The Mechanics of the Electric Field.[1]

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THE subject which I have selected for the Kelvin Lecture is one that from the very beginning of his scientific career was never long absent from Lord Kelvin's thoughts. It is one, too, which researches only dawning towards the close of his life have put into quite a new aspect. These researches have given us very definite information as to the structure of the atom; they have taught us that the atom is made up of electrons and positively electrified particles of known masses; they have told us the number of electrons and positive particles present in each atom; they have, in fact, given us a definite specification of the electrical state of the atom. With this in our possession it would seem as if we ought to be able to deduce the properties of the atom, by calculating by means of the laws of electromagnetism the behaviour of this definite electrical system. We find, however, if we do this, that the properties of our mathematical atom are in some respects in contradiction to those of the real atom. It is of course a gigantic extrapolation to pass from any system which we can test by direct experiment, and for which the laws of electromagnetism have been verified, to systems like the atoms, where the times and distances involved are of an entirely different order of magnitude. The extrapolation fails, but the point is that if the usual interpretation of these laws is the right one it ought not to fail.

I propose to discuss the question whether the equations of classical electrodynamics or, for the matter of that, classical dynamics are as fundamental as they have been thought to be; whether, instead of giving us a complete representation of the field of force, they do no more than give us the relations between the average value of the quantities used to define the field. That, in fact, they express statistical and not particle dynamics.

Let us consider some of the consequences of supposing that electric force consists of separate impulses separated by finite times. I must point out that this conception involves the existence in the universe of a structure beyond that represented by electrons and positive particles; if there were no structure of this kind, we could not account for the intervals which elapse between the impulses. This structure must be far finer in texture than the electrons; thus, on this view, the electron does not represent the last word in minuteness and there are still smaller entities awaiting discovery by the physicists.

For heuristic purposes, *i.e.* for the purpose of making our meaning clear, and without committing ourselves to the reality of this particular structure, we may liken it to a sub-atomic and sub-electronic gas the particles of which are much finer than the electrons. It is in these particles that the energy and momentum of the electric field are stored. We may regard these particles as concentrated round the electric charges, each charge carrying with it an atmosphere of these particles. The particles are crowded together near the centre of the charge, but get more and more widely separated as the distance from the centre increases. To distinguish between the positive and negative charges, we may suppose that the particles rotate round the charges and that the rotation as viewed from the centre of the charge is in one direction for the positive and in the opposite direction for the negative charge.

The particles bombard intermittently the charges round which they are congregated. If there were only one charge in the field the particles would be symmetrically distributed around it and the bombardment would not, on the average, make it move in one direction rather than in another; but when two or more charges are near together the symmetry of the distribution of the particles is disturbed and the bombardment results in the charges acquiring momentum.

Let us now consider in some detail the way in which the effects produced by intermittent forces differ from those due to continuous ones. We may represent the intermittent force analytically by saying that the chance of a body on which this force is acting receiving in time δt an increment of momentum is $\delta t/D$, where T is the average time between two increments and is a measure of the fineness of the time structure of the electric field. Let I be the increment of momentum given at each impact; then the expectation of the increase in momentum in time δt is $(I/T)\delta t$. If the force had been continuous and equal to F, the increase in momentum would have been equal to $F\delta t$ and have had a definite value. On the intermittent view, instead of a certainty we have an expectation: sometimes the results will exceed expectations, sometimes they will fall below them; but on the average, when there are a great many increments, *i.e.* when δt is large compared with T, they will differ but little from the expectation, so that the increase of momentum will be $(I/T)\delta t$, or the same as the body would receive from a continuous force $F=I/T$. Thus for effects lasting for times long compared with T, the results will be very nearly the same whether the forces are continuous or discontinuous; but for shorter times they will be very different.

We may illustrate the difference between a continuous and an intermittent force by considering a simple case. Take that of an electron projected horizontally and exposed to the influence of a vertical force for a time t. Whether the force be continuous or intermittent the horizontal velocity will remain constant and the horizontal distance travelled is not affected by the intermittence of the force. When the force is continuous and constant there is only one orbit, the parabola. If the force is intermittent there will be an infinite number of possible orbits. In fact any polygon is a possible orbit, provided the rth side makes an angle with the horizontal such that tan $\theta r = kr$, where k is a constant. Thus a horizontal straight line is a possible orbit, because there is just a chance that the electron may escape a collision for the time t.

There is an infinite number of two-sided orbits where the electron makes one collision in the time t. At the end of these orbits all the electrons have the same kinetic energy, but they will not all have suffered the same vertical fall, *i.e.* they will not all have the same potential energy; this is an illustration that the

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conservation of energy in the ordinary sense does not hold for these intermittent forces. To get the same increase in kinetic energy as they would under the action of a continuous force, some of the electrons under the intermittent force would have lost less, others more, "potential energy" than they would under the continuous force.

Again, there is an infinite number of 3-, 4-, 5-sided orbits; there is no limit to the number of sides, and the greater the number of sides the greater the kinetic energy acquired by the electron describing the orbit. All these are possible orbits, but some of them are very improbable. We can calculate the probability of any type of orbit. We have already seen that the most probable number of sides for the orbit is t/T; this makes the final momentum have the same value and direction as it would under the continuous force. But even when the number of sides is given, the individual sides may have very different lengths. We can show that the most probable orbits are those where the impacts are equally spaced over the journey. Again, the most probable orbit is the one that approximates most closely to that described under a continuous force. It is, however, only when t/T is a very large number that the chance of orbits departing widely from this becomes inconsiderable.

I have already pointed out that the principle of the conservation of energy in its usual form does not apply when the forces are discontinuous. This is because the energy is stored in the particles which constitute the electric field, and the distribution of these particles and their energy may change, even though the electrons and positive particles do not move; an electron may take energy from these particles or give up energy to them without suffering any change in its potential energy.

Take, for example, the case of an electron starting from an infinite distance from a positive particle, falling close to the particle and then receding from it until it is again at an infinite distance away. The potential energy is the same at the beginning and end, so that if the principle of the conservation of energy holds, the kinetic energy at the end must also be the same as at the beginning. If we suppose that the mass of the positive particle is infinite compared with that of the electron, so that it absorbs no kinetic energy, the velocity of the electron at the end of the journey must be the same as that at the beginning.

This need not, however, be the case if the force is discontinuous, for when the electron is falling from aphelion to perihelion the increase in its kinetic energy depends upon the number of increments of momentum it receives during its journey from aphelion, and when it goes away from perihelion to aphelion its loss of energy depends upon the number of increments of momentum it receives on the return journey. Now, according to the intermittent theory of the force, these numbers are not fixed but are a matter of chance, so that there is a finite probability that the electron on its journey from aphelion to perihelion may receive more than a normal number of increments, whilst on the return journey it would receive less. If this were so, the electron would receive more energy in its approach than it would lose on its return, so that it would have gained by the journey kinetic energy without losing potential.

The chance of losing more energy on its return than it gained on the approach is just as great as in the case we have considered, so that some electrons may lose kinetic energy by the journey without gaining potential energy. The fact that it is possible for an electron to gain energy in this way has, I think, an important application to the question of the spontaneous dissociation of atomic systems.

Let us take the case of an electron describing an elongated orbit about a positive centre, and suppose that in going from aphelion to perihelion it receives more than the normal number of increments of momentum; when it gets to perihelion it will have more than the normal amount of kinetic energy. Suppose that the increments in the return journey are not more than normal, then on reaching aphelion again the electron will have more kinetic energy than when it started. If this increase in energy exceeds a certain amount, *i.e.* if it is so great that when the electron approaches the place from which it started it has sufficient energy to carry it against the attraction of the positive centre from this place to an infinite distance, the electron will break away and separate from the positive centre.

In this way the discontinuous character of the force may give rise to a spontaneous dissociation of the system—spontaneous in the sense that it is a consequence of the character of the forces acting between the members of the system, and does not depend upon collisions with other molecules or electrons or on the influence of radiation.

An example of this spontaneous dissociation is afforded by the negative ions in gases; these have two phases, one being the electron, the other a complex of the electron and one or more molecules. The first phase is continually passing into the second by the combination of electrons with molecules, and the second into the first by the dissociation of the complex. The rate of this dissociation is independent of the pressure of the gas, and there is no evidence that it is affected by radiation. Similar considerations show that when the force is intermittent an electron moving past a positively electrified particle may acquire or lose energy by the collision, even though the mass of the particle is infinitely greater than that of an electron, when if the force were continuous there would be no transference of energy to or from the electron. Thus it might be possible for an electron projected with less than the energy required to ionise a gas to acquire by collisions with positive particles enough energy for this purpose.

Let us now consider more in detail other characteristics due to the intermittence of the electric force; these will naturally occur only when the phenomena involve times short enough to be comparable with the time interval of the electric field. This time interval, we may say in passing, is not constant but varies with the strength of the electric field, diminishing as the strength of the field increases. Now suppose the electric field acts on an element of volume which contains a very large number of systems, be they electrons, atoms, or anything else which can be effected by electric force; and suppose the time t the force acts is small compared with T the time interval of the force. We can easily show that the momentum received by the whole system will be the same as if the force had been continuous and equal to I/T. This will be true whatever the time may be during which the force acts. The distribution of momentum will, however, be very different in the two cases, when the time of action is small compared with T.

The difference between the continuous and the intermittent force is accentuated when the forces are reversed after short intervals. If the field is intermittent and t is small compared with T, only a small fraction of the systems will have received any energy. When the field is reversed, the chance that any of the few systems previously excited will receive negative momentum and so lose energy is exceedingly small; and the great majority of systems which receive energy in the second interval will not have received any in the first. Thus the systems absorb practically as much energy from the electric field in the second interval as they did in the first. Under the continuous field, instead of absorbing energy, in the second period they gave up all they had got in the first.

Thus the intermittence of the field may lead to a great increase in the absorption of energy from alternating fields by systems exposed to the action of the field. The question of the transmission of waves of electric force when the period of the wave is shorter than the time interval of the electric force, is therefore one that introduces considerations quite different from those of electrical waves of longer period, and requires special treatment.

In the first place, the equations of the electric field do not, if we take the view of the intermittence of force, represent relations between physical quantities which have an existence at any particular time; they have respect rather to the relations between certain statistical quantities, averages taken over a time which is long compared with the time interval of the electric field; for these equations represent relations between electric and magnetic forces. From the point of view of the intermittent theory, electric and magnetic forces do not represent anything that is happening at any particular instant, but an average taken over a time which is long compared with the time interval of the electric field. Thus these equations are meaningless when the times available are not long enough to allow this average to have a definite value. They would not apply, for example, to the case of electrical waves if the period of the waves were less than the time interval of the electric field.

The consideration of what would happen to electrical oscillations the period of which is shorter than the time interval of the electric field, is a matter of great interest and importance. The time interval T of the electric force is connected with F, the intensity of the force by the relation $F=I/T$, where I is the momentum communicated at each impulse, so that as the intensity of the electric field diminishes I/T diminishes also. Now, whatever view we may take of the origin of the impulses which produce the force, whether, for example, we regard them as due to collisions with a swarm of very minute particles or in any other way, we should expect the interval between the collisions to increase as the field gets weaker. The time interval would be a function of the intensity of the field and would be longer for weak fields than for strong. Now consider an electron oscillating with a definite period T_0. Close to the electrons the electric field may be very intense, and its time interval may be short compared with T_0, the period of the oscillations. In such a region as this the classical theory would apply and electrical waves would travel through it, starting from the source of the oscillations. But as the distance from the source increases, the electrical field gets weaker and the time interval continually increases until when a certain distance is reached the time interval becomes comparable with T_0. When this region is reached it seems clear that the waves must stop, as Maxwell's equations from which the wave motion is deduced do not hold.

We have seen too that when T_0, the interval between the reversals of the electric force, is small enough to be comparable with the time interval, the absorption of the energy of the electric field is far greater than when T_0 is long compared with the time interval. We should not therefore expect these waves to travel farther away from the source than the place where the time interval of the electric field is equal to the period of the oscillations. For oscillations of very long period the critical place would be one where the time interval is long, *i.e.* where the field is very weak, and thus may be at a very great distance from the source; whilst for oscillations of very short period the critical place would be one where the time interval is short, *i.e.* where the force is very intense, and thus, *ceteris paribus*, much closer to the source of oscillations than for the slow vibrations.

As an illustration we may take one often used by Lord Kelvin. This is the case of a tightly stretched long string loaded at equal intervals with equal masses. This system has many periods. If P is the fastest of these, $P=\pi\sqrt{(lm/T)}$, where T is the tension in the string, m the mass of one of the particles loading the string, and l the distance between two adjacent particles. If one end of the string is agitated harmonically with a period p, waves will travel freely along the stretched string as long as P is less than p. If, however, the string is made more sluggish by increasing the mass of the particles or otherwise, so that p becomes less than P, the string will no longer transmit the waves, and the energy, instead of travelling along the string, will be localised close to the extremity which is agitated. The model would resemble the electrical case more closely if, instead of spacing the particles at equal intervals, the distance between two adjacent particles increased with the distance from one end A of the string; the value of P would increase with the distance from this end. If the end A were agitated harmonically with a period greater than the value of P close to A, but less than the value of P at some distance from A, the waves would travel along the string until they reached the place where P was equal to the period of agitation. Here they would be reflected back and the farther parts of the string would be free from agitation.

To return to the case of the vibrating electron: we see that though it may send out electrical waves, these waves, after travelling through a distance which depends on the period of the vibrations and also upon their amplitude, will reach a region through which they cannot penetrate, and will be reflected back. Thus the energy emitted by the radiator will not travel out into space but will be reflected back and again absorbed by the radiator, and thus there will be no escape of energy.

If the oscillations were due to an electron describing a circular orbit, the reflected waves when they struck the electron and gave up their energy to it would, in general, deflect it and cause it to describe a different orbit. Thus the motion of the electron would not be steady. There may, however, be some orbits where the distance of the boundary at which the reflection takes place from the orbit is such that the reflected waves are in such a phase when they reach the electron that they just compensate for the changes in the motion of the electron produced by the emission of the radiation. For such orbits the uniform circular motion might be a steady state. It is evident that certain conditions have to be fulfilled for this to happen, so that it is only orbits with particular periods which possess this property. Since the application of a strong electric force would diminish the time-constant of the field, these orbits would be displaced by electric force. We may illustrate this point by the case of a piston vibrating at one end of an organ pipe which is closed at the other. In general, the waves reflected from the closed end will influence the motion of the piston, but they will not do so if the period of the piston is such that a loop of the vibrations of the pipe coincides with the position of the piston.

Let us apply similar considerations to light waves. Assuming that light is an electrical effect, we see at once that there can be no unlimited propagation of spherical electrical waves diverging from a source such as is contemplated in the usual conception of the electromagnetic theory of light; for on this view energy in the light is distributed continuously through space, and the energy per unit volume diminishes indefinitely as the light travels farther and farther away from the source. Now we have seen that the condition for the propagation of a periodic disturbance is that the period of the disturbance should be greater than the time interval of the electric field; this interval increases, however, as the energy in the light diminishes, so that when the energy falls below a certain value, which is small for long-period vibrations and large for short-period ones, any further propagation is impossible. Thus the intermittence of electrical force demands a corpuscular theory of light, *i.e.* a theory where the energy is done up in bundles which do not alter in size as they travel through space. The bundle may consist of a periodic distribution of electric force, like a piece cut out of what on the classical theory represents a beam of light. This piece is prevented from spreading because the energy density at its boundary has the critical value, and this boundary acts, on our view, like a reflecting surface and sends back any disturbance which tries to get outside it.

I picture these units as consisting of two parts: a central core in the form of an anchor ring, the plane of the ring being at right angles to the direction in which the unit is travelling. This ring is the seat of an intense electric field, and the circumference of the ring is equal to the wave-length of the light. This ring corresponds to the quantum of the light. This ring vibrates and emits electrical waves which, after travelling to a certain distance from the centre, get to the limit where the time interval of their electric field is equal to the period of the light. This forms the boundary of the unit, and the space occupied by the waves and the energy in them remain unaltered as the unit travels through space. On this view, light has a dual structure consisting of electrical waves with a quantum as the core. The electrical waves give rise to interference effects, the quanta to the photo-electric ones.

On the view that the force is intermittent the electric field must have a structure, and as electrons and positive particles are the centres of intense electric fields, they are probably much more complex than the usual conception of them, and must be regarded as centres of complex systems associated with an electron or a positive particle. If we compare the atom with its electrons to a solar system, we may compare an electron or a positive particle to the centre of a nebula and regard the electron as surrounded by an atmosphere of small particles.

This atmosphere can be distorted by the presence in its neighbourhood of other electrons or positive particles with their atmospheres, and will assume a shape appropriate to its surroundings. Thus the atmosphere round an electron far from other charges would be symmetrical and, if it were distorted, would vibrate about the symmetrical shape. Thus we could have vibrations associated with single electrons or single positively charged particles, even though the electron or particle were itself at rest; for example, without becoming neutralised by the absorption of an electron, a positively electrified hydrogen atom might be able to give out radiation. The possibility of vibrations of an electric field apart from any movement of the charges in the field has not, I think, been sufficiently realised.

These considerations suggest that just as matter is made up of molecules, and molecules are made up of electrons and positive particles, this is not the end of the story; there are still other worlds to conquer, the worlds which build up the electrons and positive particles.

Coal Ash and Clean Coal.[1]

IT is the normal view that the incombustible part of coal is not only a useless but even objectionable diluent. At times in the past, chemists, familiar with the theory of contact catalysis of gas reactions, have speculated that the ash constituents might well play an active rôle in the processes of carbonisation and combustion. None have been more prominent than Dr. Lessing, but his opinions met with no great support. The reactions in question seemed too complex, and no experimental confirmation had been adduced. Even Dr. Lessing himself waited until 1924 before disclosing evidence that inorganic substances altered the course of carbonisation. Since then, however, the subject has aroused greater interest. It is possible now for

[1] Cantor Lectures by Dr. R. Lessing before the Royal Society of Arts, Nov. 23, 30, and Dec. 7, 1925.