On the light thrown by recent investigations on Electricity on the relation between Matter and Ether.

THE ADAMSON LECTURE
DELIVERED AT THE UNIVERSITY
ON NOVEMBER 4, 1907

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MANCHESTER
AT THE UNIVERSITY PRESS
1908

The Adamson Lecture, delivered biennially by some person of distinction in Philosophy, Literature, or Science, was founded in 1903 by friends and former colleagues in memory of Robert Adamson, LL.D., Professor of Logic in Owens College from 1876 to 1893.

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By J. J. Thomson.

When I received the invitation to give the Adamson Memorial Lecture I felt considerable hesitation about accepting it. I felt there was some incongruity in a lecture founded in memory of a great master of Metaphysics being given by one who had no qualifications to speak on that subject. I was reassured however when I remembered how wide were Professor Adamson's sympathies with all forms of intellectual activity and how far reaching is the subject of Metaphysics. There is indeed one part of Physical Science where the problems are very analogous to those dealt with by the metaphysician, for just as it is the object of the latter to find the fewest and simplest conceptions which will cover mental phenomena, so there is one branch of physics which is concerned not so much with the discovery of new phenomena or the commercial application of old ones, as with the discussion of conceptions able to link together phenomena apparently as diverse as those of light and electricity, sound, and mechanics, heat and chemical action. To some men this side of Physics is peculiarly attractive, they find in the physical universe with its myriad phenomena and apparent complexity a problem of inexhaustible and irresistible fascination. Their minds chafe under the diversity and complexity they see around them, and they are driven to seek a point of view from which phenomena as diverse as those of light, heat, electricity, and chemical action appear as different manifestations of a few general principles. Regarding the universe as a machine such men are interested not so much in what it can do as in how it works and how it is made; and when they have succeeded, to their own satisfaction at any rate, in solving even a minute portion of this problem they experience a delight which makes the question "what is the value of hypothesis?" appear to them as irrelevant as the questions "what is the value of poetry?" "what is the value of music?" "what is the value of philosophy?"

Recent investigations on Electricity have done a good deal to unite various branches of Physics, and I wish this evening to call your attention to some of the consequences of applying the principle of the equality of action and reaction—Newton's Third Law of Motion—to some of these researches. According to this law the total amount of momentum in any self contained system, that is any system uninfluenced by other systems, is constant, so that if any part of such a system gains momentum another part of the system must simultaneously lose an equal amount of momentum. This law, besides being the foundation of our ordinary system of dynamics, is closely connected with our interpretation of the great principle of the Conservation of Energy, and its failure would deprive that principle of much of its meaning. According to that principle the sum of the kinetic and potential energies of a system is constant; let us consider a moment how we are to estimate the kinetic energy. To us the objects in this room appear at rest, and we should say that their kinetic energy was zero, but to an observer say on Mars, these objects would not appear to be at rest but moving with a considerable velocity, for they would have the velocity due to the rotation of the earth round its axis and also that due to the revolution of the earth round the sun; thus the estimate of the kinetic energy made by a Martian observer would be very different from our estimate. Now the question arises does the principle of the Conservation of Energy hold with both these estimates of the kinetic energy, or does it depend upon the particular system of axes we use to measure the velocity of the bodies? Well we can easily show that if the principle of the equality of action and reaction is true the Conservation of Energy holds whatever axes we use to measure our velocities, but that if action and reaction are not equal and opposite this principle will only hold when the velocities are measured with reference to a particular set of axes.

The principle of action and reaction is thus one of the foundations of Mechanics and a system in which this principle did not hold would be one whose behaviour could not be imitated by any mechanical model. The study of electricity however makes us acquainted with cases where the action is apparently not equal to the reaction. Take for example the case of two electrified bodies A and B in rapid motion, we can, from the laws of electricity, calculate the forces which they exert on each other, and we find that, except in the case when they are moving with the same speed and in the same direction, the force which A exerts on B is not equal and opposite to that which B exerts on A, so that the momentum of the system formed by B and A does not remain constant. Are we to conclude from this result that bodies when electrified are not subject to the Third Law, and that therefore any mechanical explanation of the forces due to such bodies is impossible, this would mean giving up the hope of regarding electrical phenomena as arising from the properties of Matter in Motion. Fortunately, however, it is not necessary. We can follow a famous precedent and call into existence a new world to supply the deficiencies of the old. We may suppose that connected with A and B there is another system, which though invisible possesses mass and is therefore able to store up momentum, so that when the momentum of the system A, B alters, the momentum which has been lost by A and has not gone to B has been stored up in the invisible system with which they are in connection, and that A and B plus the invisible system, together form a system which obeys the ordinary laws of mechanics and whose momentum is constant. We meet in our ordinary experience cases which are in all respects analogous to the one just considered. Take for example the case of two spheres A and B moving about in a tank of water, as A moves it will displace the water around it and produce currents which will wash against B and alter its motion, thus the moving spheres will appear to exert forces on each other, these forces have been calculated by Kirchhoff and resemble in many respects the forces between moving electric charges, in particular unless the two spheres are moving with the same speed and in the same direction the forces between them are not equal and opposite so that the momentum of the two spheres is not constant, if, however, instead of confining our attention to the spheres we include the water in which they are moving we find that the spheres plus the water form a system which obeys the ordinary laws of dynamics and whose momentum is constant, the momentum lost or gained by the spheres is gained or lost by the water. The case is quite parallel to that of the moving electric charges and we may infer from it that when we have a system whose momentum does not remain constant the conclusion we should draw is not that Newton's Third Law fails, but that our system, instead of being isolated as we had supposed, is connected with another system which can store up the momentum lost by the primary, and that the motion of the complete system is in accordance with the ordinary laws of dynamics.

Returning to the case of the electrified bodies we see then that these must be connected with some invisible universe, which we may call the ether, and that this ether must possess mass and be set in motion when the electrified bodies are moved. We are thus surrounded by an invisible universe with which we can get into touch by means of electrified bodies, whether this universe can be set in motion by bodies which are not electrified, is a question on which we have as yet no decisive evidence.

Let us for the moment confine ourselves to the case of electrified bodies, the fact that when these move they have to set some of the ether in motion must affect their apparent mass: for exactly the same reason that the apparent mass of a body is greater when it is immersed in water than when it is in a vacuum; when we move the body through the water we have to set in motion not merely the body itself but also some of the water around it, in some cases the increase in the apparent mass of the body due to this cause may be much greater than the mass of the body itself, this is the case, for example with air bubbles in water which behave as if their mass were many hundred times the mass of the air enclosed in them. In the case of the electrified bodies we may picture to ourselves that the connection between them and the ether around them is established in the following way, we may suppose that the lines of electric force which proceed from these charged bodies and pass through the ether, grip as it were some of the ether and carry it along with them as they move; by means of the laws of electricity we can calculate the mass of ether gripped by these lines in any portion of space through which they pass. The results of this calculation can be expressed in a very simple way. Faraday and Maxwell have taught us to look for the seat of the potential energy of an electrified system in the space around the system and not in the system itself, each portion of space possessing an amount of this energy for which Maxwell has given a very simple expression. Now it is remarkable that if we calculate the mass of the ether gripped by the lines of electric force in any part of the space surrounding the charged bodies we find that it is exactly proportional to the amount of potential energy in that space, and is given by the rule that if this mass were to move with the velocity of light the kinetic energy it would possess would be equal to the electrostatic energy in the portion of space for which we are calculating the mass. Thus the total mass of the ether gripped by an electrical system is proportional to the electrostatic potential energy of that system. Since the ether is only set in motion by the sideways motion of the lines of force and not by their longitudinal motion, the actual mass of the ether set in motion by the electrified bodies will be somewhat less than that given by the preceding rule, except in the special case when all the lines of force are moving at right angles to their length. The slight correction for this slipping of the lines of force through the ether does not affect the general character of the effect, and in what follows I shall for the sake of brevity take the mass of the ether set in motion by an electrified system to be proportional to the potential energy of that system. The electrified body has thus associated with it an etherial or astral body which it has to carry along with it as it moves and which increases its apparent mass. Now this piece of the unseen universe which the charged body carries along with it may be expected to have very different properties from ordinary matter: it would of course defy chemical analysis and probably would not be subject to gravitational attraction, it is thus a very interesting problem to see if we can discover any case in which the etherial mass is an appreciable fraction of the total mass, and to compare the properties of such a body with those of one whose etherial mass is insignificant. Now in any ordinary electrified system, such as electrified balls or charged Leyden jars the roughest calculation is sufficient to show that the etherial mass which they possess in virtue of this electrification is absolutely insignificant in comparison with their total mass. Instead, however, of considering bodies of appreciable size let us go to the atoms of which these bodies are composed, and suppose as seems probable that these are electrical systems and that the forces they exert are electrical in their origin. Then the heat given out when the atoms of different elements combine will be equal to the diminution of the mutual electrostatic potential energy of the atoms combining, and therefore by what we have said will be a measure of the diminution of the etherial mass attached to the atoms; on this view the diminution in the etherial mass will be a mass which moving with the velocity of light possesses an amount of kinetic energy equal to the mechanical equivalent of the heat developed by their chemical combination. As an example, let us take the case of the chemical combination which of all those between ordinary substances is attended by the greatest evolution of heat, that of hydrogen and oxygen. The combination of hydrogen and oxygen to form one gramme of water evolves 4000 calories, or $16{\cdot}8 \times 10^{10}$ ergs, the mass which moving with the velocity of light, *i.e.*, 3×10^{10} centimetres per second possesses this amount of kinetic energy is $3{\cdot}7 \times 10^{-10}$ grammes, and this therefore is the diminution in the etherial mass which takes place when oxygen and hydrogen combine to form 1 gramme of water; as this diminution is only about one part in 3000 million of the total mass it is almost beyond the reach of experiment, and we conclude that it is not very promising to try to detect this change in any ordinary case of chemical combination. The case of radio-active substances seems more hopeful, for the amount of heat given out by radium in its transformations is enormously greater weight for weight than that given out by the ordinary chemical elements when they combine. Thus Professor Rutherford estimates that a gramme of radium gives out during its life an amount of energy equal to $6{\cdot}17 \times 10^{16}$ ergs, if this is derived from the electric potential energy of the radium atoms, the atoms in a gramme of radium must possess at least this amount of potential energy, they must therefore have associated with them an etherial mass of between one-eighth and one-seventh of a milligramme, for this mass if moving with the velocity of light would have kinetic energy equal to $6{\cdot}7 \times 10^{16}$ ergs. Hence we conclude that in each gramme of radium at least $\frac{1}{8}$ of a milligramme, *i.e.*, about 1 part in 8,000, must be in the ether. Considerations of this nature induced me some time ago to make experiments on radium to see if I could get any evidence of part of its mass being of an abnormal kind. The best test I could think of was to see if the proportion betwen mass and weight was the same for radium as for ordinary substances. If the part of the mass of radium which is in the ether were without weight then a gramme of radium would weigh less than a gramme of a substance which had not so large a proportion of its mass in the ether. Now the proportion between mass and weight can be got very accurately by measuring the time of swing of a pendulum; so I constructed a pendulum whose bob was made of radium, set it swinging in a vacuum and determined its time of vibration, to see if this were the same as that of a pendulum of the same length whose bob is made of brass or iron. Unfortunately radium cannot be obtained in large quantities, so that the radium pendulum was very light, and did not therefore go on swinging as long as a heavier pendulum would have done; this made very accurate determinations of the time of swing impossible, but I was able to show that to about 1 part in 3,000 the time of swing of a radium pendulum was the same as that of a pendulum of the same size and shape made of brass or iron. The minimum difference we should expect from theory is 1 part in 8,000, so that this experiment shows that if there is any abnormality in the ratio of the mass to weight for radium it does not much exceed that calculated from the amount of heat given out by the radium during its transformation. With larger pendulums the value of the ratio of mass to weight can be determined with far greater accuracy than 1 part in 8,000; for example, Bessel three-quarters of a century ago showed that this ratio was the same for ivory as for brass to an accuracy of at least 1 part in 100,000; and with apparatus specially designed to test this point an even greater accuracy could be obtained. When I made my experiments with the radium pendulum the close connection between the amounts of uranium and radium in radioactive minerals had not been discovered; this connection makes it exceedingly probable that radium is derived from uranium and that this metal may have weight for weight more electric potential energy, and therefore a larger proportion of its mass in the ether, than radium itself. This points to the conclusion that the proper substance to use for the pendulum experiment is uranium rather than radium, especially since uranium can easily be obtained in sufficiently large quantities to enable us to construct the pendulum of the shape and size which would give the most accurate results, it would not, I think, be impossible to determine the ratio of mass to weight for uranium to an accuracy of 1 part in 250,000.

Though we have not been able to get direct experimental evidence of the existence of the part of the mass in the ether in this way, we are in a more fortunate position in respect to a closely-allied phenomenon, viz., the effect of the speed of a body on its apparent mass. We have seen that the mass of the ether bound by any electrical system is proportional to the electric potential energy of that system. Now let us take the simplest electrical system we can find—a charge of electricity concentrated on a small sphere. When the sphere is at rest the lines of electric force are uniformly distributed in all directions round the sphere. When the lines are arranged in this way the electric potential energy is smaller than for any other possible distribution of the lines. Now let us suppose that the sphere is set in rapid motion, the lines of electric force have a tendency to set themselves at right angles to the direction in which they are moving; they thus tend to leave the front and rear of the sphere and crowd into the middle. The electrical potential energy is increased by this process, and since the mass of the ether bound by the lines of electric force is proportional to this energy, this mass will be greater than when the sphere was at rest. The difference is very small unless the velocity of the spheres approaches the velocity of light, but when it does so the augmentation of mass is very large. Kaufman has succeeded in demonstrating the existence of this effect for the "β" particles emitted by radium; these are negatively electrified particles projected at high speeds from the radium; the velocity of the fastest is only a few per cent. less than the velocity of light; along with these there are others moving much less rapidly. Kaufman determined the masses of the different particles, and found that the greater the speed the greater the mass, the mass of the more rapidly moving particles being as much as three times that of the slower ones. These experiments also led to the very interesting result that the whole of the mass of these particles is due to the charge of electricity they carry. On the view we have been discussing this means that the whole of the mass of these particles is due to the ether gripped by their lines of force.

If lines of electric force grip the ether, then, since waves of light, according to the Electromagnetic Theory of Light, are waves of electric force travelling at the rate of 180,000 miles per second, and as the lines of electric force carry with them some of the ether, a wave of light will be accompanied by the motion of a portion of the ether in the direction in which the light is travelling. The amount of this mass can be easily calculated by the rule that it would possess, if travelling with the velocity of light, an amount of kinetic energy equal to the electrostatic potential energy in the light; as the electrostatic energy is one-half the energy in the light wave, it follows that the mass of the moving ether per unit volume is equal to the energy of the light in that volume divided by the square of the velocity of light. Thus when a body is radiating a portion of the mass of the ether gripped by the body is carried out by the radiation; this mass is in general exceedingly small; for example, we find by the application of the rule we have just given that the mass emitted by each square centimetre of surface of a body at the temperature of the sun is only about 1 milligram per year. We should expect that when some of the ether, bound to a body by its lines of force is carried off by the radiation, other portions of ether which will not be connected with the body will flow in to take its place. Thus, in consequence of the radiation which proceeds from all bodies the ether around them will be set in motion in much the same way as if a series of sources and sinks were distributed throughout the bodies.

Though the actual mass of the ether travelling with a wave of light is exceedingly small, yet its velocity is so great, being that of light, that even a very small mass possesses an appreciable amount of momentum. When the light is absorbed in its passage through a medium which is not perfectly transparent this momentum will also be absorbed and will be communicated to the medium, and will tend to make it move in the direction in which the light is travelling; the light will thus appear to exert a pressure on the medium; the pressure, which is called the pressure of radiation, has been detected and measured by Lebedew, Nicols and Hull and Poynting. All the phenomena associated with this pressure may be explained very simply by the view that light possesses momentum in the direction in which it is travelling. The possession of momentum by light, supposing light to be an electric phenomenon, has been deduced by somewhat abstruse consideration. On the old Newtonian emission theory it is obvious at once that this momentum must exist, for it is just the momentum of the particles which constitute the light. It is remarkable how recent investigations have shown that many of the properties of light which might be supposed to be peculiar to a process similar to that contemplated on the emission theory, would also be possessed by the light if it were an electric phenomenon. There is one consequence of the emission theory to which I should like briefly to allude, because I think it is more in accordance with the actual properties of light than the view to which we should be led if we took the electromagnetic theory in the form in which it is usually presented. The active agents on the emission theory are discrete particles, a ray of light consisting of a swarm of such particles, the volume occupied by these particles being only a very small fraction of the volume through which they are distributed. The front of a wave of light would on this view consist of a multitude of small bright specks spread over a dark ground; the wave front in fact is porous, and has a structure. Now on the electric theory of light as usually given, it is tacitly assumed that the electric force is everywhere uniform over the wave front, that there are no vacant spaces, and that the front has no structure. This is no necessary part of the electric theory, and I think there is evidence that the wave front does in reality much more closely resemble a number of bright specks on a dark ground than a uniformly illuminated area. Let me mention one such piece of evidence. If a flash of light, especially ultra-violet light, fall on a metal surface, negatively electrified corpuscles are emitted from the surface; but when we measure, as we can do, the number of these, we find that only a most insignificant fraction of the number of molecules passed over by the wave front have emitted these corpuscles. If the wave front were continuous then all the molecules of the metal exposed to the light would be under the same condition, and although, like the molecules of a gas, the molecules might possess very different amounts of kinetc energy, this difference would be nothing like sufficient to account for the enormous discrepancy between the number of molecules struck by the light and those which emit corpuscles. This discrepancy would, however, easily be understood if we suppose that the wave front is not continuous but full of holes, so that only a small number of molecules come under the influence of the electric force in the light. We may suppose that light consists of small transverse pulses and waves travelling along discrete lines of electric force, disseminated throughout the ether, and that the diminution in the intensity of the light as it travels outwards from a source is due not so much the enfeeblement of the individual pulses as to their wider separation from each other, just as on the emission theory the energy of the individual particles does not decrease as the light spreads out; the diminution of the intensity of the light is produced by the spreading out of the particles.

The idea that bodies are connected by lines of electric force with invisible masses of ether has an important bearing on our views as to the origin of force and the nature of potential energy. In the ordinary methods of dynamics a system is regarded as possessing kinetic energy which depends solely upon the velocities of the various parts of which it is composed, and potential energy depending on the relative position of its parts. The potential energy may be of various kinds; thus we may have potential energy due to gravity and potential energy due to stretched springs, or electrified systems, and we have rules by which we can calculate the value of these potential energies corresponding to any position of the system. When we know the value of the potential energy the method known as that of "Lagrange's equations" enables us to determine the behaviour of the system. As a means of calculation and investigation this use of the potential energy works admirably, and is very unlikely to be superseded; but, regarded from a philosophical point of view, the conception of potential energy is much less satisfactory, and stands on quite a different footing from that of kinetic energy. When we recognise energy as kinetic we feel that we know a great deal about it; when we describe energy as potential we feel that we know very little about it, and though it may be objected that from a practical point of view that little is all that is worth knowing, the answer does not satisfy an inquisitive thing like the human mind.

Let us consider a commercial analogy and compare kinetic energy to money in actual cash and potential energy to money at our credit in a bank, and suppose such a state of things to exist that when a man lost a sovereign from his pocket it was invariably collected, he did not know how, and placed to his credit in a bank situated he knew not where, from which it could always be recovered without loss or gain. Though the knowledge that this was so might be sufficient for all commercial purposes, yet one could hardly suppose that even the most utilitarian and matter-of-fact of men could refrain from speculating as to where his money was when it was not in his pocket, and endeavouring to penetrate the mystery which envelopes the transfer of the sovereign backwards and forwards. Well, so it is with the physicist and the conception of different forms of potential energy; he feels that these conceptions are not simple, and he asks himself the question whether it is necessary to suppose that these forms of energy are all different; may not all energy be of one kind—kinetic? and may not the transformation of kinetic energy into the different kinds of potential energy merely be the transfer of kinetic energy from a part of the system which affects our senses to another which does not, so that what we call potential energy is really the kinetic energy of parts of the ether which are in kinematical connection with the material system. Let me illustrate this by a simple example. Suppose I take a body A and project it in a region where it is not acted on by any force. A will move uniformly in a straight line. Suppose now I fasten another body B to it by a rigid connection, and again project it. A will not now move in a straight line nor will its velocity be uniform; it may, on the contrary, describe a great variety of curves, circles, trochoids, and so on, the curves depending on the mass and velocity of B when A was projected. Now if B and its connection with A were invisible so that all we could observe was the motion of A, we should ascribe the deviation of A's path from a straight line to the action of a force, and the changes in its kinetic energy to changes in the potential energy of A as it moved from place to place. This method is, however, the result of our regarding A as the sole member of the system under observation, whereas A is in reality only a part of a larger system; when we consider the system as a whole we see that it behaves as if it were free from the action of external forces and that its kinetic energy remains constant; what on our restricted view we regarded as the potential energy of A is seen on the more general view to be the kinetic energy of the system B. It is now many years ago since I showed that the effects of force and the existence of potential energy may be regarded as due to the connection of the primary system with secondary systems, the kinetic energy of these systems being the potential energy of the primary, the complete system having no energy other than the kinetic energy of its constituents; a similar view is the foundation of Hertz's system of Mechanics.

Let us consider one or two simple mechanical systems in which the motion of matter attached to the system produces the same effect as a force. Suppose A and B (Fig. 1) are two bodies attached to tubes which can slide vertically up and down the rod E F, and that two balls C and D are attached to A and B by rods hinged at A and B, then if the balls rotate about the rod they will tend to fly apart, and as the balls move further from the rod their points of attachment A and B must approach each other; thus A and B will tend to move towards each other, *i.e.*, they will behave as if there were an attractive force acting between; the velocities of A and B, and therefore their kinetic energy will change from time to time; the kinetic energy lost by A and B will really have gone to increase the kinetic energy of the balls. If the rotating system C and D had been invisible we should have

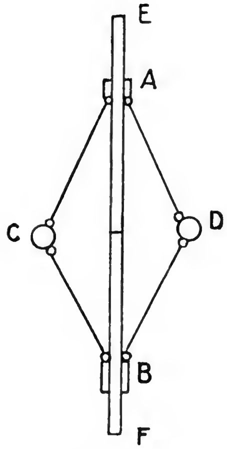

Fig. 1.

explained the behaviour of the system by assuming an attractive force with corresponding potential energy between A and B. This is due to our considering A and B as a complete system, whereas it is in reality part of a larger system, and when we consider the complete system we see that it behaves as if it were acted on by no forces and possessed no energy other than kinetic.

It may perhaps be of interest to note that we can in a similar way make two bodies appear to attract each other with a force varying inversely as the square of the

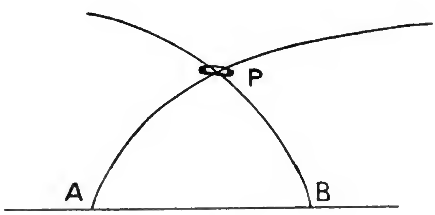

Fig. 2.

distance between them. Let A and B be the bodies, and suppose that parabolic wires without mass are fixed to them, if these are threaded through a ring P with a small but finite mass and the system caused to rotate round A and B, the effort of the ring to get away from the axis of rotation will cause A and B to approach each other, and the law of approach may easily be shown to be the same as if there was a force between them varying inversely as the square of the distance.

The result mentioned on page 10 that the potential energy of a system charged with electricity is equal to the kinetic energy of the mass of ether bound to the system when moving with the velocity of light is another example of potential energy, being in reality the kinetic energy of an associated system, and indeed, as I have endeavoured to bring before you this evening, the study of the problems brought before us by recent investigations leads us to the conclusion that ordinary material systems must be connected with invisible systems which possess mass whenever the material systems contain electrical charges. If we regard all matter as satisfying this condition we are led to the conclusion that the invisible universe—the ether—is to a large extent the workshop of the material universe, and that the phenomena of nature as we see them are fabrics woven in the looms of this unseen universe.