

ducts of the action of heat on the ethylphosphates, may aid in determining this question. Meanwhile the observation, already recorded, as to the stability of ordinary ethylphosphoric acid and its salts in the presence of permanganate of potassium requires a word or two of further comment. When argentic diethylphosphate is acted upon with iodine, the silver and one atom of ethyl may be removed, and after treatment with finely divided silver and a little oxide of silver to remove any iodine and hydriodic acid, and then with excess of carbonate of barium, an ethylphosphate of barium is obtained, which, unlike the ordinary salt, immediately reduces permanganate of potassium; perhaps the ethyl in this salt exists in a different and less intimate form of combination. I am inclined to think that the permanganates will afford, in some cases, criteria for the detection of slight differences in isomeric compounds, although it would be premature at present to hazard an exact interpretation of the phenomena to which they give rise. I may add that treatment of an ethylphosphate with strong nitric acid fails to decompose the ethylphosphoric acid; so that phosphoric acid cannot thus be separated from this remarkably stable body.

II. "A Dynamical Theory of the Electromagnetic Field." By Professor J. CLERK MAXWELL, F.R.S. Received October 27, 1864.

(Abstract.)

The proposed Theory seeks for the origin of electromagnetic effects in the medium surrounding the electric or magnetic bodies, and assumes that they act on each other not immediately at a distance, but through the intervention of this medium.

The existence of the medium is assumed as probable, since the investigations of Optics have led philosophers to believe that in such a medium the propagation of light takes place.

The properties attributed to the medium in order to explain the propagation of light are—

1st. That the motion of one part communicates motion to the parts in its neighbourhood.

2nd. That this communication is not instantaneous but progressive, and depends on the elasticity of the medium as compared with its density.

The kind of motion attributed to the medium when transmitting light is that called transverse vibration.

An elastic medium capable of such motions must be also capable of a vast variety of other motions, and its elasticity may be called into play in other ways, some of which may be discoverable by their effects.

One phenomenon which seems to indicate the existence of other motions than those of light in the medium, is that discovered by Faraday, in which the plane of polarization of a ray of light is caused to rotate by the action

of magnetic force. Professor W. Thomson* has shown that this phenomenon cannot be explained without admitting that there is motion of the luminiferous medium in the neighbourhood of magnets and currents.

The phenomena of electromotive force seem also to indicate the elasticity or tenacity of the medium. When the state of the field is being altered by the introduction or motion of currents or magnets, every part of the field experiences a force, which, if the medium in that part of the field is a conductor, produces a current. If the medium is an electrolyte, and the electromotive force is strong enough, the components of the electrolyte are separated in spite of their chemical affinity, and carried in opposite directions. If the medium is a dielectric, all its parts are put into a state of electric polarization, a state in which the opposite sides of every such part are oppositely electrified, and this to an extent proportioned to the intensity of the electromotive force which causes the polarization. If the intensity of this polarization is increased beyond a certain limit, the electric tenacity of the medium gives way, and there is a spark or "disruptive discharge."

Thus the action of electromotive force on a dielectric produces an electric displacement within it, and in this way stores up energy which will reappear when the dielectric is relieved from this state of constraint.

A dynamical theory of the Electromagnetic Field must therefore assume that, wherever magnetic effects occur, there is matter in motion, and that, wherever electromotive force is exerted, there is a medium in a state of constraint; so that the medium must be regarded as the recipient of two kinds of energy—the actual energy of the magnetic motion, and the potential energy of the electric displacement. According to this theory we look for the explanation of electric and magnetic phenomena to the mutual actions between the medium and the electrified or magnetic bodies, and not to any direct action between those bodies themselves.

In the case of an electric current flowing in a circuit A, we know that the magnetic action at every point of the field depends on its position relative to A, and is proportional to the strength of the current. If there is another circuit B in the field, the magnetic effects due to B are simply added to those due to A, according to the well-known law of composition of forces, velocities, &c. According to our theory, the motion of every part of the medium depends partly on the strength of the current in A, and partly on that in B, and when these are given the whole is determined. The mechanical conditions therefore are those of a system of bodies connected with two driving-points A and B, in which we may determine the relation between the motions of A and B, and the forces acting on them, by purely dynamical principles. It is shown that in this case we may find two quantities, namely, the "reduced momentum" of the system referred to A and to B, each of which is a linear function of the velocities of A and B. The effect of the force on A is to increase the momentum of the system

* Proceedings of the Royal Society June 1856 and June 1861.

referred to A, and the effect of the force on B is to increase the momentum referred to B. The simplest mechanical example is that of a rod acted on by two forces perpendicular to its direction at A and at B. Then any change of velocity of A will produce a force at B, unless A and B are mutually centres of suspension and oscillation.

Assuming that the motion of every part of the electromagnetic field is determined by the values of the currents in A and B, it is shown—

1st. That any variation in the strength of A will produce an electromotive force in B.

2nd. That any alteration in the relative position of A and B will produce an electromotive force in B.

3rd. That if currents are maintained in A and B, there will be a mechanical force tending to alter their position relative to each other.

4th. That these electromotive and mechanical forces depend on the value of a single function M, which may be deduced from the form and relative position of A and B, and is of one dimension in space; that is to say, it is a certain number of feet or metres.

The existence of electromotive forces between the circuits A and B was first deduced from the fact of electromagnetic attraction, by Professor Helmholtz* and Professor W. Thomson†, by the principle of the Conservation of Energy. Here the electromagnetic attractions, as well as the forces of induction, are deduced from the fact that every current when established in a circuit has a certain persistency or momentum—that is, it requires the continued action of an unresisted electromotive force in order to alter its value, and that this “momentum” depends, as in various mechanical problems, on the value of other currents as well as itself. This momentum is what Faraday has called the Electrotonic State of the circuit.

It may be shown from these results, that at every point in the field there is a certain direction possessing the following properties:—

A conductor moved in that direction experiences no electromotive force.

A conductor carrying a current experiences a force in a direction perpendicular to this line and to itself.

A circuit of small area carrying a current tends to place itself with its plane perpendicular to this direction.

A system of lines drawn so as everywhere to coincide with the direction having these properties is a system of lines of magnetic force; and if the lines in any one part of their course are so distributed that the number of lines enclosed by any closed curve is proportional to the “electric momentum” of the field referred to that curve, then the electromagnetic phenomena may be thus stated:—

The electric momentum of any closed curve whatever is measured by the number of lines of force which pass through it.

* Conservation of Force. Berlin, 1847: translated in Taylor's Scientific Memoirs, Feb. 1853, p. 114.

† Reports of British Association, 1848. Phil. Mag. Dec. 1851.

If this number is altered, either by motion of the curve, or motion of the inducing current, or variation in its strength, an electromotive force acts round the curve and is measured by the decrease of the number of lines passing through it in unit of time.

If the curve itself carries a current, then mechanical forces act on it tending to increase the number of lines passing through it, and the work done by these forces is measured by the increase of the number of lines multiplied by the strength of the current.

A method is then given by which the coefficient of self-induction of any circuit can be determined by means of Wheatstone's electric balance.

The next part of the paper is devoted to the mathematical expression of the electromagnetic quantities referred to each point in the field, and to the establishment of the general equations of the electromagnetic field, which express the relations among these quantities.

The quantities which enter into these equations are :—Electric currents by conduction, electric displacements, and Total Currents ; Magnetic forces, Electromotive forces, and Electromagnetic Momenta. Each of these quantities being a directed quantity, has three components ; and besides these we have two others, the Free Electricity and the Electric Potential, making twenty quantities in all.

There are twenty equations between these quantities, namely Equations of Total Currents, of Magnetic Force, of Electric Currents, of Electromotive Force, of Electric Elasticity, and of Electric Resistance, making six sets of three equations, together with one equation of Free Electricity, and another of Electric Continuity.

These equations are founded on the facts of the induction of currents as investigated by Faraday, Felici, &c., on the action of currents on a magnet as discovered by Oersted, and on the polarization of dielectrics by electromotive force as discovered by Faraday and mathematically developed by Mossotti.

An expression is then found for the intrinsic energy of any part of the field, depending partly on its magnetic, and partly on its electric polarization.

From this the laws of the forces acting between magnetic poles and between electrified bodies are deduced, and it is shown that the state of constraint due to the polarization of the field is such as to act on the bodies according to the well-known experimental laws.

It is also shown in a note that, if we look for the explanation of the force of gravitation in the action of a surrounding medium, the constitution of the medium must be such that, when far from the presence of gross matter, it has immense intrinsic energy, part of which is removed from it wherever we find the signs of gravitating force. This result does not encourage us to look in this direction for the explanation of the force of gravity.

The relation which subsists between the electromagnetic and the electrostatic system of units is then investigated, and shown to depend upon what

we have called the Electric Elasticity of the medium in which the experiments are made (*i. e.* common air). Other media, as glass, shellac, and sulphur have different powers as dielectrics; and some of them exhibit the phenomena of electric absorption and residual discharge.

It is then shown how a compound condenser of different materials may be constructed which shall exhibit these phenomena, and it is proved that the result will be the same though the different substances were so intimately intermingled that the want of uniformity could not be detected.

The general equations are then applied to the foundation of the Electromagnetic Theory of Light.

Faraday, in his "Thoughts on Ray Vibrations"*, has described the effect of the sudden movement of a magnetic or electric body, and the propagation of the disturbance through the field, and has stated his opinion that such a disturbance must be entirely transverse to the direction of propagation. In 1846 there were no data to calculate the mathematical laws of such propagation, or to determine the velocity.

The equations of this paper, however, show that transverse disturbances, and transverse disturbances only, will be propagated through the field, and that the number which expresses the velocity of propagation must be the same as that which expresses the number of electrostatic units of electricity in one electromagnetic unit, the standards of space and time being the same.

The first of these results agrees, as is well known, with the undulatory theory of light as deduced from optical experiments. The second may be judged of by a comparison of the electromagnetical experiments of Weber and Kohlrausch with the velocity of light as determined by astronomers in the heavenly spaces, and by M. Foucault in the air of his laboratory.

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|---|----------------------------------|
| Electrostatic units in an electromag- netic unit | } 310,740,000 metres per second. |
| Velocity of light as found by M. Fizeau | |
| Velocity of light by M. Foucault. | 298,000,000. |
| Velocity of light deduced from aberra- tion | } 308,000,000. |
| | |

At the outset of the paper, the dynamical theory of the electromagnetic field borrowed from the undulatory theory of light the use of its luminiferous medium. It now restores the medium, after having tested its powers of transmitting undulations, and the character of those undulations, and certifies that the vibrations are transverse, and that the velocity is that of light. With regard to normal vibrations, the electromagnetic theory does not allow of their transmission.

What, then, is light according to the electromagnetic theory? It consists of alternate and opposite rapidly recurring transverse magnetic disturbances, accompanied with electric displacements, the direction of the electric displacement being at right angles to the magnetic disturbance, and both at right angles to the direction of the ray.

* Phil. Mag. 1846. Experimental Researches, vol. iii. p. 447.

The theory does not attempt to give a mechanical explanation of the nature of magnetic disturbance or of electric displacement, it only asserts the identity of these phenomena, as observed at our leisure in magnetic and electric experiments, with what occurs in the rapid vibrations of light, in a portion of time inconceivably minute.

This paper is already too long to follow out the application of the electromagnetic theory to the different phenomena already explained by the undulatory theory. It discloses a relation between the inductive capacity of a dielectric and its index of refraction. The theory of double refraction in crystals is expressed very simply in terms of the electromagnetic theory. The non-existence of normal vibrations and the ordinary refraction of rays polarized in a principal plane are shown to be capable of explanation; but the verification of the theory is difficult at present, for want of accurate data concerning the dielectric capacity of crystals in different directions.

The propagation of vibrations in a conducting medium is then considered, and it is shown that the light is absorbed at a rate depending on the conducting-power of the medium. This result is so far confirmed by the opacity of all good conductors, but the transparency of electrolytes shows that in certain cases vibrations of short period and amplitude are not absorbed as those of long period would be.

The transparency of thin leaves of gold, silver, and platinum cannot be explained without some such hypothesis.

The actual value of the maximum electromotive force which is called into play during the vibrations of strong sunlight is calculated from Pouillet's data, and found to be about 60,000,000, or about 600 Daniell's cells per metre.

The maximum magnetic force during such vibrations is $\cdot 193$, or about $\frac{1}{10}$ of the horizontal magnetic force at London.

Methods are then given for applying the general equations to the calculation of the coefficient of mutual induction of two circuits, and in particular of two circles the distance of whose circumferences is small compared with the radius of either.

The coefficient of self-reduction of a coil of rectangular section is found and applied to the case of the coil used by the Committee of the British Association on Electrical Standards. The results of calculation are compared with the value deduced from a comparison of experiments in which this coefficient enters as a correction, and also with the results of direct experiments with the electric balance.