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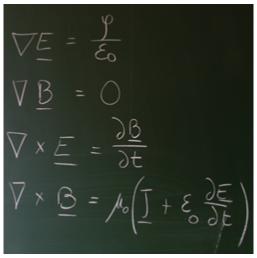
Faraday’s Lines of Force and Maxwell’s Theory of the Electromagnetic Field

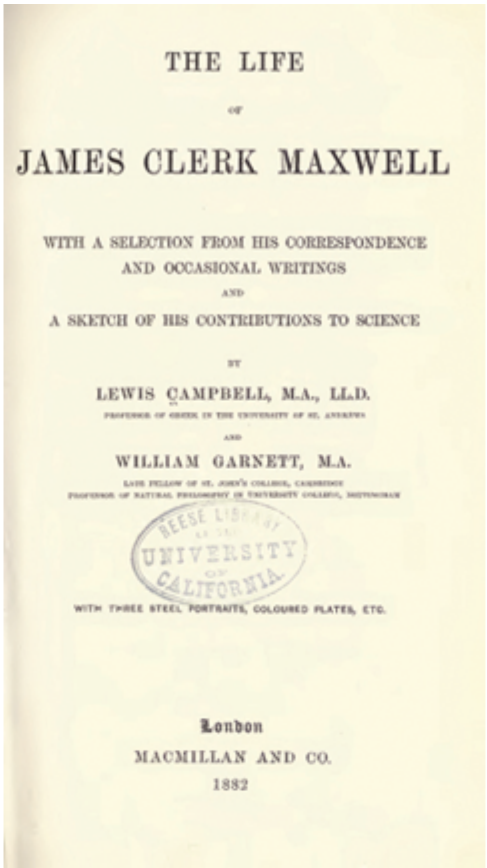
Lewis Campbell and William Garnett (https://incompliancemag.com/author/in-compliance-magazine/) July 31, 2014



A note from the Editor: In celebration of the 150th Anniversary of Maxwell’s Equations, we are honored to bring you a chapter from the book *The Life of James Clerk Maxwell*, the 1882 original biography of James Clerk Maxwell. This chapter, entitled “Faraday’s Lines of Force and Maxwell’s Theory of the Electromagnetic Field,” provides a unique insight to Maxwell’s theory of electromagnetic fields.

This paper was characterised by the late Astronomer Royal as “one of the most remarkable applications of Mathematics to Physics that I have ever seen.”

But notwithstanding the investigations above referred to, and many other original papers on almost every branch of Physical Science, it is for his researches in Electricity and in Molecular Science that Maxwell stands pre-eminent among the men of science of the present century. After taking his degree in 1854, Maxwell read through Faraday’s Experimental researches, a course which he always recommended his students to follow. In Faraday he found a mind essentially of his own type. Thoroughly conversant himself with the Theory of Attractions as developed in Mathematical Treatises, and with the laws of electrical action as illustrated by Sir William Thomson in his paper “on the Uniform motion of heat in homogeneous solid bodies, and its connection with the Mathematical Theory of Electricity” a paper published in the Cambridge



THE LIFE
OF
JAMES CLERK MAXWELL

WITH A SELECTION FROM HIS CORRESPONDENCE
AND OCCASIONAL WRITINGS
AND
A SKETCH OF HIS CONTRIBUTIONS TO SCIENCE

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WITH THREE STEEL PORTRAITS, COLOURED PLATES, ETC.

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Mathematical Journal, February 1842, and “on a Mechanical representation of Electric, Magnetic, and Galvanic Forces,” published in the Cambridge and Dublin Mathematical Journal, January 1847, Maxwell saw the connection between Faraday’s point of view and the method of research adopted by the mathematicians. He used to say that he had not a good nose to smell heresy, but whatever was good and true Maxwell would detect beneath the mass of misconception, or even falsehood, which had gathered round it, and which caused its rejection by nearly every one else without inquiry. Faraday’s conception of a medium he adopted as a guide throughout his electrical researches.

Until the sixteenth century all that was known respecting electricity was the one fact that amber when rubbed possesses the power of attracting light bodies. This property was shown (Physiologia Nova, 1600) to be possessed by a variety of substances by Dr. Gilbert of Colchester, who was Physician to Queen Elizabeth, and who may be regarded as the founder of the Science of Electricity. From this time rapid strides were made in the experimental portion of the science, and the law according to which the attraction or repulsion between two small bodies charged with electricity varies with the charges, and the distance between them, was determined by Coulomb with his torsion balance, an instrument whose value to the experimental investigator can hardly be over-estimated. But it is to Cavendish (1771-1781) that we are mainly indebted for the foundation of the Mathematical Theory of Electricity, and for the highest experimental evidence of the law of electrical action. As the preparation for the press of The Electrical Researches of the Honourable Henry Cavendish was the last of Maxwell’s contributions to science, the work being published only a few weeks before his death, we shall again have to refer to Cavendish’s investigations, and need only state that his experiments proved conclusively, and in the best possible manner as far as the instruments at his disposal would allow, that the attraction or repulsion between two small charged bodies varies directly as the product of their charges, and inversely as the square of the distance between them, so that the law of electrical action is the same as Newton’s law of gravitation, except that the stress between similarly charged bodies is repulsive, and that between dissimilarly charged bodies attractive. After Cavendish’s time comparatively little was added to the theory of statical electricity, if we except the elaborate mathematical investigations of particular problems by Poisson, and the papers of George Green, which until recently were read by few, and appreciated by only two or three, until Faraday took up the subject. Most of Cavendish’s work remained unpublished and unknown, and some of his results were independently obtained by Faraday. It is difficult to conceive what would have been the effect on Faraday’s mind of perusing Cavendish’s “thoughts on electricity,” -as well as his own accounts of his experiments. Perhaps it is best for the world that Faraday was left to work and think on independent lines; certainly it has been a boon to Mathematicians and Physicists alike that Maxwell has appeared to expound and develop, if not to perfect, the work of both.

The mathematical theory of attractions had, prior to the time of Faraday, attained a very high degree of development in the hands of Laplace, Lagrange, Poisson, and others, and could be applied to the solution of many very interesting problems in electricity. But Faraday was not satisfied with the hypothesis of direct action at a distance between charges of electricity, and held that there must be some mechanism by which electric and electromagnetic actions can be communicated from point to point. Not all the arguments by which he supported this view are conclusive, for the force upon an electrified body and the induced electrification of any conductor will be the same whether we adopt the hypothesis of direct action at a distance or of the transmission of electrical action in lines, straight or curved, through an intervening medium. But any view, whether the arguments in its favour are conclusive or not, is of value if it lead us to inquire more closely into the mechanism by which a phenomenon is brought about; and thus Faraday's conception of lines of force, transmitted through a medium, and exerting tension and pressure wherever they are to be found, are of more value as an instrument of mental research than Weber's Theory of Electro-magnetism, however perfect the latter may be from a mathematical point of view.

The following quotation, from the preface to the Electricity and Magnetism, gives Maxwell's views of Faraday in his own words (See also Maxwell's article on "Faraday" in Ency. Brit., 9th edit.):

Before I began the study of electricity I resolved to read no mathematics on the subject till I had first read through Faraday's Experimental Researches on Electricity. I was aware that there was supposed to be a difference between Faraday's way of conceiving phenomena and that of the mathematicians, so that neither he nor they were satisfied with each other's language. I had also the conviction that this discrepancy did not arise from either party being wrong. I was first convinced of this by Sir William Thomson, to whose advice and assistance, as well as to his published papers, I owe most of what I have learned on the subject.

As I proceeded with the study of Faraday, I perceived that his method of conceiving the phenomena was also a mathematical one, though not exhibited in the conventional form of mathematical symbols. I also found that these methods were capable of being expressed in the ordinary mathematical forms, and these compared with those of the professed mathematicians.

For instance, Faraday, in his mind's eye, saw lines of force traversing all space where the mathematicians saw centres of force attracting at a distance; Faraday saw a medium where they saw nothing but distance; Faraday sought the seat of the phenomena in real actions going on in the medium, they were satisfied that they had found it in a power of action at a distance impressed on the electric fluids.

Suppose a small positively electrified body to start from a point close to a positively electrified surface, and suppose it to move always in the direction in which it is urged by the force acting on it, it will, of course, be repelled by the surface, and will move away along some path straight or curved, and will continue to move indefinitely, the force diminishing as it proceeds, unless it meet with a negatively electrified surface, which will attract it, and coming into contact with this surface its career will terminate. The path traced out by such a small electrified body constitutes Faraday's line of force, which is therefore a line whose direction at any point is that of the resultant force at that point. Such lines of force always proceed from positively electrified surfaces, and terminate upon negatively electrified surfaces; or, failing this, they must proceed to infinity. Lines of force proceeding from a positively electrified body placed in a room, unless there be other negatively charged bodies in the neighbourhood, will in general terminate upon the walls, floor, and ceiling of the room, or upon objects in the room in electrical communication with these. Faraday thus conceived the whole of the space in which electrical force acts to be traversed by lines of force which indicate at every point the direction of the resultant force at that point. But Faraday went further than this: he conceived the notion of causing the lines of force to represent also the intensity of the force at every point, so that when the force is great the lines might be close together, and far apart when the force is small; and since the force in the neighbourhood of a small charged body is proportional to the charge, he endeavoured to accomplish this object by drawing from every positively electrified surface a number of lines of force proportional to its charge, and causing a similar number of lines of force to terminate in every negatively electrified surface. In a paper entitled “On Faraday’s Lines of Force,” read before the Cambridge Philosophical Society on December 10th, 1855, and February llth, 1856, Maxwell showed that if a system of lines could be drawn according to Faraday’s method, then, in virtue of the law of electrical action being that of the inverse square of the distance, the number of lines of force passing through a unit area of any surface, drawn perpendicular to the direction of the force, is proportional to the magnitude of the force in the neighbourhood, and that the number of lines passing through the unit area of any other surface is proportional to the component of the force at right angles to that surface. Maxwell therefore imagined the positively electrified surfaces from which the lines started to be divided into areas, each containing one unit of electricity, and lines of force to be drawn through every point in each bounding line. These lines therefore divide the whole of space into “unit tubes,” whose boundaries are lines of force, and Maxwell showed that, in virtue of “the law of inverse squares,” the force at any point in any direction is inversely proportional to the area of the section of the unit tube of force made by a plane perpendicular to that direction. Maxwell further showed that on the negatively electrified surface upon which these tubes terminate, each tube will enclose one, unit of negative electricity, and consequently, if a metallic surface be introduced so as to cut the lines of force, the surface being placed at right angles to the tube, a unit of negative electricity will be induced on each portion of the surface contained within the trace of a tube of force; and hence, in any isotropic medium, these unit tubes of force are also unit tubes of induction. If, therefore, a system of tubes of force be drawn in connection with any electrified system, and in accordance with this plan, the whole of the space in which the force acts will be divided into tubes each originating from a unit of positive electricity and terminating upon a unit of negative electricity, while the direction of the force at any point will be indicated by that of the tube, and the magnitude of the force will be inversely proportional to the area of the cross section of the tube. Now, if the law of force had been any other than that of the inverse square, and tubes had been drawn starting from an electrified surface as above, and such that the area of any section of a tube is inversely proportional to the force across the section, these tubes would either leave spaces between them as they recede from the surface, or would intersect one another; so that it is only for the law of inverse squares that the system of tubes above described is possible. Faraday pointed out that there is not only a tension exerted along each line of force, but that the several lines exert a repulsion upon one another, and Maxwell showed that a tension along the lines of force, accompanied by an equal pressure in every direction at right angles to these lines, is consistent with the equilibrium of the medium. Taking an illustration from the flow of water in a river, Maxwell pointed out that the stream lines or paths along which particles of water flow, are analogous to lines of electric force, the velocity of the water being analogous to the intensity of the force. If the river be supposed to be divided into tubes, the boundaries of which are lines of flow, and if these tubes be so drawn that unit volume of water passes across a particular section of each tube in a second, then, if the flow be steady, unit volume of water will flow across every section of each tube in a second, since no water enters or leaves the tube except at its ends. Such tubes may be called unit tubes of flow, and if no tributaries enter the river there will be the same number of unit tubes crossing each section of the river. Where the bed widens the section of each tube increases, being always inversely proportional to the velocity of the water, and hence the number of unit tubes of flow which cut any unit of area in a cross section of the river will be proportional to the velocity of the water in the neighbourhood. Such a system of tubes, therefore, will represent both the direction of motion and velocity of the water at every point, and will exactly correspond, mutatis mutandis, with a system of unit tubes of electric force.

The following letter was addressed to Maxwell by Faraday on receiving a copy of the paper on “Lines of

Force:”

> Albemarle Street, W.,
> 25th March 1857.
> MY DEAR SIR I received your paper, and thank you very much for it. I do not say I venture to thank you for what you have said about “ Lines of Force,” because I know you have done it for the interests of philosophical truth ; but you must suppose it is work grateful to me, and gives me much encouragement to think on. I was at first almost frightened when I saw such mathematical force made to bear upon the subject, and then wondered to see that the subject stood it so well. I send by this post another paper to you; I wonder what you will say to it. I hope however, that bold as the thoughts may be, you may perhaps find reason to bear with them. I hope this summer to make some experiments on the time of magnetic action, or rather on the time required for the assumption of the electrotonic state, round a wire carrying a current, that may help the subject on. The time must probably be short as the time of light ; but the greatness of the result, if affirmative, makes me not despair. Perhaps I had better have said nothing about it, for I am often long in realising my intentions, and a failing memory is against me.
> Ever yours most truly,
> M. FARADAY. Prof. C. Maxwell.

The paper, read before the Cambridge Philosophical Society, and published in vol. x. of their Proceedings, is confessedly only a translation of Faraday’s ideas into mathematical language, with illustrations and extensions, and it makes no attempt at explaining the nature of the action in the dielectric, or the mechanism by which the observed effects are brought about. About five years later, in a series of three papers communicated to the Philosophical Magazine in 1861 and 1862, Professor Maxwell gave a simple sketch of a system of mechanism, capable of producing not only the electrostatic effects above alluded to, but also of accounting for magnetic attraction, the action of electric currents upon one another, and upon magnets, and electromagnetic induction; but before giving an account of these papers it will be necessary briefly to mention the principal phenomena, an explanation of which was required.

The ordinary phenomena of magnetism, including the attraction between dissimilar and the repulsion between similar poles, as well as the still more familiar phenomena of the attraction of soft iron by a magnetic pole, are too well known to require more than a passing mention. Coulomb showed that the law of inverse squares obtained equally for magnetic repulsions as for electrical, so that the stress between two magnetic poles is proportional to the product of the strengths of the poles and inversely proportional to the square of the distance between them, provided the steel of which the magnets are composed is sufficiently hard to prevent the actions of the magnets on each other altering the strengths of their poles.

If a sheet of paper be supported horizontally above the poles of a magnet, and iron filings be sprinkled over the paper, each filing becomes magnetised by induction in the direction of the resultant magnetic force at the point where it is situated, and if the paper be gently tapped so as to overcome friction, the mutual attraction of the unlike poles in the filings causes them to adhere together in threads or filaments, the North pole of one filing attaching itself to the South pole of a neighbouring filing, and so on, the points of attachment all lying along a line of force. In this way the filings form a graphic representation of the lines of magnetic force, and it was this experiment which first suggested to Faraday the idea of the physical existence of such lines; and as he found it difficult to conceive of curved lines of force being due to “direct action at a distance” (Exp. Kes.1166), he considered that there must be some medium which is the vehicle both of magnetic and electric forces, and that such forces are propagated from particle to particle of the medium. Faraday also supposed that the same medium might serve as the vehicle for the transmission of light. The investigation of the properties of the medium necessary to account for observed electric and magnetic actions, the explanation of these actions, and the determination of the velocity of light from purely electro-magnetic considerations on the hypothesis of the existence of a such a medium constitute Maxwell's greatest contribution to electrical science. The action of an electric current upon a magnet was first observed by (Ersted. It is said that he made many attempts in his laboratory to discover an action between a magnet and a wire conveying a current, but in all his attempts he carefully placed the wire at right angles to the magnetic needle, and could detect no effect whatever. On attempting to repeat the experiment in the presence of his class he placed the wire parallel to the needle, and the latter immediately swung round and ultimately came to rest nearly at right angles to the wire. Whenever the North pole (i.e. the North seeking pole) of a magnet is brought near to a wire conveying a current, the pole tends to go round the wire in a certain direction, while the South (or South seeking) pole of the magnet tends to go round the wire in the opposite direction, and hence if the magnet be free to turn about its centre, the magnet will come to rest at right angles to the wire. Many memoriae technicce have been given for determining the manner in which a magnet will behave in the neighbourhood of a current. Maxwell's rule was as follows: Suppose a righthanded screw to be advancing in the direction of the current, and of necessity rotating as it advances, as if it were piercing a solid. The North pole of a magnet will always tend to move round the wire conveying the current in the direction in which such a screw rotates, while the South pole will tend to move in the opposite direction.

We may thus suppose every wire conveying a current to be surrounded by lines of magnetic force which form closed curves around the wire, and the direction of the force is that in which a right-handed screw would rotate if advancing with the current. In the case of a straight wire of infinite length, these curves are of course circles. Since action and reaction are equal and opposite, it follows that whatever be the mechanical force exerted by a current upon a pole of a magnet, the latter will always exert an equal and opposite force upon the wire or other conductor conveying the current. Many experiments have been devised to show this. Maxwell used to illustrate it in a very simple way. Having attached a piece of insulated copper wire to a small round plate of copper, he placed the plate at the bottom of a small beaker. A disc of sheet zinc was then cut of such size as to fit loosely in the beaker, a small "tail" of zinc being left attached to it; this was bent up and united to the copper wire above the top of the beaker, while the plate of zinc was suspended in a horizontal position an inch or two above the copper plate. The beaker was filled up with dilute sulphuric acid and placed on one pole of an electromagnet, some sawdust or powdered resin being placed in the liquid to show its movements. On exciting the magnet the liquid rotated in one direction, and on reversing the polarity of the magnet the direction of rotation was reversed. If the plates be suspended by a string, so that they can readily turn round in the beaker about a vertical axis, the action of the magnet on the current in the vertical wire will cause the plates to turn always in the direction opposite to that of the liquid.

The laws of the mechanical action of conductors conveying currents upon magnets and upon each other were investigated by Ampere in a series of experiments which were at once conclusive and exhaustive. These experiments were alluded to in the highest terms by Professor Maxwell. Any account of them would be out of place here, and we only refer to them as furnishing the experimental evidence for the statements which follow.

We have already described the manner in which magnetic lines of force may be supposed to surround a wire conveying a current. Now let such a wire be bent into a closed curve or ring which need not necessarily be circular. The lines of force, which themselves form closed curves around the wire, will all pass in the same direction through the ring formed by the wire conveying the current, as if they were strung upon the wire, and hence the North pole of a magnet will tend to pass through the ring in the direction of the lines of force; and a moment's reflection will show that this direction is that in which a right-handed screw would advance if rotating in the direction of the current in the wire. Hence, if the North pole of a magnet be brought near to such a small closed circuit, on the one side it will be attracted and tend to pass through the circuit ; on the other side it will be repelled. The South pole of a magnet will be acted upon in precisely the opposite manner. Hence if a small magnetic needle be suspended within a coil of wire conveying a current, it will tend to set itself at right angles to the plane of the coil. Such an arrangement constitutes a galvanometer.

Now suppose that we have a small disc of steel of the same size and shape as the ring formed by the wire, and that this disc is magnetised so that one side is a north pole and the other a south pole. Such a disc will act upon external magnets in the same manner as the current if it be magnetised, so that a right-handed screw rotating with the current would enter at the south face and emerge at the north face. Such a magnetised disc is called a magnetic shell, and it will of course be acted upon by a magnet with forces exactly equal and opposite to those with which the magnet is acted upon by it. The magnetic lines of force proceeding from a circuit conveying an electric current are therefore the same as would proceed from the magnetic shell above described, the strength of the magnetization being properly adjusted; in other words, the magnetic field around such a circuit is the same as that surrounding the magnetic shell, and hence it follows that two circuits, each conveying electric currents, will act upon one another in the same way as two magnetic shells whose circumferences coincide with the wires, and which are magnetised as above described.

Now if the shells be parallel and magnetised in the same direction, they will have their opposite faces presented towards each other, and will attract one another. If they are magnetised in the opposite directions they will repel one another. Similarly, two parallel circuits will attract one another if the currents be passing in the same direction in both, and will repel one another if they be going in opposite directions. Also two parallel wires, which may be considered as parts of such circuits, will attract one another hen the currents in them are going in the same direction, and repel one another if they are going in the opposite directions. Maxwell's rule for determining the manner in which a circuit conveying a current will behave in the presence of other currents or of magnets is a very simple expression of Faraday's results. Defining the positive direction through a circuit as that in which a right-handed screw would advance if rotating with the current, he enunciated the rule thus:

> If a wire conveying a current be free to move in a magnetic field it will tend to set itself so that the greatest possible number of lines of magnetic force may pass through the circuit in the positive direction.

Since the magnetic field may be produced either by magnets or by electric currents themselves, as above described, this rule combined with the principle that action and reaction are equal and opposite will serve to determine the character of the action either upon circuits conveying currents or upon magnets in every possible case which may arise, and, in fact, embodies the magnificent results of Ampere's investigations in this subject.

Previously to the experiments of Faraday the induction of electric currents was unknown. The principal phenomenon depending upon this action, which had been observed, and of which no satisfactory

explanation had been offered, was that of Arago's rotating disc. In this experiment a disc of copper was made to rotate rapidly in its own horizontal plane above a compass needle, when the needle was observed to follow the disc and rotate on its vertical pin. This experiment was subsequently repeated by Sir John Herschel and Mr. Babbage, who employed discs of various substances, and found that it was only when the discs were good conductors of electricity that Arago's result was obtained. Faraday, in the first series of his Experimental Researches, describes an experiment in which a copper disc was made to rotate between the poles of an electro-magnet, while one electrode
of a galvanometer was connected with the axis of the disc, and the other with a wire which was held in contact with the edge of the disc, which edge was amalgamated to secure a good connection. On spinning the disc a current was immediately obtained, the direction of which was reversed with that of the rotation. This experiment may be regarded as the starting-point of the dynamo machines of Wilde, Gramme, Siemens, and others, which seem destined to play so important a part in the civilized life of the future.

Faraday also showed that when two circuits are placed near to one another, if a current be started in one circuit there is an instantaneous current produced in the opposite direction in the neighbouring circuit, while on stopping the "primary" current a transient current in the same direction as the primary occurs in the other or "secondary" circuit. This experiment was the origin of the now well-known induction coil. Again, when the current was flowing steadily in the primary circuit, if the secondary circuit were brought nearer to it, a current was induced in the secondary in the direction opposite to that in the primary, and continued during the approach of the circuits. On removing the secondary circuit a transient current was set up in the same direction as that in the primary.

We cannot here spare space to trace the development of the laws of induced currents. The character of the action may in all cases be inferred from the very concise statement of Lenz, generally quoted as Lenz's law, and which may be thus expressed:

If a conductor move in a magnetic field, an electromotive force will be induced in the conductor which will tend to produce a current in such direction that the mechanical force upon the conductor tends to oppose its motion.

This law, taken in conjunction with the statements made above respecting the mechanical action in a magnetic field upon a conductor conveying a current, serves to determine the character of the induced current whenever a conductor moves in the neighbourhood of magnets or electric currents. Moreover, the starting of a current in a neighbouring circuit must have the same effect upon the wire as if the conductor were suddenly brought from an infinite distance into the position which.it actually occupies. Hence Lenz's law will apply to every case of induced currents.

Maxwell's statement expresses the laws of induced currents quantitatively as well as qualitatively. It is as follows:

> *Whenever the number of lines of magnetic force passing through a closed circuit is changed there is an electro-motive force round the circuit represented by the rate of diminution of the number of lines of force which pass through the circuit in the positive direction.*

If, then, the number of magnetic lines of force passing through a circuit is diminished, there will be an electromotive force round the circuit in the direction in which a right-handed screw would rotate if advancing along the lines of force; a line of force being always supposed to be drawn in the direction in which a north magnetic pole tends to move along it. If the number of lines of force passing through the circuit is increased, the electro-motive force will be in the opposite direction. This law can be deduced from that which expresses the mechanical action upon a circuit conveying a current when placed in a magnetic field together with the principle of the conservation of energy. That it may be numerically true all the quantities involved must be expressed in terms of the electromagnetic system of units.

The telephone is a beautiful example of the application of this law. Every movement of the iron disc in front of the pole of the magnet alters the number of magnetic lines of force passing through the coils of wire surrounding the pole, and hence induces a current in one direction or the other in the coil, which current, increasing or diminishing the strength of the magnetism in the receiving telephone, causes a corresponding motion in the iron disc of the receiver, which therefore emits sounds similar to those incident upon the receiving instrument.

From what has been stated it will appear that the motion of a conductor will produce a current therein only when the conductor is moving in a magnetic field, that is, a portion of space through which magnetic lines of force pass. Faraday supposed that a conductor under these circumstances was thrown into a peculiar condition, which he termed "the electrotonic state," and that a current was induced whenever this state varied. Maxwell showed that this electrotonic state, on the variations of which the induced current in a circuit depends, corresponds to the number of magnetic lines of force which pass through the circuit. Because every change in this quantity involved the action of electromotive force, its relations to electromotive force being the same as those of momentum to force in dynamics, he called the quantity itself electromagnetic momentum. Maxwell's conception of the physical nature of this quantity will be described presently.

The determination of the laws of self-induction in electric currents is another of Faraday's many contributions to electrical science. After one of the Friday evening lectures at the Royal Institution, a certain Mr. Jenkin informed Faraday that when he broke the connection of the circuit in his electromagnet by separating two pieces of wire which he held in his hands, he felt a smart shock. Faraday said that this was the only suggestion, out of a very great number, made to him by ordinary members of a popular audience which ever led to any result. On investigating the matter, Faraday found that when a current is flowing in a coil of wire if the battery be removed there is a tendency for the current to continue after the removal of the battery, and that this tendency is increased by increasing the number of turns of wire in the coil, and still more so by inserting soft iron in the centre of the coil. This tendency does not depend so much on the length of the wire as upon the relative positions of its parts, and if the wire be first doubled and then wound into a coil the tendency disappears. If a few Grove's cells send a current through a short straight piece of wire and the circuit be broken a very feeble spark will be seen on breaking, but if a large electromagnet be introduced into the circuit a very much brighter spark will appear on breaking contact, though the current sent by the battery is feebler. Thus, when a current flows in such a coil its behaviour reminds us of that of water flowing in a pipe which, when an obstruction is suddenly introduced so as to stop the flow, exerts an enormous pressure for a short time upon the pipe and obstruction, in virtue of the momentum which the water has acquired; but that the action is not due to any momentum actually possessed by the moving electricity is shown by the fact that it depends on the configuration of the wire. This property of a coil is called self-induction. If the poles of an electro-magnet be joined by a wire of great resistance as well as by the battery, when the battery is removed a considerable current will flow through the wire. This current Faraday called the extra- current. It is more generally referred to as the self-induction current.

A similar action takes place when connection is made between a battery and a coil. The current does not at once acquire its full value, but for a short time goes on steadily increasing; the self-induction of the coil causing it to behave as if the current in it possessed considerable mass, which has in the first instance to be put into motion. All these actions are immediate consequences of the law of induced currents stated on p. 526. (input correct information here)

There is a well-known experiment of Faraday in which a specimen of his heavy glass, or borate of lead, was placed between the poles of a powerful electro-magnet and a beam of plane polarised light was passed through the glass in the direction of the magnetic force. Faraday found that when the light passed from the north to the south pole of the magnet the plane of polarisation was turned through an angle in the same direction as a right-handed screw would rotate if piercing a solid and advancing with the light. When the light passed in the opposite direction, the rotation of the plane of polarisation was in the same direction with respect to the magnet, and therefore reversed with respect to the path of the light. In this respect the heavy glass under the influence of the magnet behaved differently from a solution of sugar which always turns the plane of polarization of the light in the same direction with reference to its direction of transmission. This was the first experiment which showed any relation between light and magnetism, and indicated that the medium which serves as the vehicle of light the luminiferous ether must at least be affected by the presence of magnetic force, though the fact that the presence of ponderable matter is necessary to the production of this rotation, and that the direction of the rotation depends on the nature of the matter, renders it doubtful how far magnetic force affects the ether directly.

All transparent solids and liquids exhibit the same action on light in different degrees. If a tube of water with plate glass ends be placed within a coil of wire through which an electric current is passing, and plane polarised light be transmitted through the tube, the plane of polarisation will be turned through an angle in the direction in which the current circulates, and this angle will be proportional to the current,

Verdet showed that in the case of a transparent (para-)magnetic substance the rotation is in the opposite direction to that of the current.

The curious effect of a magnet upon the luminous discharge in a vacuum tube and the recent experiments of Dr. Kerr, may indicate other relations between light and electricity and magnetism. Having thus very briefly referred to the principal phenomena of magnetism and electromagnetism, we may proceed to give a short explanation of the medium or mechanism by which Maxwell accounted for these phenomena and their mutual interdependence.

From the well-known laws of the propagation of light, Maxwell assumed “as a datum derived from a branch of science independent of that with which we have to deal, the existence of a pervading medium, of small but real density, capable of being set in motion, and of transmitting motion from one part to another with great, but not infinite, velocity.” Inasmuch as this medium can transmit undulations with finite velocity, it follows that it possesses a property analogous to mass, so that its motion implies kinetic energy; in addition to elasticity, in virtue of which its deformation implies potential energy.

It is well known that if a body rotate about a fixed centre there will be a tension along any radius drawn in the plane of rotation. The form which the earth would assume under the action of gravity only, if there were no rotation, would be that of a sphere. The diurnal rotation tends to cause the polar axis to contract and the equatorial diameter to increase; and this action would go on indefinitely were it not that at a certain early stage it is balanced by the attraction of gravitation, and thus the earth assumes a nearly spherical form, in which the polar axis is shorter than the equatorial diameter.

Referring again to the case of the earth, it is demonstrable from the fundamental laws and principles of dynamics that if matter were conveyed from the equatorial regions to the poles, and there deposited so as to lengthen the polar axis at the expense of the equatorial diameter, the ' rate of rotation of the earth would be increased and the length of the day would be diminished; while if the earth became more oblate its velocity of rotation would diminish. In fact, if any body be in rotation, and be unacted upon by external forces, or if the forces acting upon it be such as not to affect its rotation, and if the system be altered in shape by internal stresses or otherwise, so that its moment of inertia about the axis of rotation is increased, the angular velocity will be diminished and, in the case of a sphere becoming an oblate spheroid, the velocity at the circumference will also be diminished, while if the moment of inertia be diminished, the reverse effect takes place.

Now Maxwell supposed that any medium which can serve as the vehicle of magnetic force consists of a vast number of very small bodies or cells capable of rotation, and which we may consider to be spherical or nearly so when in their normal condition, until we have reason to believe them to be of some other form. When magnetic force is transmitted by the medium, these bodies are supposed to be set in rotation about the lines of magnetic force as axis, and with a velocity depending on the intensity of the force. For the sake of fixing our ideas he supposed the rotation to be in the direction in which a right-handed screw would turn if it advanced in the direction of the force. We thus have the magnetic field filled with "molecular vortices," all rotating in the same direction about the lines of magnetic force as axes. As we have seen, these vortices will tend to contract in the direction of their axes of rotation, and to expand at right angles to this direction, so that if initially they are elastic spheres, they will tend to become oblate spheroids like the earth. This tendency will involve a tension in the medium along the lines of force, these being the lines along which contraction tends to take place, and this will be accompanied by an equal pressure in every direction perpendicular to the lines of force, on account of the tendency of the vortices to expand equatorially.

Now suppose that we have a north magnetic pole and a south magnetic pole placed near to one another. Lines of force will proceed from the North pole, generally in curved lines, to the South pole. The space in the neighbourhood of the poles will be filled with molecular vortices, which will be most energetic along the line joining the poles, and the velocities of the vortices will diminish as we pass into weaker portions of the field. The tension along the lines of force, tending to draw the North and South poles together, affords sufficient explanation of the apparent attraction between the poles; the kinetic energy of the molecular vortices accounts for the potential energy of the separated poles, which we thus suppose to be really kinetic energy, though possessed by the medium between the apparently attracting bodies and not by the bodies themselves. (Perhaps all examples of so-called potential energy we shall some day find to be really kinetic energy possessed by a medium with the properties of which we have been hitherto unacquainted.) When the poles approach one another, the field which is occupied by the vortices is diminished in extent, and though the velocity of the vortices is increased, the whole energy of the field is diminished, and the difference is expended in work done upon the approaching magnets. If the poles are of equal strength, and can come absolutely to coincide, the field is destroyed, all the vortices come to rest, and the energy possessed by them is all expended in work done on the magnets.

If two like poles, north poles for example, be placed near to one another, the lines of force proceeding from the one, instead of going to the other, will be turned aside, and if the poles be of equal strength, a plane bisecting, at right angles, the line joining the poles, will separate the lines of force due to the one from those due to the other, so that no line will cut the plane (Fig. 10). The lines of force thus passing nearly parallel to one another, the pressure exerted by the molecular vortices in every direction at right angles to the lines of force will cause an apparent repulsion between the poles.

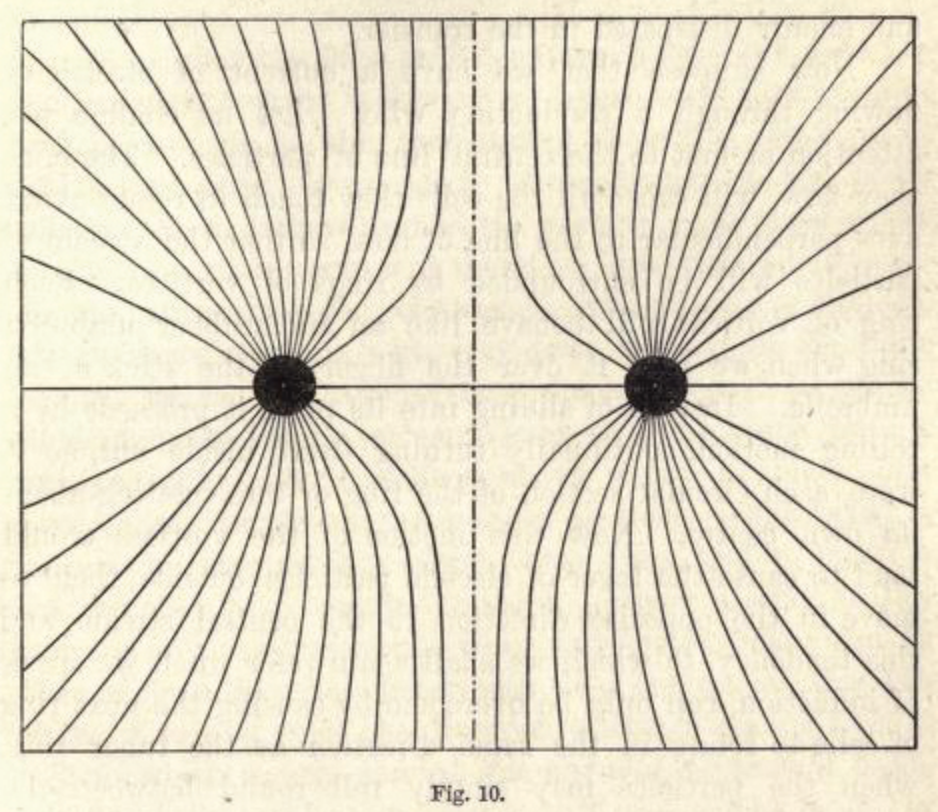

Fig. 10.

To account for the transmission of rotation in the same direction from one molecular vortex to the next, Maxwell supposed that there exists between them a number of extremely minute spherical bodies which roll, without sliding, in contact with the surfaces of the vortices. These bodies serve the same purpose as "idle wheels" in machinery, which, coming between a driver and follower, transmit the motion of the former to the latter unchanged in direction. These minute spherical particles Maxwell supposed to constitute electricity. They roll upon the cells or vortices as if the surfaces in contact were perfectly rough, or provided with teeth gearing into one another, and thus, whatever forces may be applied, sliding is impossible. What we ordinarily consider as molecules of matter are supposed to be very large compared with the molecular vortices, and therefore d fortiori with the particles of electricity. In an insulator, or dielectric, it is supposed that the electric particles are unable to pass from molecule to molecule of the body, but in a conductor they can do so, the passage, however, being opposed by friction, so that heat is generated and energy dissipated in the transfer.

Now suppose that we have a current of electricity flowing through a conducting wire. Let us confine our attention at first to the central line of particles. These, as they flow, will cause all the cells they touch to rotate about axes perpendicular to the line of flow, so that the stream of particles will be surrounded by rings of vortices. Each ring of vortices will behave like an indiarubber umbrella ring when we pass it over the finger or the stick of an umbrella. Instead of sliding into its place it proceeds by a rolling motion, continually turning itself inside out, as it were, each circular section of the ring or tore rotating about its own centre. Now this motion of the vortices would tend to cause the layer of electric particles outside them to move in the opposite direction to the central stream, and this tendency, to which we shall again refer when we speak of induction, can only be overcome by causing the next ring of cells to rotate in the same direction as the inner ring, when the particles may simply roll round between the coaxial rings of vortices without moving backwards or forwards. But if the layer of particles be compelled to move forwards like the inner stream the layer of vortices surrounding it must rotate more rapidly that the layer within it, and so on, each successive shell of vortices rotating more rapidly until we reach the extreme layer contained within the conducting wire. The shell of vortices which bounds the conductor must by the same mechanism set up molecular vortices in the dielectric, the motion being communicated in ever-widening circles to an unlimited distance. It does not follow that this communication of motion is instantaneous. The cells may consist of elastic material which does not assume its final state of motion as soon as the tangential action of the electric particles is exerted upon it, but begins at first to undergo a deformation, the time taken to set up a given rotation in each depending on its density and elasticity. Hence electro-magnetic induction, which is the name given to the action we are now discussing, will be propagated through space with a finite velocity, but of this we must say more hereafter.

From what has been said it appears that when a steady (i.e. constant) current is flowing in a wire, molecular vortices will be set up in the surrounding dielectric, the axis of rotation of each vortex being perpendicular to the plane passing through the wire and the vortex. The axes about which the vortices turn will therefore form circles surrounding the wire, while the vortices themselves will constitute vortex rings, spinning with very great velocity in the same manner as the indiarubber ring above referred to, or the rings of smoke which are sometimes seen to emerge from a tobacco pipe. But the lines about which the molecular vortices rotate are magnetic lines of force, there being a tension in the medium along these lines, and a pressure everywhere at right angles to them. Hence a straight line carrying an electric current will be surrounded with magnetic lines of force, forming circles with their centres on the axis of the wire, and since the direction of the magnetic force is that in which a right-handed screw would advance if rotating with the vortices, it follows that the direction of the magnetic force around the wire will be that in which a righthanded screw would rotate if advancing with the current. The medium will be subject to tension in circles around the wire, and to pressure in planes passing through the wire, reminding us of the cylinders of an Armstrong gun.

If the wire be bent the same will be true in kind, but the lines will no longer be accurately circles. All the magnetic lines of force pass through a closed circuit in the direction in which a right-handed screw would advance if rotating in the direction of the current. Fig. 11, taken from the paper in the Philosophical Magazine, shows the relations between the current, the lines of magnetic force, and the direction of motion of the vortices, the arrows E E’ representing the current, S N indicating the direction of the magnetic force, while the arrows V V’ show the direction of rotation of the vortices.

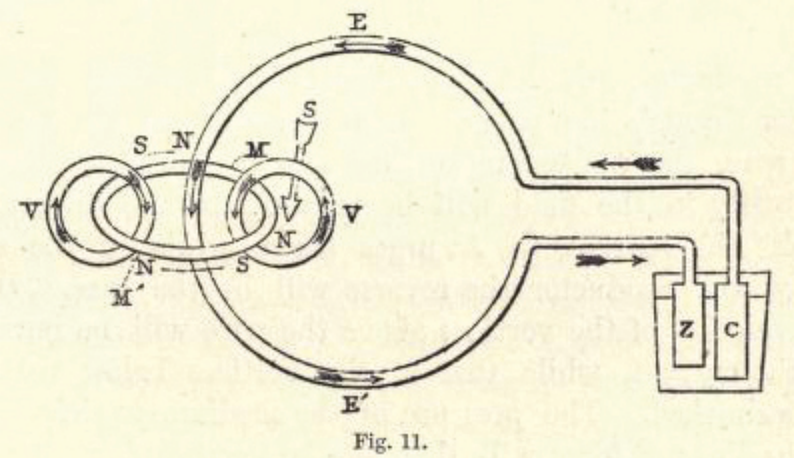

Fig. 11.

Now suppose a wire conveying a current to be placed in a magnetic field at right angles to the lines of force. Let S N (Fig. 12) represent the lines of force, A the section of the conductor, and let the current be travelling from the reader through the paper. In the space immediately above the wire, the molecular vortices due to the magnetic force originally in the field will be rotating in the direction in which the current A urges them, while in the space below the conductor the reverse will be the case. Hence the velocity of the vortices above the wire will be increased by the current, while that of the vortices below the wire is diminished. The pressure of the medium at right angles to the lines of force will therefore be greater above the wire than below it, and the wire will be urged downwards at right angles to the lines of force and to its own direction.

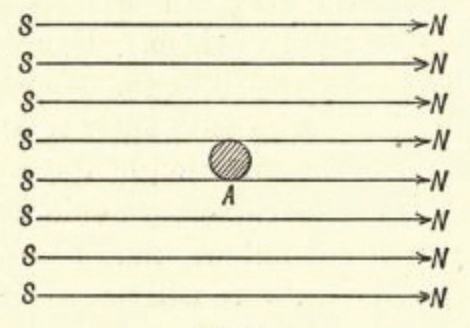

Fig. 12.

Again, suppose two parallel wires to be near together and to convey currents in opposite directions. The strength of a current determines the difference between the velocities of the molecular vortices on opposite sides of it, the electric [particles being related to the vortices in the same way as a differential wheel in mechanism; but the vortices on one side of a moving stream of electric particles may be brought to rest if the velocity of those on the other side be doubled, the current remaining the same though the electric particles themselves will now have to spin round, but this makes no difference. Hence, when parallel wires convey currents in opposite directions, the vortices between them being made to spin in the same direction by both currents, will rotate faster than those on the opposite sides of the wires, and pressing as they do with force proportional to the squares of their circumferential velocities, the wires will be pushed apart as if they repelled one another.

When two parallel wires convey currents in the same direction, they tend to make the cells in the space between them spin in opposite directions, and the velocities of the molecular vortices there will consequently be less than on the other side of the wires. The pressure of the medium between the wires will therefore be less than in the space beyond, and the wires will be pushed together as if they attracted one another.

Now, suppose that a current of electricity commences to flow in a wire. Molecular vortices will be set up in the immediate neighbourhood of the wire, and these vortices acting on the electric particles on the other side of them, remote from the wire, will endeavour to set them in motion in the direction opposite to the current in the wire. But if the medium be a dielectric, the particles cannot be displaced through a sensible distance. They will therefore be made to rotate and start another and larger layer of vortices surrounding the wire, and so the motion will be propagated as above explained. But suppose that at a certain distance there is placed another wire parallel to the first, and forming part of a closed circuit in which no current is flowing. The particles of electricity in this wire will be acted on in the same way as those in the dielectric, but meeting with very little resistance to their motion along the wire, they find it easier to move through the wire than at once to transmit the vortex motion to the elastic bodies on the other side of them. But when a driver and follower are connected by a differential wheel, if the follower be retarded only by its own inertia, however small a resistance the differential wheel may experience to its motion of translation it will at length cause the follower to turn at the same rate as the driver, and will itself cease to move. Hence the resistance of the conductor at length brings the electric particles to rest, and causes them to communicate the vortex motion to cells beyond them. Thus when a current is started in a wire transitory currents in the opposite direction will be induced in neighbouring conductors, while electric stress will be produced in the dielectric, the elastic cells whose motion constitutes the molecular vortices being at first deformed by the tangential stress of the electric particles, but both the induced currents and the stress will have entirely ceased as soon as all the molecular vortices are in full swing.

Before a current can be maintained in a primary wire, the molecular vortices in the surrounding field must be properly started, and this requires the expenditure of work in consequence of the mass of the bodies which constitute the vortices. It is therefore impossible for a finite electromotive force to start a finite current in an indefinitely short time, in the same way as it is impossible for a finite force to produce instantaneously a finite velocity in a material body, and, just as in dynamics we sometimes speak of the reaction of a body against acceleration as though it were a force opposing the force applied, so we sometimes speak of the corresponding action in the case of the current as though it were a force opposing the battery or other electro-motor, and speak of it as the electro-motive force of self-induction. As, however, this depends not on the current in the wire simply, but on the molecular vortices in the surrounding medium, it is clear that the self-induction of a wire will depend on the energy of these vortices, and this must depend on the relations of the several portions of the wire to one another and to the medium, as well as on the density of the medium. The density of the medium Maxwell identified with its magnetic permeability. This is greater in (para-)magnetic substances than in air or vacuum; greatest of all in iron. In fact, it is so great in the case of iron, that Maxwell supposed the particles of the iron itself to take part in the vortex motion. Hence the energy of the field, and therefore the self-induction of the wire, is greater the greater the magnetic permeability of the surrounding medium, and the presence of an iron core in a coil immensely increases its self-induction and the energy corresponding to a given current flowing in the coil.

If, after a current has been established in a wire, the circuit be broken or the electro-motive force removed, the molecular vortices refuse to come to rest till they have expended their energy. The only outlet for this energy is a current in the wire, since there is no opportunity of doing work in a non-conducting medium, where there can be no slipping between the elements of the mechanism. The vortices, therefore, keep the electricity moving in the wire after the battery has been removed, until they have expended all their energy in doing work against the resistance of the wire.

But if there be another conductor in the field parallel or slightly inclined to the first, there is another partial outlet for the energy of the system, and a “secondary” current will be set up in the second wire in the same direction as the current in the primary, while that in the primary will be less than it would have been if no secondary circuit had existed. In this way the hypothesis of molecular vortices affords an explanation both of the mutual induction of two circuits and the self-induction of one.

Suppose a wire to be placed in a magnetic field at right angles to the lines of force, and then to be moved so as to cut the lines at right angles, we should expect that in front of the moving wire the lines of force or threads of vortices would be squeezed together transversely, but extended in the direction of their length, somewhat in the same way as elastic strings would be affected by the wire before they broke and allowed it to pass through. Behind the wire the lateral pressure will be relieved, the vortices will contract in the direction of their axes and expand equatorially. But we have seen that the effect of stretching a rotating elastic body in the direction of its axis of rotation, and compressing it at right angles to this direction, increases the velocity of rotation so that the actual velocity of every point on the surface is increased; while the contraction of the body along the axis of rotation diminishes the velocity. Hence as long as the wire is moving across the lines of force the velocity of the vortices in front of the wire will be greater than that of the vortices behind, and the electric particles in the wire, coming, as they do, between two sets of vortices, which are rotating with different velocities, will flow in a stream along the wire. The direction of the current in the wire will be that which would cause the vortices in front to rotate more rapidly than those behind, and therefore to exert a greater pressure on the wire; in other words, there will be a current induced in such direction as to oppose the motion of the wire. We arrive at a similar result if we suppose the lines of force to be cut obliquely instead of orthogonally. Thus Lenz’s law is a consequence of the hypothesis of molecular vortices. If we suppose the magnetic force to act from south to north horizontally, the wire to be vertical and to move from west to east, we have magnetic force acting from south to north, mechanical force acting from east to west, and opposing the motion of the wire, and electro-motive force acting in the wire vertically upwards.

Suppose that all over a certain area the electricity is pushed forwards through a very small distance along the normal, so that it does not pass from molecule to molecule of the substance, but in each molecule undergoes a displacement from back to front. The electric particles pressing tangentially on the walls of the elastic cells are unable to set them rotating, because each cell is acted upon equally all round in the direction in which the electricity tends to move, and the substance of the cell therefore undergoes a shearing strain which is resisted by its elasticity, and the state of strain of the cells is propagated through the dielectric by means of the displacement of the electric particles which behave like perfectly incompressible bodies. When the force producing the original displacement is removed the cells resume their original form in virtue of their elasticity, the electric particles return to their normal positions, and the energy of the strained elastic cells expends itself in the work done during the electric discharge. Thus the same medium which serves as the vehicle of magnetic force and produces all the phenomena of electromagnetism also serves for the transmission of the force between charges of statical electricity and as a reservoir of the energy due to electrostatic charges. If the dielectric be divided into cells by unit tubes of force and equipotential surfaces drawn for every unit difference of potential, each cell will contain the same amount of energy (See *Elementary Treatise on Electricity* by Professor James Clerk Maxwell, published by the Clarendon Press, 1881.). The following quotations from the paper in the Philosophical Magazine explain the application of the hypothesis of molecular vortices to statical electricity in Maxwell’s own words:

> According to our theory the particles which form the partitions between the cells constitute the matter of electricity. The motion of these particles constitutes an electric current; the tangential force with which the particles are pressed by the matter of the cells is electromotive force, and the pressure of the particles on each other corresponds to the tension or potential of the electricity.
>
> A conducting body may be compared to a porous membrane which opposes more or less resistance to the passage of a fluid; while a dielectric is like an elastic membrane, which may be impervious to the fluid, but transmits the pressure on the one side to [the fluid] on the other.
>
> In a dielectric under induction, we may conceive that the electricity in each molecule is so displaced that one side is rendered positively and the other negatively electrical, but that the electricity remains entirely connected with the molecule, and does not pass from one molecule to another.

> The effect of this action on the whole dielectric is to produce a general displacement of the electricity in a certain direction. This displacement does not amount to a current, because when it has attained a certain value it remains constant, but it is the commencement of a current, and its variations constitute currents in the positive or negative direction, according as the displacement is increasing or diminishing. . . . When we find electromotive force producing displacement in a dielectric, and when we find the dielectric recovering from its state of electric displacement with an equal electromotive force, we cannot help regarding the phenomena as those of an elastic body, yielding to a pressure and recovering its form when the pressure is removed.

Suppose we have a body positively electrified. This means that a displacement of the electricity in the medium takes place in all directions around the body and away from its surface. The cells are thus exposed to a shearing strain, diminishing as the distance increases, because the surface over which the displacement takes place being increased the linear displacement of the electricity is proportionately diminished, the particles of electricity behaving like a perfectly incompressible fluid. The medium being isotropic the lines of electric displacement coincide with those of electric stress, which stress is everywhere proportional to the displacement. The distortion which the cells experience by the pressure of the electric particles induces an elastic pressure in all directions, at right angles to the direction of displacement, so that there is a pressure in the medium at right angles to the lines of force.

Now suppose that we have two positively charged bodies in the field, which we may suppose to possess equal charges. Each produces a displacement of the medium outwards from itself, but the electric particles behaving like an incompressible fluid, it is clear that there can be no lines of displacement from the one to the other, but that between the bodies the lines of displacement will be curved so as to avoid one another in the same way as the stream lines emanating from two pipes, each of which is supplying water to a tank, would be curved round, and would avoid one another. The lines of displacement, and consequently the lines of force which coincide with them, will therefore be bent in exactly the same manner as the magnetic lines of force represented in Fig. 10, and the pressure in the medium at right angles to these lines will cause an apparent repulsion of the bodies.

For the same displacement, that is, for the same charges of the little bodies, the repulsion will be proportional to the elasticity of the medium. It is also proportional to the product of the charges, or, since they are equal, to the square of one of them. Suppose then that the medium is exchanged for one of greater elasticity. If we wish to keep the repulsion between the bodies the same, the displacements and therefore the charges must be diminished, the product of these charges, that is, the square of either charge, being made inversely proportional to the elasticity of the medium. The magnitude of each charge must therefore vary inversely as the square root of the elasticity of the medium when the dielectric is changed. Hence, if we define the electrostatic unit of electricity as “that quantity of positive electricity which, acting on an equal quantity at unit distance repels it with unit force,” it follows that the unit will vary with the character of the dielectric, being inversely proportional to the square root of its elasticity.

But the attraction or repulsion between two given charges of electricity varies inversely as the specific inductive capacity of the dielectric, so that the electrostatic unit of electricity varies directly as the square root of the specific inductive capacity, and thus the specific inductive capacity is a quantity which varies inversely as the elasticity of the medium.

Suppose we have two parallel wires conveying equal electric currents in the same direction. Other things remaining unchanged, the velocity of the molecular vortices at any point is proportional to the strength of the currents. The attraction between the wires we know to be proportional to the product of the strength of the currents, that is to the square of one of them. The pressure excited by the vortices is, cœteris paribus, proportional to their density and the square of their velocity. Suppose we keep the attraction between the wires the same, but change the density of the medium. Then the velocity of the vortices at any point must vary inversely as the square root of the density of the medium. But the velocity of the vortices is proportional to the strength of the currents. Hence the strength of each current must vary inversely as the square root of the density of the medium. If then the electromagnetic unit of current be defined as that current which, flowing in a certain wire, attracts an equal current in another given wire with unit force, the unit of current, and therefore the unit of electricity, which is the amount flowing per second across any section of a wire conveying a unit current, will vary inversely as the square root of the density of the medium.

The ratio of the electromagnetic to the electrostatic unit of electricity will therefore be proportional to the ratio of the square root of the elasticity to the square root of the density of the medium. But this is known to be the velocity with which a transverse vibration is propagated through the medium. Hence the ratio of these units is a concrete velocity, and is proportional to the velocity of propagation of an electromagnetic disturbance, or of the vortex motions above described, through the dielectric. If the units are chosen according to the ordinary system their ratio is not only proportional to but identical with this velocity.

In a paper published in the *Phil. Trans*, for 1868, Professor Maxwell gave an account of an experiment for determining the ratio of the electrostatic and electromagnetic units of electricity where air is the dielectric. The principle of the method lay in balancing the attraction between two electrified discs by the repulsion between two coils of wire in which currents were flowing in opposite directions. One of the discs and one coil was placed at one end of the beam of a torsion balance, the other disc and coil being fixed, but a third coil, conveying the same current as the other two, was placed at the other end of the beam in order to eliminate the magnetic action of the earth and the suspended coil. The apparatus is now in the Cavendish Laboratory. The result of the experiment gave for the ratio of the units a velocity of 288,000,000 metres, or 179,000 statute miles per second. The result obtained by another method by MM. Weber and Kohlrausch is 310,740,000 metres per second. The battery employed for the electrostatic charges was M. Gassiot’s battery of 2600 cells, charged with corrosive sublimate. The accuracy of this result depends on that of the B. A. unit of resistance, the velocity being in fact represented by
28 · 8 Ohms.

Now, according to the undulatory theory, light consists of transverse vibrations of an elastic substance pervading space and all bodies, and the velocity of light as determined by Foucault is 298,000,000 metres per second, or very near the mean of the values obtained by Maxwell, and by Weber and Kohlrausch, for the velocity of propagation of electromagnetic disturbances. If this is found to be always the case, clearly the same medium will serve to account for the phenomena of electrostatics and electromagnetism, and for the propagation of light which must consequently be of the nature of an electromagnetic disturbance. If an electromagnetic disturbance take place in a perfect insulator we have seen that it must be transmitted to an unlimited distance, for as no slipping can take place between the electric particles and the cells, and as the particles themselves cannot be displaced except by inducing a corresponding elastic stress in the medium, there is no outlet for the energy of the disturbance, which must therefore be communicated from cell to cell without limit. But if the medium be a conductor, that is, if the electric particles can undergo a permanent displacement passing from molecule to molecule against a frictional resistance and without any tendency to return, the energy of the electromagnetic disturbance will be gradually dissipated ; for the electric particles, instead of communicating the whole of the motion of one layer of cells to the next, will themselves be set in motion, and part of the energy will be dissipated as heat instead of being imparted to the external layer of cells. The disturbance will therefore continually diminish as it is propagated, until it very soon becomes insensible. The behaviour is the same as that of a driver and follower connected by a differential wheel, whose epicyclic motion is retarded by forces of the nature of friction. Hence electromagnetic disturbances cannot be propagated in conductors of electricity, and we therefore infer that all true conductors are opaque to light.

The transparency of electrolytes, such as saline solutions and the like, offers no difficulty in the face of this conclusion, as the transference of electricity in them is by a process entirely different from true conduction and more allied to the convection of heat, but Maxwell pointed out that the transparency of gold leaf is much greater than the theory would indicate. Thus the resistance of a particular piece of gold leaf was such that it ought to transmit only 10~50 of the light incident upon it, which would be totally imperceptible, while the amount of green light actually transmitted by it was easily perceived. This result Professor Maxwell could reconcile with the theory only by supposing “that there is less loss of energy when the electromotive forces are reversed with the rapidity of the vibrations of light than when they act for sensible times, as in our experiments.”

We have seen that the velocity of transmission of an electromagnetic disturbance in any medium is expressed by the quotient of the square root of the elasticity divided by the square root of the density of the dielectric. We have learned that the elasticity is inversely proportional to the specific inductive capacity of the medium while the density corresponds with the magnetic permeability. Hence we infer that the velocity of transmission of an electromagnetic disturbance varies inversely as the square root of the specific inductive capacity, and also inversely as the square root of the magnetic permeability of the dielectric, and this must be true for the velocity of light if light be an electromagnetic disturbance. Now the magnetic permeability of most transparent media, such as glass, quartz, sulphur, hydro carbons, and the like, does not differ sensibly from that of a vacuum, and hence in these substances the velocity of light must be inversely proportional to the square root of their specific inductive capacity; or, since the index of refraction of a medium is the ratio of the velocity of light in a vacuum to its velocity in that medium, it follows that the refractive index must be directly proportional to the square root of the specific inductive capacity. As all our measurements of specific inductive capacity refer to the action of electromotive forces which continue for a much longer time than the duration of a luminous vibration, we should expect the last mentioned relation to agree most nearly with experiment the longer the wave length of the light, or, as it is sometimes stated, the specific inductive capacity of a dielectric should be equal to the square of its refractive index for “light of infinite wave length.”

The results of the measurements of the specific inductive capacity of certain liquids by Silow, and of gases, sulphur, paraffin, and resin, agree with this theory as well as can be expected. Boltzmann also finds that the specific inductive capacities of crystalline sulphur along its three crystallographic axes are different, these differences coinciding with the differences of the squares of the refractive indices for light transmitted along these three directions.

Dr. Hopkinson (*Phil. Trans*. Part II. 1881) has recently measured the specific inductive capacities of turpentine, benzol, petroleum, ozokerit lubricating oil, castor oil, sperm oil, olive oil, and neats’ foot oil. The hydrocarbons give results which are quite in accordance with Maxwell’s theory, but the fatty oils, which are compounds of glycerine with fatty acids, have inductive capacities far too great. The same appears to be the case with all the varieties of glass tested by Hopkinson, the specific inductive capacities of which vary from 6 · 61 in the case of very light flint to 9 · 896 for "double extra-dense" flint. In the case of solid paraffin, Hopkinson's result agrees very nearly with that of Boltzmann and with Maxwell's theory. In the case of glass, as in that of the fatty oils, the high specific inductive capacity is associated with a complex chemical constitution, glass consisting essentially of metallic silicates, including silicates of the alkaline and alkaline-earthy metals. The measurement of the specific inductive capacity of glass is attended with great difficulty on account of the phenomenon generally known as residual charge or electric absorption, that is the apparent soaking of the electricity into the substance of the glass. This is a subject in which Maxwell took very great interest, and in his work on electricity and magnetism he has given a mechanical illustration of the action on the supposition that it is due to a want of homogeneity in the glass, some parts of which he supposed to conduct electricity better than others, though badly at the best. A form of experiment, very beautiful in its design, was devised by Maxwell for measuring specific inductive capacities, and was carried out by Mr. J. E. H. Gordon, who was able to reverse the electric stress in the glass 12,000 times per second; but this is of course no approximation to the rapid alternations of the "waves" of light. With the apparatus employed, however, the reduction of the observations involves great mathematical difficulties, and the results must therefore be received with caution whether we regard them as supporting the theory or as opposed thereto.

In applying the hypothesis of molecular vortices to the action of a magnetic field on polarised light, Maxwell "found that the only effect which the rotation of the vortices will have on the light will be to make the plane of polarization rotate in the same direction as the vortices, through an angle proportional

A. to the thickness of the substance.
B. to the resolved part of the magnetic force parallel to the ray.
C. to the index of refraction of the ray.
D. inversely to the square of the wave length in air.
E. to the mean radius of the vortices.
F. to the capacity for magnetic induction."

The relation (E) between the amount of rotation and the size of the vortices, shows that different substances may differ in rotating power independently of any observable difference in other respects. We know nothing of the absolute size of the vortices; and on our hypothesis the optical phenomena are probably the only data for determining their relative size in different substances.

Now, independently of the action of a magnetic field on polarised light, all the phenomena of diamagnetism can be accounted for on the hypothesis that the magnetic permeability of diamagnetic substances is less than that of a vacuum, so that they behave like a paramagnetic substance immersed in a medium more magnetic than itself. But Maxwell has pointed out that "since M. Verdet has discovered that magnetic substances have an effect on light opposite to that of diamagnetic substances, it follows that the molecular rotation must be opposite in the two classes of substances."

We can no longer, therefore, consider diamagnetic bodies as those whose coefficient of magnetic induction is less than that of space empty of gross matter. We must admit the diamagnetic state to be the opposite of the paramagnetic; and that the vortices, or at least the influential majority of them, in diamagnetic substances, revolve in the direction in which positive electricity revolves in the magnetising bobbin, while in paramagnetic substances they revolve in the opposite direction.

Perhaps we cannot conclude this account of the hypothesis of molecular vortices better than by quoting

Maxwell's own words:

I think we have good evidence for the opinion that some phenomenon of rotation is going on in the magnetic field; that this rotation is performed by a great number of very small portions of matter, each rotating on its own axis, this axis being parallel to the direction of the magnetic force, and that the rotations of these different vortices are made to depend on one another by means of some kind of mechanism connecting them.

The attempt which I [have] made to imagine a working model of this mechanism must be taken for no more than it really is, a demonstration that mechanism may be imagined capable of producing a connection mechanically equivalent to the actual connection of the parts of the electro-magnetic field. The problem of determining the mechanism required to establish a given species of connection between the motions of the parts of a system always admits of an infinite number of solutions. Of these some may be more clumsy or more complex than others, but all must satisfy the conditions of mechanism in general.

The following results of the theory, however, are of higher value:

A. Magnetic force is the effect of the centrifugal force of the vortices.
B. Electromagnetic induction of currents is the effect of the forces called into play when the velocity of the vortices is changing.
C. Electromotive force arises from the stress on the connecting mechanism.
D. Electric displacement arises from the elastic yielding of the connecting mechanism.

In a paper entitled "A Dynamical Theory of the Electromagnetic Field," read before the Royal Society on December 8, 1864, Maxwell deduced all the above results by purely mechanical reasoning, only assuming the existence of a medium capable of receiving and storing up potential and kinetic energy, and therefore capable of doing work in "recovering from displacement in virtue of its elasticity," while the parts of the medium are connected by" a complicated mechanism capable of a vast variety of motion, but at the same time so connected that the motion of one part depends, according to definite relations, on the motion of other parts, these motions being communicated by forces arising from the relative displacements of the connected parts, in virtue of their elasticity." For the existence of such a medium we have evidence independent of electrical actions. With regard to the mechanism no attempt is made in the paper to give to it any definite constitution. This paper has been regarded as Maxwell's greatest contribution to electrical science, but most of the results obtained in it have been already mentioned.

The following is a good specimen of Maxwell's humorous irony, of which there are many samples in his scientific works. He is discussing certain developments by Bernhard Riemann Lorenzo, of Weber and Neumann's theory of Electro-magnetism, which is based on the assumption that the action between two quantities of electricity is direct action at a distance, and depends not only on the distance between the charges but upon their relative motion.

From the assumption of both these papers we may draw the conclusions first, that action and reaction are not always equal and opposite; and second, that apparatus may be constructed to generate any amount of work from its own resources.

I think that these remarkable deductions from the latest developments of Weber and Neumann's theory can only be avoided by recognising the action of a medium in electrical phenomena.

While at the Cavendish Laboratory Maxwell constructed a mechanical model which illustrates in a very beautiful manner the principal phenomena of induced currents. As a piece of mechanism it is simply a differential train, such as is often employed as a dynamometer for measuring the power absorbed by a machine. The apparatus is sketched in Fig. 13. The grooved wheel P is keyed to the same shaft as the bevel wheel A, which therefore turns with it, and the rotation of this piece represents the primary current. A second bevel wheel D turns loosely on the arm C D, which is one of four arms (of which only two are shown in the figure) forming a cross, which can turn freely on the central shaft at C. Sliding weights M M', etc., can be fixed in any desired position on these arms so as to alter the moment of inertia of the cross, which is the differential piece in the mechanism. A third bevel wheel B is keyed to the same hollow shaft with the wheel S, which is similar to P, and the rotation of the piece B S represents the current in the secondary circuit. As the shaft B S is hollow, and rides loosely on the shaft A C, the wheels A and B can turn quite independently of one another, except in so far as they are connected by the wheel D. P' is an index attached to the interior shaft and turning with P. A loop of string is hung over each of the wheels P and S, and carries a small weight. These strings act as friction brakes to the wheels, and the friction represents the resistance of the primary and secondary circuits respectively. The moment of inertia of the loaded cross, or differential piece, represents the moments of inertia of the cells which constitute the molecular vortices in the dielectric. Its kinetic energy when rotating represents the energy of the vortices, and its angular momentum is proportional to the electromagnetic momentum of the system. The moments of inertia of the other portions of the mechanism are very small compared with that of the loaded cross. The motion of the cross and the wheel D is impeded by as little friction as possible.

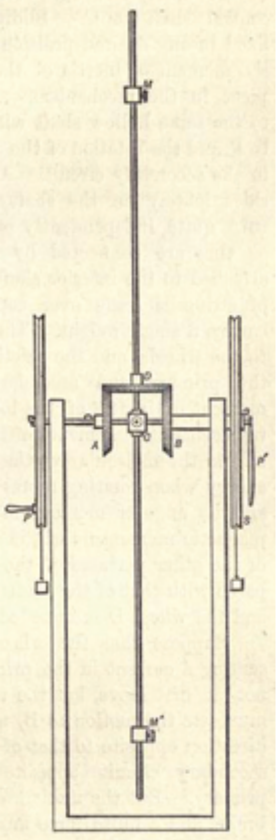

Fig. 13.

Suppose that the wheel P is made to revolve, representing a current in the primary wire ; the heavy cross will not at first move, but the wheel D will revolve and communicate the motion to B, which, with S, will rotate in the direction opposite to that of P, representing a current in the secondary circuit opposite in direction to that in the primary. But the motion of S is resisted by the friction brake, and a finite force must therefore be exerted by D on B to drive it. The reaction of B, together with "the force exerted by A, will constantly tend to make the cross revolve in the same direction as P, and the velocity of the cross being constantly accelerated, it will presently revolve with a velocity half that of P, and then D will roll round B, which, with S, will remain at rest. The piece B S will then continue at rest as long as the rotation of P remains constant corresponding to the cessation of the current in the secondary circuit, while that in the primary remains unchanged, but if P be accelerated, S will revolve in the direction opposite to the motion of P. Now suppose P to be suddenly stopped. The kinetic energy of the cross will cause it to continue to revolve until it has done a corresponding amount of work against resistances, and A being at rest, D will roll upon it and compel B, with S, to revolve in the same direction as the cross, that is, in the same direction in which P formerly revolved, and whatever be the resistance to the motion of S, it will be overcome, and S will revolve till the work done against resistance is equal to the kinetic energy originally possessed by the cross. This corresponds to a current induced in the secondary coil on stopping the current in the primary, which current is in the same direction as the primary current, and continues until the energy of rotation of the molecular vortices has been used up in work done against electrical resistance.

If one operator lay hold of the wheel S, and endeavor to keep it at rest while another applies a steady force to P, the motion of P will be accelerated much less rapidly than if the same force had been applied to it, and S had been free, because P can only move by setting in motion the cross with its great moment of inertia. If the operator who is turning P now suddenly stops it, a great shock will be experienced by the machinery, and the wheel S will slip from the grip of the other operator however firmly he may hold it. The force applied to S may correspond to an airbreak in the secondary coil, and this is sufficient to prevent a spark when the battery current is started in the primary, but by suddenly stopping the primary current, as in KuhmkorfFs coil, a disruptive discharge or spark passes through the air between the terminations of the secondary wire. (If the operator who endeavours to keep the wheel S at rest is inexperienced the effect upon him is very striking).

If a pin be placed in the face of the wheel S, and one end of a spring press against the pin, while the other end is fixed to the frame of the apparatus, we have a representation of a secondary coil in which the circuit is broken, and a Leyden jar inserted with its coatings in connection with the ends of the wire. When the motion of P is changed, S will begin to move, and will deflect the spring, corresponding to a current in the secondary coil charging the Leyden jar. If the spring admit of very great deflection, so that a great amount of work must be done upon it before it slips from the pin, the primary current may have attained its full strength before the slip takes place. This corresponds to the capacity of the Leyden jar being too great to allow of its being charged to a sufficient potential to produce a spark. In this case no spark takes place, but when the force between the wheels D and B diminishes on account of the diminution of the acceleration of P, the spring relieves its strain by forcing the wheel S backwards, and the Leyden jar under corresponding circumstances quietly discharges itself through the secondary coil, reversing the operation by which it was charged. But if the pin slips from the spring, the wheel S will revolve, and the spring will fly back corresponding to a disruptive discharge through the air, and if the acceleration of P continue long enough several such disruptive discharges may take place.

We must, of course, be careful not to endeavour to learn from such a model lessons which it was not designed to teach, and we must remember that the behaviour of the mechanism does not represent the electrical action in all respects.

For many years Maxwell rendered valuable service to the British Association, especially in connection with electrical science. Some account of the meetings which he attended will be found in the letters printed in another part of this work, and though during the last few years of his life other engagements prevented his attendance at the annual gatherings, he always showed signs of keen enjoyment when discussing the "British Asses." In 1862 he was appointed a member of "The Committee on Standards of Electrical Resistance." In the report issued in 1863, the Appendix, "On the Elementary Relations between Electrical Measurements," bears the name of Professor Maxwell in conjunction with that of Professor Fleeming Jenkin, while the general description of the method employed in the determination of the Ohm or B. A. unit of resistance, together with the mathematical theory and details of the experiments, are from Maxwell's pen. In 1863-4 Maxwell was again at work on the same subject in the laboratory of King's College, and most of the "spins" were conducted under his own supervision. In 1869 the results of Maxwell's experiments on the relation of the electromagnetic to the electrostatic unit of electricity, described above, were embodied in the Report to the British Association at the meeting at Dundee, and this forms the last of the Reports of the Committee.

In 1874 Professor Maxwell was elected a member of the committee appointed by the British Association for the purpose of investigating Ohm's law. Most of the work executed by this committee was carried out by Professor Chrystal in the Cavendish Laboratory, under the supervision and at the suggestion of Professor Maxwell. An account of the investigations will be found in the report presented to the Association at the Glasgow meeting in 1876.

Before concluding our notice of Maxwell's contributions to electrical science we must mention the preparation for the press of The Electrical Researches of the Honourable Henry Cavendish, published in 1879, only a few weeks before the death of its editor. The amount of labour which Professor Maxwell bestowed on this work during the last five years of his life can only be known to those who were constantly in his company. Nearly all the MS. he transcribed with his own hand, the greater part being copied after midnight, while he watched over Mrs. Maxwell during the long illness to which allusion has elsewhere been made. Every obscure passage or allusion was the subject of a long and searching investigation; and many were the letters written to the Librarian of the Royal Society and to scientific and literary friends in different parts of the country, to gain information respecting the meaning of obsolete words and symbols, or the history of individuals. But besides this, and a comparison of Cavendish's results with those obtained by subsequent investigators, Maxwell repeated many of Cavendish's experiments almost in their original form, only employing modern instruments for the purposes of measurement. The introduction and the appendices to the work evidence much labour, patient investigation, and very extensive acquaintance with the literature bearing on the subject. Maxwell was by no means one of the class of "thinkers" who only read their own writings; his acquaintance not only with scientific literature, but with nearly every other class of books was astonishing; and if any question of physics was brought before him, he could generally give an account of nearly all that had been done in the subject. In this respect he resembled the late Professor W.

H. Miller, whom Cambridge men used to consult about everything.

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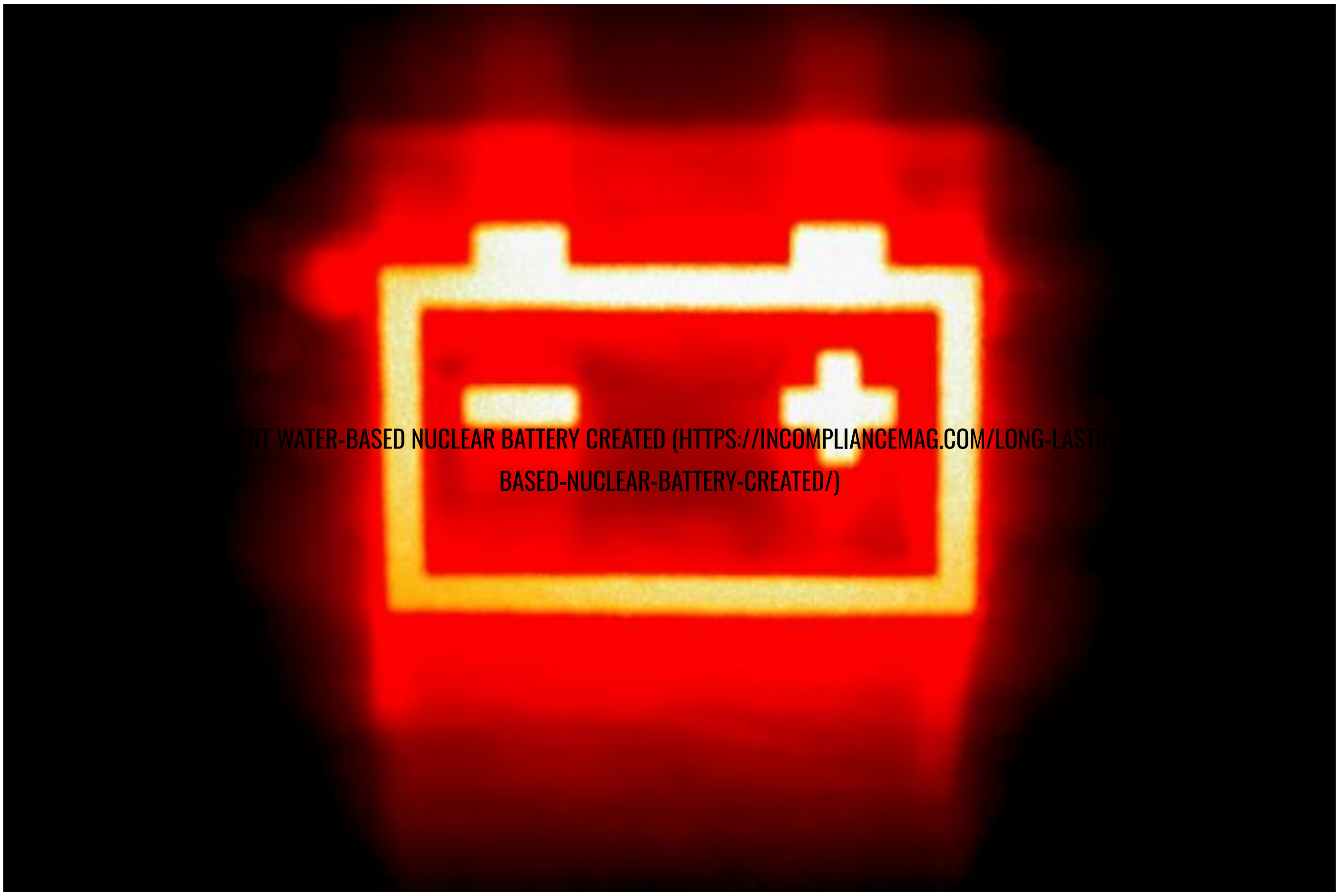

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