING in his translation of DEMONFERRAND's Manual of Electro-Dynamics: "In the present state of science it is perhaps expedient to consider electrical currents in another point of view, namely, as being continuous or discontinuous. The first are those which are transmitted by perfect conductors, and whose intensity varies insensibly in two consecutive instants; as in the thermo-electric or in the common galvanic circuits. When the conductors are imperfect, the currents are discontinuous: for bodies of this description permit the electricity to accumulate for a certain time, after which, the insulating force being overcome, it passes with an explosion; and if the electro-motive power continues to act, there ensues a second accumulation and explosion as before, and so on successively. The distinctive character of such currents is, that they are incapable of producing a deviation in the magnetic needle *."

From the manner in which this distinction is laid down by the French writers, I had always taken it for granted that a needle suspended above the liquid part of a conductor of voltaic electricity was feebly deflected, and should probably have remained in this belief had I not entered on the present ex-

* CUMMING's Translation of DEMONFERRAND's Electro-Dynamics, p. 116.

perimental investigation. This assertion I put to the test of experiment, as follows:

Exp. X. Having cemented a glass tube, about an inch in diameter and four inches long, into two wooden boxes A, B, as in fig. 7, and filled the whole with water, I placed two plates of copper *c*, *c'*, having copper wires soldered to each, opposite the ends of the glass tube T. The wire proceeding from *c'*, after extending about a foot upwards, was bent towards the left at D, and then made to descend at E and pass parallel to the needle N S, and thence to the end of a battery. The other wire *w* was connected with the other end of the battery. It is obvious from this arrangement, that the effects of the electricity arranged in the cylinder of water, and those of the horizontal branch of the wire above the needle, would be to turn the needle in opposite directions. When the branch G H was further from the needle than the axis of the tube, represented by the dotted line, the needle was deflected in obedience to the cylinder of water; but when the wire was brought nearest the needle, it was deflected in the opposite direction.

When the wire was placed at the same distance from the needle as the axis of the cylinder, the needle remained perfectly stationary. When a disc of zinc was substituted for one of the copper plates, and the wires connected so as to form an elementary battery, the needle was deflected with the same force by the column of water as by the metallic part of the circuit. Hence it is obvious that a cylindrical column of water conducting voltaic electricity deflects the needle with the same energy as a metallic wire passing along its axis and forming a part of the same circuit.

22. To complete this part of the inquiry, I was anxious to make a hollow column of water revolve about the pole of a magnet. This was accomplished as follows:

Exp. XI. Having procured two thin hollow cylinders of wood, the one about two inches and a half in diameter, and the other about an inch and a half, I cemented the one within the other at the bottom. Two flat rings of copper were then fixed parallel to each other, at the bottom and top of the cylindrical box, the space between them being for the reception of water or diluted acid. This annular space was divided into two compartments by thin slips of wood, placed perpendicularly to prevent the water revolving without carrying the

box along with it. Two small metallic points were made to pass from the lower copper ring through the bottom of the box, for the purpose of dipping into a cup for holding mercury. The opposite sides of the upper ring were connected by a wire, to the middle of which was soldered a metallic point to dip into a small metallic cup for holding mercury on the top of the magnet. The whole arrangement will be obvious from the simple inspection of fig. 8, in which the cylinder C is seen in perspective, with the metallic point to dip into the mercury contained in the wooden cup which is used for the common rotation of a wire, and N the magnet. The box is partly suspended by an untwisted thread T, so that the metallic point may not rest on the bottom of the cup on the top of the magnet, but simply dip into the mercury.

When the wire *w*, from the cup on the top of the magnet, is connected with one end of a powerful battery, and the wire from the wooden cup into which the metallic point dips, connected with the other, the water in the box is rapidly decomposed, and the whole revolves about the pole of the magnet. By changing the poles, the box and its contents are made to turn round in the opposite direction. I was now anxious to make the hollow cylinder of water revolve, whilst the vessel in which it was contained remained stationary. This was accomplished by the following arrangement.

Exp. XII. Two glass cylinders were cemented into grooves in a circular piece of wood, through the centre of which the magnet was made to pass, as in the preceding experiment. The circular rims of copper were fixed as in the wooden cylinder, the breadth of the upper ring being considerably less than that of the lower. The inspection of fig. 9. will render the whole obvious, in which A B is a section of the glass cylinders, N the magnet, W the wire connected with the lowest copper ring, W′ that connected with the other and reaching to the ends of the battery; V represents a wooden vane, having two vertical branches immersed in the conducting liquid, and balanced on a fine point resting on the top of the magnet.

When the wires are connected with a powerful battery, the water begins to revolve, forming a real vortex and carrying the wooden vane along with it. When bodies of the same specific gravity as that of the fluid are thrown into it, the rotation is rendered obvious without the wooden vane. When the lower ring is connected with the negative end of the battery, the bubbles of

hydrogen as they ascend wind round in a spiral direction till they reach the surface of the fluid.

These experiments demonstrate that the action of magnets is entirely on the electric current or electric arrangement, without any relation to the ponderable substances with which it combined; and they may yet enable us to assign the causes of currents in the ocean which have not received a satisfactory explanation.

23. In examining the changes which take place in water placed between the platina poles of a powerful galvanic battery, I was struck with the difference of temperature which I observed in the water at the two poles. The phenomena which thus presented themselves appearing to me new and highly interesting, I was induced to examine the subject by careful experiments and investigation. The following arrangement presented itself, and brought out new and unexpected results, which seem to open a wide field for future inquiry.

Exp. XIII. Having made a small rectangular box, I divided it into three compartments by diaphragms of bladder, as in fig. 10, in which A, B, C are the three chambers. Platina poles were introduced into the extreme chambers, and the box nearly filled with common water. The copper wires *w, w'* being connected with the ends of a powerful battery, the water was rapidly decomposed through the moist bladder. After decomposition had gone on for eight or ten minutes, the temperature of the water in the three cells was examined, when it was found that the temperature of the water in each of the cells had risen during the experiment, that the temperature of the water at the positive pole had risen several degrees higher than that in the negative cell; but what seemed most remarkable was the fact that the water in the middle cell had risen several degrees higher than the water in the positive or hottest chamber. The cause of this curious result soon presented itself.

The general rise of temperature in the conducting fluid is undoubtedly caused by the same agency which raises the temperature of a metallic wire performing the same office as the fluid. The difference of temperature in the extreme cells depends on the specific heats of the gases disengaged. The specific heat of oxygen is nearly the same as that of hydrogen. But there being twice as much hydrogen given off at the negative pole as oxygen at the

positive, it will absorb nearly twice as much heat from the water in that chamber as the oxygen does from the water in the other. The temperature of the water in the negative chamber must therefore be kept lower than that in the other compartment. If liquids could conduct voltaic electricity without suffering decomposition, the temperature of the whole mass between the poles would have its temperature equally elevated in every point; but the two unequal cooling processes going on in the extreme chambers, occasion the striking inequality of temperature in the three divisions. But this experiment appears to me to establish another point of vast importance in the theory of voltaic electricity. If the hydrogen which is set at liberty at the negative pole traversed the fluid between the two poles, it is obvious it must have acquired its specific heat at the positive pole, and consequently could not have lowered the temperature in the negative cell. The oxygen, then, which is disengaged at the positive pole must have belonged to the film of water in contact with that pole, and the hydrogen set at liberty at the negative pole must have been the hydrogen belonging to the film of water in contact with the negative pole. There appears, therefore, to be no actual transfer of the component parts of water, but, agreeably to the views of M. Grotthus, a continued series of decompositions and recompositions along the whole chain of aqueous particles between the two poles.

24. The explanation now given of this curious phenomenon receives the strongest confirmation from the decomposition of other substances besides water. When a solution of sulphate of copper was placed between the poles of a powerful battery, and the temperatures of the cells examined as before, it was found that a much greater difference between the temperatures of the extreme chambers took place; but the temperature of the negative chamber was now higher than that of the positive. In some of my experiments the temperature of the negative cell rose eight or ten degrees above that of the positive, whilst the middle chamber was nearly of the same temperature with the negative compartment. The same striking difference was observed when a solution of acetate of lead was employed.

The cause of this change of temperature depends, as in the case of water, on the specific heats of the elements separated at the two poles. When a metallic salt is decomposed by the agency of voltaic electricity, the pure

metal is separated at the negative pole, whilst the oxygen appears at the other pole. Now, the specific heats of metals are exceedingly small. The change of state, then, from the liquid to the solid, which took place in the negative chamber, must have raised the temperature, whilst no such change of state took place in the positive compartment. Hence the temperature of the negative cell must be higher than that of the positive. It is unnecessary to multiply examples. If we know the specific heats of the substances set at liberty in the extreme chambers, we can tell, à priori, which of the compartments will have the highest temperature,—which affords the most satisfactory evidence of the accuracy of the explanation given of these interesting phenomena.