

XLII.—*On the Modern Development of Faraday's Conception of Electricity.*

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[The Faraday Lecture, delivered before the Fellows of the Chemical Society, in the Theatre of the Royal Institution, on Tuesday, April 5, 1881.]

LADIES AND GENTLEMEN,

As I have the honour of speaking to you in memory of the great man, who from the very place where I stand has so often revealed to his admiring auditors the most unexpected secrets of nature, I hope at the outset to gain your assent if I limit my exposition to that side of his activity, which I know the best from my own experience and studies: I mean the theory of Electricity. The majority, indeed, of Faraday's own researches were connected directly or indirectly with questions regarding the nature of electricity, and his most important and most renowned discoveries lay in this field. The facts which he discovered are universally known. Every physicist, at present, is acquainted with the rotation of the plane of polarisation of light by magnetism, with dielectric tension and diamagnetism, and with the measurement of the intensity of galvanic currents by the voltameter, whilst induced currents act on the telephone, are applied to paralysed muscles, and nourish the electric light. Nevertheless, the fundamental conceptions by which Faraday was led to these much admired discoveries, have not received an equal amount of consideration. They were very divergent from the trodden path of scientific theory, and appeared rather startling to his contemporaries. His principal aim was to express in his new conceptions only facts, with the least possible use of hypothetical substances and forces. This was really an advance in general scientific method, destined to purify science from the last remnants of metaphysics. Faraday was not the first, and not the only man, who has worked in this direction, but perhaps nobody else at his time did it so radically. But every reform of fundamental and leading principles introduces new kinds of abstract notions, the sense of which the reader does not catch in the first instance.

Under such circumstances it is often less difficult for a man of original thought to discover new truth than to discover why other people do not understand and do not follow him. This difficulty must increase in Faraday's case because he had not gone through the same common course of scientific education as the majority of his readers. Now that the mathematical interpretation of Faraday's conceptions

regarding the nature of electric and magnetic forces has been given by Clerk Maxwell, we see how great a degree of exactness and precision was really hidden behind the words, which to Faraday's contemporaries appeared either vague or obscure; and it is in the highest degree astonishing to see what a large number of general theorems, the methodical deduction of which requires the highest powers of mathematical analysis, he found by a kind of intuition, with the security of instinct, without the help of a single mathematical formula. I have no intention of blaming his contemporaries, for I confess that many times I have myself sat hopelessly looking upon some paragraph of Faraday's descriptions of lines of force, or of the galvanic current being an axis of power, &c. A single remarkable discovery may, of course, be the result of a happy accident, and may not indicate the possession of any special gift on the part of the discoverer; but it is against all rules of probability, that the train of thought which has led to such a series of surprising and unexpected discoveries, as were those of Faraday, should be without a firm, although perhaps hidden, foundation of truth. We must also in his case acquiesce in the fact that the greatest benefactors of mankind usually do not obtain a full reward during their lifetime, and that new ideas need the more time for gaining general assent the more really original they are, and the more power they have to change the broad path of human knowledge.

Faraday's electrical researches, although embracing a great number of apparently minute and disconnected questions, all of which he has treated with the same careful attention and conscientiousness, really always aim at two fundamental problems of natural philosophy, the one, more regarding the nature of the forces termed physical, or of forces working at a distance; the other, in the same way, regarding chemical forces, or those which act from molecule to molecule, and the relation between these and the first.

I shall give you only a short exposition on the degree of development which has been reached in the present state of science with regard to the first of these problems. The discussion of this question amongst scientific men is not yet finished, although, I think, it approaches its end. It is entangled with many geometrical and mechanical difficulties. How these are to be solved, and what are the arguments *pro* and *contra*, I cannot undertake to explain in a short public lecture, with any hope of gaining your scientific conviction. I can therefore give only a short statement of this side of the question, representing my own opinions; but I must not conceal the fact, that several men of great scientific merit, principally among my own countrymen, do not yet agree with me.

The great fundamental problem which Faraday called up anew for discussion was the existence of forces working directly at a distance

without any intervening medium. During the last and the beginning of the present century, the model, after the likeness of which nearly all physical theories had been formed, was the force of gravitation acting between the sun, the planets, and their satellites. It is known with how much caution and even reluctance, Sir Isaac Newton himself proposed his grand hypothesis, which was destined to become the first great and imposing example of the power of true scientific method. We need not wonder that Newton's successors attempted at first to gain the same success by introducing analogous assumptions into all the various branches of natural philosophy. Electrostatic and magnetic phenomena especially appeared as near relations to gravitation, because electric and magnetic attractions and repulsions, according to Coulomb's measurements, diminish in the same proportion as gravity with increasing distance.

But then came Oerstedt's discovery of the motions of magnets under the influence of electric currents. The force acting in these phenomena had a new and very singular character. It seemed as if this force would drive a single isolated pole of a magnet in a circle around the wire conducting the current, on and on, without end, never coming to rest. And although it is not possible really to separate one pole of a magnet from the other, Ampère succeeded in producing such continuous circular motions by making a part of the current itself moveable with the magnet.

This was the starting point for Faraday's researches on electricity. He saw that a motion of this kind could not be produced by any force of attraction or repulsion, working from point to point. The first motive which guided him seems to have been an instinctive foreboding of the law of conservation of energy, which many attentive observers of nature had entertained before it was brought by Joule to a precise scientific definition. If the current is able to increase the velocity of the magnet, the magnet must react on the current. So he made the experiment, and discovered induced currents. He traced them out through all the various conditions under which they ought to appear. He found that an electromotive force striving to produce these currents arises wherever and whenever magnetic force is generated or destroyed. He concluded that in a part of space traversed by magnetic force there ought to exist a peculiar state of tension, and that every change of this tension produces electromotive force. This unknown hypothetical state he called provisionally the electrotonic state, and he was occupied for years and years in finding out what this electrotonic state was. He first discovered in 1838 the dielectric polarisation of electric insulators subject to electric forces. Such bodies, under the influence of electric forces, exhibit phenomena perfectly analogous to those observed in soft iron under the influence

of the magnetic force. Eleven years later, in 1849, he was able to demonstrate that all ponderable matter is magnetised under the influence of sufficiently intense magnetic force, and at the same time he discovered the phenomena of diamagnetism, which indicated that even space, devoid of all ponderable matter, is magnetisable. The most simple explanation of these phenomena, indeed, is, that diamagnetic bodies are less magnetisable than a vacuous space, or than the luminiferous ether filling that space. In this way real changes corresponding to that hypothetical electrotonic state were demonstrated, and now, with quite a wonderful sagacity and intellectual precision, Faraday performed in his brain the work of a great mathematician without using a single mathematical formula. He saw with his mind's eye that magnetised and dielectric bodies ought to have a tendency to contract in the direction of the lines of force, and to dilate in all directions perpendicular to the former, and that by these systems of tensions and pressures in the space which surrounds electrified bodies, magnets or wires conducting electric currents, all the phenomena of electro-static, magnetic, electro-magnetic attraction, repulsion, and induction could be explained, without recurring at all to forces acting directly at a distance. This was the part of his path where so few could follow him; perhaps a Clerk Maxwell, a second man of the same power and independence of intellect, was needed to reconstruct in the normal methods of science the great building, the plan of which Faraday had conceived in his mind, and attempted to make visible to his contemporaries.

Nobody can deny that this new theory of electricity and magnetism, originated by Faraday and developed by Maxwell, is in itself well consistent, in perfect and exact harmony with all the known facts of experience, and does not contradict any one of the general axioms of dynamics, which have been hitherto considered as the fundamental truths of all natural science, because they have been found valid, without any exception, in all known processes of nature. A confirmation of great importance was given to this theory by the circumstance demonstrated by Clerk Maxwell, that the qualities which it must attribute to the imponderable medium filling space are able to produce and sustain magnetic and electric oscillations, propagating like waves, and with a velocity exactly equal to that of light. Several parts even of the theory of light are deduced with less difficulty from this new theory than from the well-known undulatory theory of Huyghens, which ascribes to the luminiferous ether the qualities of a rigid elastic body.

Nevertheless, the adherents of direct action at a distance have not yet ceased to search for solutions of the electromagnetic problem. The moving forces exerted upon each other by two wires conducting

galvanic currents had long ago been reduced in a very ingenious way by Ampère, to attracting or repelling forces belonging to the linear elements of every current. The intensity of these forces is considered to depend not only on the distance of both parts of the current, but also in a rather complicated manner on the angles which the directions of the two currents make with each other and with the straight line joining them both. Ampère was not acquainted with induced currents, but the phenomena of these could be derived from the law of Ampère, connecting it with the general law, deduced by Faraday from his experiments, that the current induced by the motion of a magnet or of another current always resists this motion. The general mathematical expression of this law was established by Professor Neumann, of Königsberg. It gave directly, not the value of the forces, but the value of their mechanical work, the value of what mathematicians call an electrodynamic potential, and it reduced electromagnetic phenomena to forces acting, not from point to point, but from one linear element of a current to another. Linear elements of a wire conducting a galvanic current are, of course, complicated structures compared with atoms. I have myself elaborated several mathematical papers to prove that this formula of Professor Neumann was in harmony with all the known phenomena exhibited by closed galvanic circuits, and that it did not come into contradiction with the general axioms of mechanics in any case of electric motion. I succeeded in finding an experimental method of observing electrostatic effects of electromagnetic induction under conditions in which closed circuits could not be generated. This experiment decided against the supposition that Neumann's theory was complete so long as only the electric motions in metallic or fluid conductors were considered as active currents, but it was in accordance with the theory of Faraday and Maxwell, who supposed that from the extremities of conducting bodies, where an electric charge collects, electric motion is continued through the insulating media separating them.

Other eminent men have tried to reduce electromagnetic phenomena to forces acting directly between distant quantities of the hypothetical electric fluids, with an intensity which depends not only on the distance, but also on the velocities and accelerations of those electric quantities. Such theories have been proposed by Professor W. Weber, of Göttingen, by Riemann, the too early-deceased mathematician, and by Professor Clausius, of Bonn. All these theories explain very satisfactorily the phenomena of closed galvanic currents. But applied to other electric motions, they all come into contradiction with the general axioms of dynamics.

The hypothesis of Professor Weber makes the equilibrium of electricity unstable in any conductor of moderate dimensions, and

renders possible the development of infinite quantities of work from finite bodies. I do not find that the objections, brought forward at first by Sir W. Thomson and Professor Tait in their *Treatise on Natural Philosophy*, and discussed and specialised afterwards by myself, have been invalidated by the discussions going on about this question. The hypothesis of Riemann, which he did not himself publish during his lifetime, labours under the same objection, and is at the same time in contradiction to Newton's axiom, which established the equality of action and reaction for all natural forces.

The hypothesis of Professor Clausius avoids the first objection, but not the second, and the author himself has conceded that this objection could be removed only by the assumption of a medium filling all space, between which and the electric fluids the forces acted.

The present development of science shows then, I think, a state of things very favourable to the hope that Faraday's fundamental conceptions may in the immediate future receive general assent. His theory, indeed, is the only one existing which is at the same time in perfect harmony with the facts as far as they are observed, and does not beyond the reach of facts lead into any contradiction of the general axioms of dynamics.

Clerk Maxwell himself has developed his theory only for closed conducting circuits. I have endeavoured during the last few years to investigate the results of this theory also for conductors not forming closed circuits. I can already say that the theory is in harmony with all the observations we have on the phenomena of open circuits: I mean (1) the oscillatory discharge of a condenser through a coil of wire, (2) my own experiments on electromagnetically induced charges on a rotating condenser, and (3) Mr. Rowland's observations on the electromagnetic effect of a rotatory disc charged with one kind of electricity.

The deciding assumption which removes the theoretical difficulties is that introduced by Faraday, who assumed that any electric motion in a conducting body which charges its surface with electricity is continued in the surrounding insulating medium as beginning or ending dielectric polarisation with an intensity equivalent to that of the current. A second inference from this supposition is, that the forces working at a distance do not exist, or are at least unimportant, when compared with the tensions and pressures of the dielectric medium.

It is not at all necessary to accept any definite opinion about the ultimate nature of the agent which we call electricity. Faraday himself avoided as much as possible giving any affirmative assertion regarding this problem, although he did not conceal his disinclination to believe in the existence of two opposite electric fluids.

For our own discussion of the electrochemical phenomena, to which we shall now turn, I beg permission to use the language of the old dualistic theory, which considers positive and negative electricity as two imponderable substances, because we shall have to speak principally on relations of quantity.

We shall try to imitate Faraday as well as we can by keeping carefully within the domain of phenomena, and, therefore, need not speculate about the real nature of that which we call a quantity of positive or negative electricity. Calling them substances of opposite sign, we imply with this name nothing else than the fact that a positive quantity never appears or vanishes without an equal negative quantity appearing or vanishing at the same time in the immediate neighbourhood. In this respect they behave really as if they were two substances, which cannot be either generated or destroyed, but which can be neutralised and become imperceptible by their union.

I see very well that this assumption of two imponderable fluids of opposite qualities is a rather complicated and artificial machinery, and that the mathematical language of Clerk Maxwell's theory expresses the laws of the phenomena very simply and very truly, with a much smaller amount of hypothetical implications; but I confess I should really be at a loss to explain without the use of mathematical formulæ, what he considers as a quantity of electricity, and why such a quantity is constant, like that of a substance. The original old notion of substance is not at all identical with that of matter. It signifies, indeed, that which behind the changing phenomena lasts as invariable, which can be neither generated nor destroyed, and in this oldest sense of the word we may really call the two electricities substances.

I prefer the dualistic theory, because it expresses clearly the perfect symmetry between the positive and negative side of electric phenomena, and I keep the well known supposition that as much negative electricity enters where positive goes away, because we are not acquainted with any phenomena which could be interpreted as corresponding with an increase or a diminution of the total electricity contained in any body. The unitary theory, which assumes the existence of only one imponderable electrical substance, and ascribes the effects of opposite kind to ponderable matter itself, affords a far less convenient basis for an electrochemical theory.

I now turn to the second fundamental problem aimed at by Faraday, the connection between electric and chemical force.

Already before Faraday went to work, an elaborate electrochemical theory had been established by the renowned Swedish chemist, Berzelius, which formed the connecting link of the great work of his life, the systematisation of the chemical knowledge of his time. His

starting point was the series in which Volta had arranged the metals according to the electric tension which they exhibit after contact with each other. Metals easily oxidised occupied the positive end of this series, those with small affinity for oxygen the negative end. Metals widely distant in the series develop stronger electric charges than those near to each other. A strong positive charge of one metal, and a strong negative of the other, must cause them to attract each other and to cling to each other. The same faculty of exciting each other electrically was ascribed by Berzelius to all the other elements; he arranged them all into a series, at the positive end of which he placed potassium, sodium, barium, calcium, &c.; at the negative end oxygen, chlorine, bromine, &c. Two atoms of different elements coming into contact are supposed to excite each other electrically, like the metals in Volta's experiment. Berzelius's conceptions about the distribution of opposite electricities in the molecules, and his deductions regarding the intensity of these forces, were not very clear, and not in harmony with the laws of electric forces which had already been developed by Green and Gauss. A fundamental point which Faraday's experiment contradicted was the supposition that the quantity of electricity collected in each atom was dependent on their mutual electrochemical differences, which Berzelius considered as the cause of their apparently greater chemical affinity.

His theory of the binary character of all chemical compounds was also connected with this electrochemical theory. Two elements, as he supposed, one positive, the other negative, could unite to a compound of the first degree, a basic oxide or an acid; two such compounds into a compound of the second degree, a salt. But there was nothing to prevent one atom of every positive element from uniting as directly with two, three, or even seven of another negative element as with one. The same was assumed by Berzelius for negative elements. The modern experience of chemistry directly contradicts these statements. But although the fundamental conceptions of Berzelius' theory have been forsaken, chemists have not ceased to speak of positive and negative constituents of a compound body. Nobody can overlook that such a contrast of qualities as was expressed in Berzelius' theory really exists, well developed at the extremities, less evident in the middle terms of the series, and playing an important part in all chemical actions, although often subordinated to other influences.

When Faraday began to study the phenomena of decomposition by the galvanic current, which of course were considered by Berzelius as amongst the firmest supports of his theory, he put a very simple question, the first question, indeed, which every chemist speculating about electrolysis ought to have thought of. He asked, what is the quantity of electrolytic decomposition if the same quantity of electricity is sent

through several electrolytic cells. By this investigation he discovered that most important law, generally known under his name, but called by him the law of definite electrolytic action.

When he began his experiments, neither Daniell's nor Grove's battery was known, and there were no means of producing currents of constant intensity; the methods of measuring this intensity were also in their infancy. This may excuse his predecessors. Faraday overcame this difficulty by sending the same current of electricity for the same time through a series of two or more electrolytic cells. He proved at first that the dimensions of the cell, and the size of the metallic plates through which the current entered and left the cell, had no visible influence upon the quantity of the products of decomposition. Cells containing the same electrolytic fluid between plates of the same metals gave always the same quantity, after being traversed by the same current. Then he compared the amount of decomposition in cells containing different electrolytes, and he found it exactly proportional to the chemical equivalents of the elements, which were either separated or converted into new compounds.

Faraday concluded from his experiments that a definite quantity of electricity cannot pass a voltametric cell containing acidulated water between electrodes of platinum, without setting free at the negative electrode a corresponding definite amount of hydrogen, and at the positive electrode the equivalent quantity of oxygen, one atom of oxygen for every pair of atoms of hydrogen. If instead of hydrogen any other element capable of replacing hydrogen is separated from the electrolyte, this is done also in a quantity exactly equivalent to the quantity of hydrogen which would have been evolved by the same electric current. According to the modern chemical theory of quantivalence, therefore, the same quantity of electricity passing through an electrolyte either sets free, or transfers to other combinations, always the same number of units of affinity at both electrodes; for instance,

instead of $\left. \begin{matrix} \text{H} \\ \text{H} \end{matrix} \right\}$, either $\left. \begin{matrix} \text{K} \\ \text{K} \end{matrix} \right\}$, or $\left. \begin{matrix} \text{Na} \\ \text{Na} \end{matrix} \right\}$, or Ba}, or Ca}, or Zn},

or Cu} from cupric salts,

or $\left. \begin{matrix} \text{Cu} \\ \text{Cu} \end{matrix} \right\}$ from cuprous salts, &c.

The simple or compound halogens separating at the other electrodes, are equivalent of course to the quantity of the metallic element with which they were formerly combined.

According to Berzelius' theoretical views, the quantity of electricity collected at the point of union of two atoms ought to increase with the strength of their affinity. Faraday demonstrated by experiment, that so far as this electricity came forth in electrolytic decomposition,

its quantity did not at all depend on the degree of affinity. This was really a fatal blow to Berzelius' theory.

Since that time our experimental methods and our knowledge of the laws of electrical phenomena have made enormous progress, and a great many obstacles have now been removed which entangled every one of Faraday's steps, and obliged him to fight with the confused ideas and ill-applied theoretical conceptions of some of his contemporaries. The original voltameter of Faraday, an instrument which measured the quantity of gases evolved by the decomposition of water, in order to determine with it the intensity of the galvanic current, has been replaced by the silver voltameter of Poggendorff, which permits of much more exact determinations by the quantity of silver deposited from a solution of silver nitrate on a strip of platinum. We have galvanometers which not only indicate that there is a galvanic current, but likewise measure its electromagnetic intensity very exactly and in a very short time, and do this as well for the highest as for the lowest degrees of intensity. We have electrometers, like the quadrant electrometer of Sir W. Thomson, able to measure differences of electric potential corresponding to less than one-hundredth of a Daniell's cell. As for the frequently-used term of electric potential, a term introduced by Green, you may translate it as signifying the electric pressure to which the positive unit of electricity is subject at a certain place. We need not hesitate to say that the more experimental methods were refined, the more completely were the exactness and generality of Faraday's law confirmed.

In the beginning Berzelius and the adherents of Volta's original theory of galvanism, based on the effects of metallic contact, raised many objections against Faraday's law.

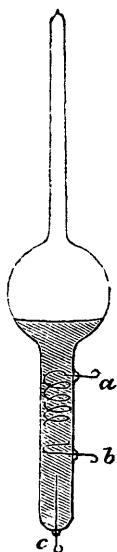
By the combination of Nobili's astatic pairs of magnetic needles with Schweigger's multiplier, a coil of copper wire with numerous circumvolutions, galvanometers became so delicate that they were able to indicate the electrochemical equivalent of currents so feeble as to be quite imperceptible by all chemical methods. With the newest galvanometers you can very well observe currents which would require to last a century before decomposing one milligram of water, the smallest quantity that is usually weighed on chemical balances. You see that if such a current lasts only some seconds or some minutes, there is not the slightest hope of discovering its products of decomposition by chemical analysis. And even if it should last a long time, the minute quantities of hydrogen collected at the negative electrode may vanish, because they combine with the traces of atmospheric oxygen absorbed by the liquid. Under such conditions a feeble current may continue as long as you like without producing any visible trace of electrolysis, not even of galvanic polarisation, the appearance of which can be used as

an indication of previous electrolysis. Galvanic polarisation, as you know, is an altered state of the metallic plates which have been used as electrodes during the decomposition of an electrolyte. Polarised electrodes, when connected by a galvanometer, give a current which they did not give before being polarised. By this current the plates are discharged again and returned to their original state of equality. The most probable explanation of this polarisation is that molecules of the electrolyte, charged with electricity, are carried by the current to the surface of the metal, itself charged with opposite electricity, and are retained there by electric attraction. That really constituent atoms of the electrolyte partake in the production of galvanic polarisation cannot well be doubted, because this state can be produced and also destroyed purely by chemical means. If hydrogen has been carried to an electrode by the current, contact with the atmospheric oxygen removes the state of polarisation.

The depolarising current is indeed a most delicate means of discovering previous decomposition. But even this may fail if the nascent polarisation is destroyed by an intervening chemical action, like that of the oxygen of the air. To avoid this, delicate experiments on this subject cannot be performed except in vessels carefully purified of all gases.

I have lately succeeded in doing this in a far more perfect way than before, by using the hermetically sealed cell (Fig. 1), which contains

FIG. 1.



water acidulated with sulphuric acid. Two platinum wires, *b* and *c*, and a third platinum wire, *a*, which in the interior is connected with a spiral of palladium, can be used as electrodes. The tube, before it had been closed, was connected with a water-pump, and at the same time oxygen was evolved from *b* and *c* by two Grove's elements; the hydrogen carried to the palladium wire, *a*, was occluded in the metal. In this way the liquid in the tube is washed out with oxygen under low pressure and freed from all other gases. After the closing of the tube, the remaining small traces of electrolytic oxygen combine slowly with the hydrogen of the palladium. Traces of hydrogen occluded in the platinum wires *b* and *c* can be transferred by a feeble electromotive force into the palladium; and even new quantities of electrolytic gases, evolved after closing the tube, can be removed again by a Daniell's cell, which carries hydrogen to the palladium, where it is occluded, and oxygen to *b* and *c*, where it combines with hydrogen, as long as traces of this gas are dissolved in the liquid. The rest of the oxygen absorbed by the liquid combines with the occluded hydrogen.

I have ascertained with this apparatus that under favourable conditions one can observe the polarisation produced during a few seconds by a current which would decompose only one milligram of water in a century.

But even if the appearance of galvanic polarisation should not be acknowledged by opponents as a sufficient indication of previous decomposition, it is not difficult at present to reduce the indications of a good galvanometer to absolute measure, and to calculate the amount of decomposition which ought to be expected according to Faraday's law, and to verify that in all the cases in which no products of electrolysis can be discovered, their amount is too small for chemical analysis.

Products of decomposition cannot appear at the electrodes without the occurrence of motions of the constituent molecules of the electrolyte throughout the whole length of the liquid. On this point the majority of Faraday's predecessors were already agreed, but they differed from each other as soon as they came to the question what those motions were. Faraday saw very clearly the importance of this problem, and again appealed to experiment. He filled two cells with an electrolytic fluid, connecting them by a thread of asbestos wetted with the same fluid, in order to determine separately the quantity of all the chemical constituents transferred to the one and the other extremity of the electrolytic conductor. You know that he proposed for these atoms or groups of atoms transported by the current through the fluid the Greek word "Ions," the "Travellers;" and comparing the current of positive electricity with a stream of water, he called "cations" those

atoms which went down the stream in the same direction with the positive electricity to the cathode, the metallic plate through which this electricity left the fluid. The "anions," on the contrary, go up the stream to the anode, the metal plate which is the source of the current of + E. Cations generally are atoms which are substitutes of hydrogen; anions are halogens.

This subject has been studied very carefully and for a great number of liquids, by Professor Hittorff, of Münster, and Professor G. Wiedemann, of Leipsic. They found that generally the velocity of the cation and the anion is different. Professor F. Kohlrausch, of Würzburg, has brought to light the very important fact that in diluted solutions of salts, including hydrates of acids and hydrates of caustic alkalis, every ion under the influence of currents of the same density moves on with its own peculiar velocity, independently of other ions moving at the same time in the same or in opposite directions.

Among the cations hydrogen has the greatest velocity, then follow potassium, ammonium, silver, sodium, afterwards the bivalent atoms of barium, copper, strontium, calcium, magnesium, zinc; near to the latter appears univalent lithium. Among the anions hydroxyl (OH) is the first, then follow the other univalent atoms iodine, bromine, cyanogen, chlorine, the compounds NO_3 , ClO_3 , the bivalent halogens of sulphuric and carbonic acid; after these fluorine and the halogen of acetic acid ($\text{C}_2\text{H}_3\text{O}_2$). The only exception to this rule is the difference observed between the decomposition of univalent and bivalent compounds. Generally the velocity of any ion when separated from a bivalent mate is less than when separated from one or two univalent mates.

It seems possible that the majority of molecules SO_4H_2 may be divided electrolytically into SO_4 and H_2 , some of them on the other hand into SO_4H and H . By the latter some hydrogen would be carried backwards, and therefore the velocity of the total amount might appear diminished.

If both ions are moving, we shall find liberated at each electrode (1) that part of the corresponding ion which has been newly carried to that side: (2) another part which has been left by the opposite ion, with which it had been formerly combined. The total amount of chemical motion in every section of the fluid is, therefore, represented by the sum of the equivalents of the cation gone forwards, and of the anion gone backwards, in the same way as in the dualistic theory of electricity the total amount of electricity flowing through a section of the conductor corresponds to the sum of positive electricity going forwards and of negative electricity going backwards.

This established, Faraday's law tells us that through each section of an electrolytic conductor we have always equivalent electrical and chemical motion. The same definite quantity of either positive or

negative electricity moves always with each univalent ion, or with every unit of affinity of a multivalent ion, and accompanies it during all its motions through the interior of the electrolytic fluid. This quantity we may call the electric charge of the atom.

I beg to remark that hitherto we have spoken only of phenomena. The motion of electricity can be observed and measured. Independently of this, the motion of the chemical constituents can also be measured. Equivalent of chemical elements and equivalent quantities of electricity are numbers which express real relations of natural objects and actions. That the equivalent relation of chemical elements depends on the pre-existence of atoms may be hypothetical; but we have not yet any theory sufficiently developed which can explain all the facts of chemistry as simply and as consistently as the atomic theory developed in modern chemistry.

Now the most startling result of Faraday's law is perhaps this. If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions, which behave like atoms of electricity. As long as it moves about on the electrolytic liquid, each ion remains united with its electric equivalent or equivalents. At the surface of the electrodes decomposition can take place if there is sufficient electromotive force, and then the ions give off their electric charges and become electrically neutral.

The same atom can be charged in different compounds with equivalents of positive or of negative electricity. Faraday pointed out sulphur as being an element which can act either as anion or as cation. It is anion in sulphide of silver, a cation perhaps in strong sulphuric acid. Afterwards he suspected that the deposition of sulphur from sulphuric acid might be a secondary result. The cation may be hydrogen, which combines with the oxygen of the acid, and drives out the sulphur. But if this is the case, hydrogen recombined with oxygen to form water must retain its positive charge, and it is the sulphur, which in our case must give off positive equivalents to the cathode. Therefore this sulphur of sulphuric acid must be charged with positive equivalents of electricity. The same may be applied to a great many other instances. Any atom or group of atoms which can be substituted by secondary decomposition for an ion must be capable of giving off the corresponding equivalent of electricity.

When the positively charged atoms of hydrogen or any other cation are liberated from their combination and evolved as gas, the gas becomes electrically neutral; that is, according to the language of the dualistic theory, it contains equal quantities of positive and negative electricity; either every single atom is electrically neutralised, or one atom, remaining positive, combines with another charged negatively.

This latter assumption agrees with the inference from Avogadro's law, that the molecule of free hydrogen is really composed of two atoms.

Now arises the question: Are all these relations between electricity and chemical combination limited to that class of bodies which we know as electrolytes. In order to produce a current of sufficient strength to collect enough of the products of decomposition without producing too much heat in the electrolyte, the substance which we try to decompose ought not to offer too much resistance to the current. But this resistance may be very great, and the motion of the ions may be very slow, so slow indeed that we should need to allow it to go on for hundreds of years before we should be able to collect even traces of the products of decomposition; nevertheless all the essential attributes of the process of electrolysis could subsist. In fact we find the most various degrees of conducting power in various liquids. For a great number of them, down to distilled water and pure alcohol, we can observe the passage of the current with a sensitive galvanometer. But if we turn to oil of turpentine, benzene, and similar substances, the galvanometer becomes silent. Nevertheless these fluids also are not without a certain degree of conducting power. If you connect an electrified conductor with one of the electrodes of a cell filled with oil of turpentine, the other with the earth, you will find that the electricity of the conductor is discharged unmistakably more rapidly through the oil of turpentine than if you take it away and fill the cell only with air.

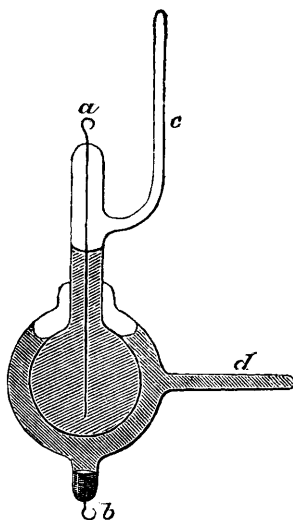
We may in this case also observe polarisation of the electrodes as a symptom of previous electrolysis. Connect the two pieces of platinum in oil of turpentine with a battery of eight Daniells, let it stay 24 hours, then take away the battery, and connect the electrodes with a quadrant electrometer; it will indicate that the two surfaces of platinum, which were homogeneous before, produce an electromotive force which deflects the needle of the electrometer. The electromotive force of this polarisation has been determined in some instances by Mr. Picker in the Laboratory of the University of Berlin; he has found that the polarisation of alcohol decreases with the proportion of water which it contains, and that that of the purest alcohol, ether, and oil of turpentine, is about 0.3, that of benzene 0.8 of a Daniell's element.

Another sign of electrolytic conduction is, that liquids placed between two different metals produce an electromotive force. This is never done by metals of equal temperature, or by other conductors which, like metals, let electricity pass without being decomposed. The production of an electromotive force is observed even with a great many rigid bodies, although very few of them allow us to observe electrolytic conduction with the galvanometer, and even these

only at temperatures near their melting points. I remind you of the galvanic pile of Zamboni, in which pieces of dry paper are intercalated between thin leaves of metal. If the connection lasts long enough, even glass, resin, shellac, paraffin, sulphur—the best insulators we know—do the same. It is nearly impossible to prevent the quadrants of a delicate electrometer from being charged by the insulating bodies by which they are supported.

In all the cases which I have quoted, one might suspect that traces of humidity absorbed by the substance or adhering to their surface were the electrolytes. I show you, therefore, this little Daniell's cell, Fig. 2, constructed by my former assistant, Dr. Giese, in which a solu-

Fig. 2.



tion of sulphate of copper with a platinum wire, *a*, as an electrode, is enclosed in a bulb of glass hermetically sealed. This is surrounded by a second cavity, sealed in the same way, which contains a solution of zinc sulphate and some amalgam of zinc, to which a second platinum wire, *b*, enters through the glass. The tubes *c* and *d* have served to introduce the liquids, and have been sealed afterwards. It is, therefore, like a Daniell's cell, in which the porous septum has been replaced by a thin stratum of glass. Externally all is symmetrical at the two poles; there is nothing in contact with the air but a closed surface of glass, through which two wires of platinum penetrate. The whole

charges the electrometer exactly like a Daniell's cell of very great resistance, and this it would not do if the septum of glass did not behave like an electrolyte: for a metallic conductor would completely destroy the action of the cell by its polarisation.

All these facts show that electrolytic conduction is not at all limited to solutions of acids or salts. It will, however, be rather a difficult problem to find out how far the electrolytic conduction is extended, and I am not yet prepared to give a positive answer. What I intended to remind you of was only that the faculty to be decomposed by electric motion is not necessarily connected with a small resistance to the current. It is easier for us to study the cases of small resistance, but the illustration which they give us about the connection of electric and chemical force is not at all limited to the acid and saline solutions usually employed.

Hitherto we have studied the motions of ponderable matter as well as of electricity, going on in an electrolyte. Let us now study the forces which are able to produce these motions. It has always appeared somewhat startling to everybody who knows the mighty power of chemical forces, and the enormous quantity of heat and mechanical work which they are able to produce, how exceedingly small is the electric attraction at the poles of a battery of two Daniell's cells, which nevertheless is able to decompose water. 1 gram of water, produced by burning hydrogen with oxygen, develops so much heat, that this heat transformed by a steam engine into mechanical work would raise the same weight to a height of 1,600,000 metres. And on the contrary we require to use the most delicate contrivances to show that a gold leaf or a little piece of aluminium hanging on a silk fibre can be at all moved by the electric attraction of the battery. The solution of this riddle is found if we look at the quantities of electricity with which the atoms appear to be charged.

The quantity of electricity which can be conveyed by a very small quantity of hydrogen, when measured by its electrostatic forces, is exceedingly great. Faraday saw this, and endeavoured in various ways to give at least an approximate determination. He ascertained that even the most powerful batteries of Leyden jars, discharged through a voltameter, give scarcely any visible traces of gases. At present we can give definite numbers. The electrochemical equivalent of the electromagnetic unit of the galvanic current has been determined by Bunsen, and more recently by other physicists. This determination was followed by the very difficult comparison of the electromagnetic and electrostatic effects of electricity, accomplished at first by Professor W. Weber, and afterwards under the auspices of the British Association by Professor Clerk Maxwell.* The result is,

* According to the latest and most careful measurements of the electrochemical

that the electricity of 1 mgrm. of water, separated and communicated to two balls, 1 kilomt. distant, would produce an attraction between them equal to the weight of 26,800 kilogr.

As I have already remarked, the law that the intensity of the force is inversely proportional to the square of the distance, and directly proportional to the quantities of attracting and of attracted mass, holds good as well in the case of gravitation as in that of electric attraction and repulsion. We may, therefore, compare the gravitation acting between two quantities of hydrogen and oxygen with the attraction of their electric charges. The result will be independent of the size and the distance of these quantities. We find that the electric force is as great as the gravitation of ponderable masses, being 71,000 billion times greater than that of the oxygen and hydrogen* containing these electric charges.

effect, performed by Professor Kohlrausch, junr., the electromagnetic unit of the galvanic current, as it was defined by W. Weber (= 0.1 of the British Association unit), decomposes 0.009476 mgrm. of water per second. This same unit-current of Weber transfers about $300 \cdot 10^9$ electrostatic units of electricity (Weber himself gave $311 \cdot 10^9$, Maxwell $288 \cdot 10^9$) through each section of the circuit per second, half of them being positive, half of them negative, the two halves going in opposite directions. The electrostatic unit introduced by Gauss and W. Weber is that quantity of electricity which repels the same quantity at the distance of one millimeter with unit force, that is, with a force which, acting during one second upon one milligram, transmits to it a velocity of one millimeter per second. Gravity acting upon one milligram produces an acceleration 9,809 times as great. Weber's unit force, therefore, is equal to $\frac{1}{9809}$ of the weight of one milligram.

The force, F , measured by weight, with which the electric quantity, $+E$, measured in electrostatic units, attracts the opposite quantity $-E$, at a distance r is equal to—

$$F = \frac{E^2}{r^2} \cdot \frac{1}{9809} \text{ mgrm.}$$

If E is the quantity carried to each electrode during the decomposition of one milligram of water, it is according to the determinations quoted before = $1618 \cdot 10^{10}$ units, and if we put $r = 1$ kilometer = 1,000,000 millimeters, we get the result quoted above.

* The gravity of a weight m is the force of attraction between it and the mass of the earth, which may be considered as concentrated in the central point of the earth. If h is the mean density of the earth, and r its radius, the mass of the earth will be—

$$\frac{4\pi}{3} r^3 h.$$

If G is the force of attraction between two units of mass at unit of distance, the attraction of the mass m by the earth will be—

$$gm = \frac{4\pi}{3} rh \cdot Gm.$$

Take—

$$\frac{\pi}{2} r = 10^7 \text{ meters} = 10^{10} \text{ mm.}$$

$$h = 5.62 \text{ mgrms. per cub. mm.,}$$

The total force exerted by the attraction of an electrified body upon another charged with opposite electricity is always proportional to the quantity of electricity contained on the attracting as on the attracted body.

Although, therefore, the attracting forces exerted by the poles of a little battery able to decompose water on such electric charges as we can produce with our electric machines, are very moderate, the forces exerted by the same little apparatus on the enormous charges of the atoms in one milligram of water may very well compete with the mightiest chemical affinity.

If we now turn to investigate how the motions of the ponderable molecules are dependent upon the action of these forces, we must distinguish two different cases. At first we may ask what forces are wanted to call forth motions of the ions with their charge through the interior of the fluid; secondly, what are wanted to separate the ion from the fluid and its previous combinations?

Let us begin with the case in which the conducting liquid is surrounded everywhere by insulating bodies. Then no electricity can enter, none can go out through its surface, but positive electricity can be driven to one side, negative to the other, by the attracting and repelling forces of external electrified bodies. This process going on as well in every metallic conductor is called "electrostatic induction." Liquid conductors behave quite like metals under these conditions. Great quantities of electricities are collected, if large parts of the surfaces of the two bodies are very near to each other. Such an arrangement is called an electric condenser. We can arrange electric condensers in which one of the surfaces is that of a liquid, as Messrs. Ayrton and Perry have done lately. The water-dropping collector of electricity, invented by Sir W. Thomson, is a peculiar form of such a condenser, which can be charged with perfect regularity by the slightest electromotive force perceptible only to the most sensitive electrometer.

the attraction between $\frac{8}{9}$ mgrm. of oxygen and $\frac{1}{9}$ mgrm. of hydrogen contained in 1 mgrm. of water, and separated by a distance of 1 mm. will be—

$$\frac{1}{9} \cdot \frac{8}{9} \cdot G = \frac{g}{27 \cdot 5,62 \cdot 10^{16}}$$

or equal to the weight of—

$$\frac{65904}{10^{17}} \text{ mgrm.}$$

The attraction of the electric charges, which has been calculated before for a distance of 1 kilometer, reduced to that of 1 mm., will be equal to the weight of—

$$20800 \cdot 10^{18} \text{ mgrms.}$$

From this it follows that the attraction by gravitation of those two masses would become equal to the attraction of their electric charges, if each of the masses could be increased 71,300 billions of times.

Professor Wüllner has proved that even our best insulators, exposed to electric forces for a long time, are ultimately charged quite in the same way as metals would be charged in an instant. There can be no doubt that even electromotive forces less than $\frac{1}{100}$ Daniell produce perfect electrical equilibrium in the interior of an electrolytic liquid.

Another somewhat modified instance of the same effect is afforded by a voltametric cell containing two electrodes of platinum, which are connected with a Daniell's cell the electromotive force of which is insufficient to decompose the electrolyte. Under this condition the ions carried to the electrodes cannot give off their electric charges. The whole apparatus behaves, as was first accentuated by Sir W. Thomson, like a condenser of enormous capacity. The quantity of electricity, indeed, collected in a condenser under the same electromotive force is inversely proportional to the distance of the plates. If this is diminished to $\frac{1}{100}$, the condenser takes in 100 times as much electricity as before. Now, bringing the two surfaces of platinum and of the liquid into immediate contact, we reduce their interval to molecular distances. The capacity of such a condenser has been measured by Messrs. Varley, Kohlrausch, and Colley. I have myself made some determinations which show that oxygen absorbed in the fluid is of great influence on the apparent value. By removing all traces of gas I have got a value a little smaller than that of Kohlrausch, which shows that if we divide equally the total value of the polarisation between two platinum plates of equal size, the distance between the two strata of positive and negative electricity, the one lying on the last molecules of the metal, the other on those of the fluid, ought to be a ten millionth part (Kohlrausch $\frac{1}{15000000}$) of a millimeter. We always come nearly to the same limit, when we calculate the distances through which molecular forces are able to act, as already shown in several other instances by Sir W. Thomson.

Owing to the enormous capacity of such an electrolytic condenser, the quantity of electricity which enters into it, if it is charged even by a feeble electromotive force, is sufficiently great to be indicated easily by a galvanometer. What I now call charging the condenser, I have before called polarising the metallic plate. Both, indeed, are the same process, because electric motion is always accompanied in the electrolytes by chemical decomposition.

Observing the polarising and depolarising currents in a cell like that represented in Fig. 1, we can observe these phenomena with the most feeble electromotive forces of $\frac{1}{100}$ Daniell, and I found that down to this limit the quantity of electricity entering into the condenser was proportional to the electromotive force by which it was collected. By taking larger surfaces of platinum, I suppose it will be possible to reach a limit much lower than that. If any chemical force existed besides that

of the electrical charges which could bind all the pairs of opposite ions together, and required any amount of work to be vanquished, an inferior limit ought to exist to such electromotive forces as are able to attract the ions to the electrodes, and to charge these as condensers. No phenomenon indicating such a limit has as yet been discovered, and we must, therefore, conclude that no other force resists the motions of the ions through the interior of the liquid than the mutual attractions of their electric charges. These are able to prevent the atoms of the same kind which repel each other from collecting at one place, and atoms of the other kind attracted by the former from collecting at any other part of the fluid, as long as no external electric force favours such distribution. The electric attraction, therefore, is able to produce an equal distribution of the opposite constituent atoms throughout the liquid, so that all parts of it are neutralised electrically as well as chemically.

On the contrary, as soon as an ion is to be separated from its electrical charge, we find that the electrical forces of the battery meet with a powerful resistance, the overpowering of which requires a good deal of work to be done. Usually the ions, losing their electric charges, are at the same time separated from the liquid; some of them are evolved as gases, others are deposited as rigid strata on the surface of the electrodes, like galvanoplastic copper. But the union of two constituents having powerful affinity to form a chemical compound, always produces, as you know very well, a great amount of heat, and heat is equivalent to work. On the contrary, decomposition of the compound substance requires work, because it restores the energy of the chemical forces which has been spent by the act of combination. Oxygen and hydrogen separated from each other contain a store of energy, for on burning the hydrogen in the oxygen they unite, form water, and develop a great amount of heat. In the water the two elements are contained, and their chemical attraction continues to work as before, keeps them firmly united, but can no more produce any change, any positive action. We must reduce the combined elements into their first state, we must separate them, applying a force which is capable of vanquishing their affinity before they are ready to renew their first activity. The amount of heat produced by the chemical combination is the equivalent of the work done by the chemical forces brought into action. It requires the same amount of work to separate the compound and to restore hydrogen and oxygen uncombined. I have already given the value of this amount calculated as a weight raised against the force of gravity.

Metals uniting with oxygen or halogens produce heat in the same way, some of them, like potassium, sodium, and zinc, even more than an equivalent quantity of hydrogen; less oxidisable metals, like copper,

silver and platinum, less. We find, therefore, that heat is generated when zinc drives copper out of its combination with the compound halogen of sulphuric acid, as is the case in a Daniell's cell.

If a galvanic current passes through any conductor, a metallic wire, or an electrolytic fluid, it evolves heat. Dr. Joule was the first who proved experimentally that if no other work is done by the current, the total amount of heat evolved in a galvanic circuit during a certain time is exactly equal to that which ought to have been generated by the chemical actions which have been performed during that time. But this heat is not evolved at the surface of the electrodes where these chemical actions take place, but is evolved in all the parts of the circuit, proportionally to the galvanic resistance of every part. From this it is evident that the heat evolved is an immediate effect, not of the chemical action, but of the galvanic current, and that the chemical work of the battery has been spent to produce only the electric action.

To keep up an electric current through an electric conductor, indeed, requires work to be done. New stores of positive electricity must be continually introduced at the positive end of the conductor, the repulsive force acting upon them having to be overcome; negative electricity, in the same way, into the negative end. This can be done by mere mechanical force, with an electric machine working by friction, or by electrostatic or by electromagnetic induction. In a galvanic current it is done by chemical force, but the work required remains the same.

If we apply Faraday's law, a definite amount of electricity passing through the circuit corresponds with a definite amount of chemical decomposition going on in every electrolytic cell of the same circuit. According to the theory of electricity, the work done by such a definite quantity of electricity which passes, producing a current, is proportionate to the electromotive force acting between both ends of the conductor. You see, therefore, that the electromotive force of a galvanic circuit must be, and is indeed, proportional to the heat generated by the sum of all the chemical actions going on in all the electrolytic cells during the passage of the same quantity of electricity. In the cells of the galvanic battery chemical forces are brought into action able to produce work; in cells in which decomposition is occurring, work must be done against opposing chemical forces; the rest of the work done appears as heat evolved by the current, as far as it is not used up to produce motions of magnets or other equivalents of work.

You see the law of the conservation of energy requires that the electromotive force of every cell must correspond exactly with the total amount of chemical forces brought into play, not only the mutual affinities of the ions, but also those minor molecular attractions pro-

duced by the water and other constituents of the fluid. These minor attractions have lately formed the subject of most valuable and extended calorimetric researches by Messrs. Andrews, Thomsen, and Berthelot. But even influences too minute to be measured by calorimetric methods may be discovered by measuring the electromotive force. I have myself deduced from the mechanical theory of heat the influence which the quantity of water contained in a solution of metallic salts has on the electromotive force. The chemical attraction between salt and water can be measured in this instance by the diminution of the tension of the aqueous vapours over the liquid, and the results of the theoretical deduction have been confirmed in a very satisfactory manner by the observations of Dr. James Moser.

Hitherto we have supposed that the ion with its electric charge is separated from the fluid. But the ponderable atoms can give off their electricity to the electrode, and remain in the liquid, being now electrically neutral. This makes scarcely any difference in the value of the electromotive force. For instance, if chlorine is separated at the anode, it will at first remain absorbed by the liquid; if the solution becomes saturated, or if we make a vacuum over the liquid, the gas will rise in bubbles. The electromotive force remains unaltered. The same may be observed with all the other gases. You see in this case that the change of electrically negative chlorine into neutral chlorine is the process which requires so great an amount of work, even if the ponderable matter of the atoms remains where it was.

On the contrary, if the electric attraction does not suffice to deprive the ions collecting at the surface of the electrodes of their electric charge, you will find the cation attracted and retained by the cathode, the anion by the anode, with a force far too great to be overpowered by the expansive force of gases. You may make a vacuum as perfect as you like over a cathode polarised with hydrogen, or an anode polarised with oxygen; you will not obtain the smallest bubble of gas. Increase the electric potential of the electrodes, so that the electric force becomes powerful enough to draw the electric charge of the ions over to the electrode: the ions will be liberated and free to leave the electrode, passing into the gaseous state or spreading in the liquid by diffusion. One cannot assume, therefore, that their ponderable matter is attracted by the electrode; if this were the case, this attraction ought to last after discharge as before. We must conclude, therefore, that the ions are drawn to the electrode only because they are charged electrically.

The more the surface of the positive electrode is covered with negative atoms of the anion, and the negative with the positive ones of the cation, the more is the attracting force of the electrodes exerted upon the ions of the liquid diminished by this second stratum of opposite

electricity covering them. On the contrary, the force with which the positive electricity of an atom of hydrogen situated at the surface of the electrode itself is attracted towards the negatively charged metal increases in proportion as more negative electricity collects before it on the metal, and behind it in the fluid.

The electrical force acting on equal quantities of electricity situated at the inside of one of the electric strata of a condenser is proportional to the electromotive force which has charged the condenser, and inversely proportional to the distance of the charged surfaces. If these are $\frac{1}{100}$ mm. apart, it is 100 times as great as if they are one millimeter apart. If we come, therefore, to molecular distances, like those calculated from the measurement of the capacity of polarised electrodes, the force is ten million times as great, and becomes able, even with a moderate electromotive force, to compete with the powerful chemical forces which combine every atom with its electric charge, and hold the atoms bound to the liquid.

Such is the mechanism by which electric force is concentrated at the surface of the electrodes and increased in its intensity to such a degree that it becomes able to overpower the mightiest chemical affinities we know of. If this can be done by a polarised surface, acting like a condenser charged by a very moderate electromotive force, can the attractions between the enormous electric charges of anions and cations be an unimportant and indifferent part of chemical affinity?

In a decomposing cell the ions resist external forces striving to separate them from their electric charges. Let the current go in the opposite direction, and you will have an opposite effect. In a Daniell's cell neutral zinc enters as cation into the electrolyte, taking with it only positive electricity, and leaving its negative electricity to the metallic plate. At the copper electrode positive copper separates from the electrolyte and is neutralised, giving off its charge to the electrode. But the Daniell's cell in which this goes on does work, as we have seen. We must conclude, therefore, that an equivalent of positive electricity, on charging an atom of zinc, does more work than the same equivalent does on charging an atom of copper.

You see, therefore, if we use the language of the dualistic theory and treat positive and negative electricities as two substances, the phenomena are the same as if equivalents of positive and negative electricity were attracted by different atoms, and perhaps also by the different values of affinity belonging to the same atom with different force. Potassium, sodium, zinc, must have strong attraction to a positive charge; oxygen, chlorine, bromine to a negative charge.

Do we perceive effects of such an attraction in other cases? Here we come to the much discussed question of Volta's assumption that electricity is produced by contact of two metals. About the fact there

can be no doubt. If we produce metallic contact between a piece of copper and a piece of zinc, opposed to each other like the two plates of a condenser, and carried by isolating rods of shell-lac we find that after contact the zinc is charged positively, the copper negatively. This is just the effect we ought to expect if zinc has a higher attracting force to positive electricity, this force working only through molecular distances. I have proposed this explanation of Volta's experiments in my little pamphlet on the "Conservation of Energy," published in 1847. All the facts observed with different combinations of metallic conductors are perfectly in harmony with it. Volta's law of the series of tension comprising all metallic conductors is easily deduced from it. If only metals come into play, their galvanic attractions produce instantaneously a state of electric equilibrium, so that no lasting current can occur. Electrolytic conductors, on the contrary, are decomposed chemically by every motion of electricity through their surface. Electric equilibrium, therefore, will not be possible before this decomposition has been finished, and till that stage is reached, the electric motion must continue. This point has been accentuated already by Faraday, as the essential difference between the two classes of conductors.

The original theory of Volta was incomplete in an essential point, because he was not acquainted with the fact of electrolytic decomposition. His original conception of the force of contact is, therefore, in contradiction to the law of Conservation of Energy; and even before this law was established and enunciated with scientific precision, there were many chemists and physicists, amongst them Faraday, who had the right instinct that this could not be the true explanation. The opponents of Volta's opinions tried to give chemical explanations also of those experiments of his, which were carried out exclusively with metal conductors. They might be oxidised by the oxygen of the air, and the amount of oxidation required for a very slight electric charge was so infinitesimal, that no chemical analysis could ever discover it; so small, that even in the highest vacuum, and in the purest specimens of hydrogen or nitrogen with which we might surround the plates, there was oxygen enough to continue the effect for years. From this point of view the chemical theory cannot be refuted. On the contrary, the so-called chemical theory of Volta's fundamental experiments was rather indefinite; it scarcely did more than tell us: here is the possibility of a chemical process, here electricity can be produced. But which kind, how much, to which potential, remained indefinite. I have not found in all the papers which have been written for the defence of the chemical theory, a clear explanation why zinc opposed to copper in liquids, where zinc really is oxidized and dissolved, becomes negative, and why in air and other gases it becomes positive, if the same cause,

namely oxidation, is at work. The hypothesis, on the contrary, of a different degree of affinity between the metals and the two electricities, gives a perfectly definite answer. I do not see why an actual chemical process should be wanted to charge the zinc and copper on contact. But you see that the forces, which according to their hypothesis produce the electric effect, are the same as those which must be considered as the cause of a main part of all chemical actions.

Again, the electric charges produced by contact of zinc and copper are very feeble. They have become measurable only with the help of the latest improvements introduced into the construction of electrometers by Sir W. Thomson; but the cause of their feeble intensity is evident. If you bring into narrow contact two plain and well-polished plates of zinc and copper, the quantity of electricity collected at both sides of their common surface is probably very great; but you cannot observe it before having separated the plates. Now it is impossible to separate them at the same instant over the whole extent of their surface. The charge which they retain will correspond with the inclined position which they have at the moment when the last point of contact is broken; then all the other parts of the surfaces are already at a distance from each other infinitely greater than molecular distance, and conduction in metals always establishes nearly instantaneously the electric equilibrium corresponding to the actual situation. If you wish to avoid this discharge during the separation of the plates, one of them must be isolated; then indeed we get a far more striking series of phenomena, those belonging to electricity of friction. Friction, probably, is only the means of producing a very close contact between the two bodies. If the surfaces are very clean and free from air, as for instance in a Geissler's tube, the slightest rolling contact is sufficient to develop the electric charge. I can show you two such tubes exhausted so far that very high electric tension is necessary to make the vacuum luminous, one containing a small quantity of mercury, the other the fluid compound of potassium and sodium. In the first the negative metal is intensely negative relatively to glass, in the second the metal is on the positive extremity of Volta's series; the glass proves to be more positive also in this case, but the difference is much smaller than with mercury, and the charge is feeble.

Faraday very often recurs to this to express his conviction that the forces termed chemical affinity and electricity are one and the same. I have endeavoured to give you a survey of the facts connected with the question, and to avoid as far as possible the introduction of hypotheses, except the atomic theory of modern chemistry. I think the facts leave no doubt that the very mightiest among the chemical forces are of electric origin. The atoms cling to their electric charges, and opposite electric charges cling to each other; but I do not suppose

that other molecular forces are excluded, working directly from atom to atom. Several of our leading chemists have lately begun to distinguish two classes of compounds, viz., molecular aggregates and typical compounds, the latter being united by atomic affinities, the former not.

Electrolytes belong to the latter class. If we conclude from the facts that every unit of affinity is charged with one equivalent either of positive or of negative electricity, they can form compounds, being electrically neutral only if every unit charged positively unites under the influence of a mighty electric attraction with another unit charged negatively. You see that this ought to produce compounds in which every unit of affinity of every atom is connected with one and only one other unit of another atom. This, as you will see immediately, is the modern chemical theory of quantivalence, comprising all the saturated compounds. The fact that even elementary substances, with few exceptions, have molecules composed of two atoms, makes it probable that even in these cases electric neutralisation is produced by the combination of two atoms, each charged with its full electric equivalent, not by neutralisation of every single unit of affinity.

Unsaturated compounds with an even number of unconnected units of affinity offer no objection to such an hypothesis; they may be charged with equal equivalents of opposite electricity. Unsaturated compounds with one unconnected unit, existing only at high temperatures, may be explained as dissociated by intense molecular motion of heat in spite of their electric attractions. But there remains one single instance of a compound which, according to the law of Avogadro, must be considered as unsaturated even at the lowest temperature, namely, nitric oxide (NO), a substance offering several very uncommon peculiarities, the behaviour of which will be perhaps explained by future researches.

But I abstain from entering into further specialities; perhaps I have already gone too far. I would not have dared to do it, had I not felt myself sheltered by the authority of that great man who was guided by a never-erring instinct of truth. I thought that the best I could do for his memory was to recall to the minds of the men by whose energy and intelligence chemistry has undergone its modern astonishing development, what important treasures of knowledge lie still hidden in the works of that wonderful genius. I am not sufficiently acquainted with chemistry to be confident that I have given the right interpretation, the interpretation which Faraday himself would have given, if he had been acquainted with the law of chemical quantivalence. Without the knowledge of this law I do not see how a consistent and comprehensive electrochemical theory could be established. Faraday did not try to develop a complete theory of this kind. It is as characteristic of a man of high intellect to see where to avoid

going further in his theoretical speculations for want of facts, as to see how to proceed when he finds the way open. We ought therefore to admire Faraday also in his cautious reticence, although now, standing on his shoulders, and assisted by the wonderful development of organic chemistry, we are able, perhaps, to see farther than he did. I shall consider my work of to-day well rewarded if I have succeeded in kindling anew the interest of chemists in the electrochemical part of their science.
