ELECTRICAL PAPERS

BY

OLIVER HEAVISIDE

IN TWO VOLUMES

VOL. I.

London
MACMILLAN AND CO.
AND NEW YORK
1892

Heaviside's greatest contribution, "Theory H";

"Now, in Maxwell's theory there is the potential energy .... They are supposed to be set up by the current in the wire [Theory N] .... **We reverse this**; the current in the wire is set up by the energy transmitted through the medium around it [Theory H] ."

The field causes the current [H], not the current the field [N].

438 ELECTRICAL PAPERS.

be compared to the energy of a machine which is transmitting motion; if done at a steady rate, it remains constant and definite, and the rate of transmission is definite.

Now, in Maxwell's theory there is the potential energy of the displacement produced in the dielectric parts by the electric force, and there is the kinetic or magnetic energy of the magnetic induction due to the magnetic force in all parts of the field, including the conducting parts. They are supposed to be set up by the current in the wire. We reverse this; the current in the wire is set up by the energy transmitted through the medium around it. The sum of the electric and magnetic energies is the energy of the electric machinery which is transmitting energy from the battery to the wire. It is definite in amount, and the rate of transmission of energy (total) is also definite in amount.

Below is the closest Heaviside got to "Theory C";

434

By the way, is there such a thing as an electric current? Not that it is intended to cast any doubt upon the existence of a phenomenon so called; but is it a current—that is, something moving through a wire? Now, although nothing but very careful inculcation at a tender age, continued unremittingly up to maturity, of the doctrine of the materiality of electricity, and its motion from place to place, would have made me believe it, still, there is so much in electric phenomena to support the idea of electricity being a distinct entity, and the force of habit is so great, that it is not easy to get rid of the idea when once it and is either a little greater or a little less in most bodies. But in some bodies it, very singularly, runs up to large numbers. Iron is the principal offender; then come nickel and cobalt, minor magnetics, but far removed from the crowd of almost unmagnetisable substances. Fe = 56, Ni and Co about 58·5. What can it be?

The linear connection between **H** and **B** is very unsatisfactory. Not merely does μ vary with the temperature, and enormously from one piece of iron to another, being, with moderate strength of magnetic force, largest in the softest iron and smallest in hard steel, but it varies with the magnetic force, first increasing with the force, and then, more importantly, decreasing greatly; how far down is unknown. To make matters worse, part of the induction produced by applied magnetising force becomes fixed, for the time, remaining after the removal of the force. Thus the linear connection between **H** and **B** must be taken with salt. But within moderate limits, and excluding permanent magnetisation, which requires separate consideration, μ in equation (10) may be taken to be, like k and c before, a scalar constant in case of isotropy, and a linear vector operator in eolotropic media, being then, like c, self-conjugate, or without the rotatory power.

μ in soft iron is said to run up to 5,000 or 10,000 (Rowland's experiments. I forget the exact figures). But in general it is very far lower than these tremendous figures. From experiments on the retardation of coils made some years ago, including straight solenoids, I concluded that μ = from 50 to 200 was safe, [for small forces].

Not **B**, but $\mathbf{B}/4\pi$ should be the magnetic induction to compare with **D**, the electric induction, or displacement. So, dividing (11) by 4π, and then multiplying by $\frac{1}{2}\mathbf{H}$, we have

$$\tfrac{1}{2}\mathbf{HB}/4\pi = \mathbf{H}\mu\mathbf{H}/8\pi = T, \text{ say. (Magnetic energy)} \quad (11)$$

T is the energy of the magnetic induction per unit volume, when wholly induced, and acting conservatively, [within the elastic limits].

o 1885

Section II. On the Transmission of Energy through Wires by the Electric Current.

Consider the electric current, how it flows. From London to Manchester, Edinburgh, Glasgow, and hundreds of other places, day and night, are sent with great velocity, in rapid succession, backwards and forwards, electric currents, to effect mechanical motions at a distance, and thus serve the material interests of man.

By the way, is there such a thing as an electric current? Not that it is intended to cast any doubt upon the existence of a phenomenon so called; but is it a current—that is, something moving through a wire? Now, although nothing but very careful inculcation at a tender age, continued unremittingly up to maturity, of the doctrine of the materiality of electricity, and its motion from place to place, would have made me believe it, still, there is so much in electric phenomena to support the idea of electricity being a distinct entity, and the force of habit is so great, that it is not easy to get rid of the idea when once it has been formed. In the historical development of the science, static phenomena came first. In them the apparent individuality of electricity, in the form of charges upon conductors, is most distinctly indicated. The fluids may be childish notions, appropriate to the infancy of science; but still electric charges are easily imaginable to be quantities of a something, though not matter, which can be carried about from place to place. In the most natural manner possible, when dynamic electricity came under investigation, the static ideas were transferred to the electric current, which became the actual motion of electricity through a wire. This has reached its fullest development in the hands of the German philosophers, from Weber to Clausius, resulting in ingenious explanations of electric phenomena based upon forces acting at a distance between moving or fixed individual elements of electricity. It so happened that my first acquaintance with electricity was with the dynamic phenomena, and after I had read with absorbed interest that instructive book, Tyndall's "Heat as a Mode of Motion." This may explain why, when it came later to book-learning regarding electricity, I had the greatest possible repugnance to all the explanations, and could not accept the electric current to be the motion of electricity (static) through a wire, but thought it something quite different. I simply did not believe, except so far as mere statements of experimental facts were concerned. This had its disadvantages; one can get on faster if one has sufficient faith—which we know moves mountains—to accept a certain hypothesis unhesitatingly as a fact, and work out its consequences undoubtingly, regardless of the danger of fixing one's ideas prematurely.

As Maxwell remarked, we know nothing about the velocity of electricity; it may be an inch in a year or a million miles in a second. Following this up, it may be nothing at all. In fact, it is only on the hypothesis that the electric current is something moving, a definite quantity in a given space, that we can entertain the idea of its possessing velocity. Then, the product of its hypothetical density into its velocity is the measure of the current; but, being a mere hypothesis, unless we chose to accept it, to talk of the velocity of electricity in the electric current becomes meaningless. On the other hand, when we apply the ideas of abstract dynamics to electricity, and compare the electric current to a velocity, it is not the above supposititious velocity of electricity that is referred to in any way. It has no meaning now. It is the supposed velocity of electricity in the electric current; whereas, in the dynamical theory, it is the electric current itself that is a velocity, in the generalized sense, with the electromotive force as the generalized force; so that force × velocity = activity. In only one sense do I think we can speak of the velocity of electricity, consistent with Maxwell's theory, viz., by the hypothesis that the electric current in a wire is the continuous discharge of contiguous charged molecules, when plainly we can call the velocity of motion of a molecule the velocity of the charge it carries. As between the molecules we have the electric medium the ether, this view of the conduction current ultimately resolves itself into "displacement" currents in a dielectric.

But is there not the fact that we can send a current into a long circuit, and that it plainly travels along the wire, taking some time to arrive at the other end? Does that not show that electricity travels through the wire? To this I should have answered formerly, when filled with "Heat as a Mode of Motion," that it is a fact that there is a transformation of energy in the battery, and that this energy is transmitted through the wire, there suffering another transformation, viz., into heat; that when the current is set up steadily, the heat is generated uniformly; that the electric current in the wire is therefore some kind of stationary motion of the particles of the wire, not exactly like heat, but having some peculiarity of a directional nature making the difference between a positive and a negative current; but that there was no evidence in the closed circuit of any motion of electricity through the wire, but only of a transfer of energy through the wire.

However, leaving personal details of no importance to anyone but myself, let us consider the transmission of energy through a wire. To fix ideas, let our circuit be an insulated suspended wire from London to Edinburgh, and that we transmit energy to Edinburgh from a battery in London, the circuit being completed through the earth. Let the current be kept on. In the first place the phenomenon is steady. It does not change with the time. Next we find that the magnetic force about the wire is the same everywhere at the same distance, or the wire is in the same condition as regards the magnetic induction outside it, and when we apply our knowledge to the interior of the wire, regarded as a bundle of smaller wires, we find that the magnetic force *in* the wire does not vary along its length. Again, heat is being generated within the wire at a uniform rate (a part of the steadiness above mentioned), and next, this phenomenon is also the same all along the wire. Heat is undoubtedly a kinetic phenomenon, hence the electric current is also, at least in part, a kinetic phenomenon. The electric current is not itself heat; but as its existence in the wire involves the continued production of heat, we conclude that some kind of motion is necessarily involved in the electric current apart from the heat produced, and from the uniformity of effect in different parts of the wire, that it is a kind of stationary motion. Again, the electric force is the same all through the wire. There seems no difference between one part and another. Outside the wire, in the dielectric, however, there is a difference, for the electric force varies not only at different distances from the wire but also at the same distance outside different parts of the wire. (We disregard here all irregularities due to other conductors and currents.)

Passing to the battery, the complexity of conditions makes it more difficult to follow, though the state of electric force and magnetic force and heat generation is reducible to the same, and may be made identically the same as in the wire by properly choosing its shape, etc. But in the battery there is a very remarkable thing taking place, namely, the loss of chemical energy at a steady rate; and in the system generally, a still more remarkable thing, an exactly equivalent steady gain of heat. Heat that might have been produced on the spot by the chemical action, otherwise conducted, appears all over the circuit. How does it get there? The natural answer is, through the wire. But to get to the further parts of the wire it must go through the nearer, hence there must be what we may call an energy-current, which, in the wire, at a given place, would be the rate of transfer of energy through a cross section there. Now, which way is the energy-current directed? It would seem only fair to let it go both ways equally from the battery. Let it be so first. Then there is an energy-current entering the wire, equal to one-half the dissipativity, which falls in strength regularly up to the middle of the wire, where it is zero. It falls in strength on account of the heat generation. Similarly the other energy-current goes through the earth to Edinburgh almost unabated in strength, and is then directed from Edinburgh to the middle of the wire, where its strength also falls to nothing. This seems absurd. Then let the energy-current be directed one way only, say with the positive current. If the positive pole of the battery is to line, we have an energy-current in one direction all round the circuit, London to Edinburgh, and back through earth. If of maximum strength at the battery it falls nearly to nothing at the distant end, and quite to nothing through the earth up to the other pole of the battery. But we have no data whatever to fix whereabouts the place of maximum energy-current is. It requires a second assumption. The reader may similarly consider the effect of reversing the battery, or of making the energy-current be directed with the negative current. There is no getting at anything definite, except that the energy-current must vary very widely, though regularly, in strength, whilst there is nothing to fix which way it is directed, or where the maximum strength is. Again, the energy-current is a kinetic phenomenon, and as it varies so widely in different parts, we might expect different parts of the wire itself to be in different electrical states, which is exactly what we do not do; for though its potential varies, yet potential is not a physical state, but a mere scientific concept.

Had we not better give up the idea that energy is transmitted through the wire altogether? That is the plain course. The energy from the battery neither goes through the wire one way nor the other. Nor is it standing still. The transmission takes place entirely through the dielectric. What, then, is the wire? It is the sink into which the energy is poured from the dielectric and there wasted, passing from the electrical system altogether. All [the above mentioned] difficulties now disappear.

That the energy of the battery passes into heat immediately would require its instantaneous transmission to all parts of the wire, which cannot be entertained. There must be an intermediate state or states, after leaving the battery and before becoming heat. And there must be a definite amount of energy in transit at a given moment; in the steady state this must be of constant amount, just as the total rate of transmission is of constant amount. We must not, however, individualize particular elements of energy, and follow their motions, but regard the matter quantitatively only. The energy in transit may be compared to the energy of a machine which is transmitting motion; if done at a steady rate, it remains constant and definite, and the rate of transmission is definite.

Now, in Maxwell's theory there is the potential energy of the displacement produced in the dielectric parts by the electric force, and there is the kinetic or magnetic energy of the magnetic induction due to the magnetic force in all parts of the field, including the conducting parts. They are supposed to be set up by the current in the wire. We reverse this; the current in the wire is set up by the energy transmitted through the medium around it. The sum of the electric and magnetic energies is the energy of the electric machinery which is transmitting energy from the battery to the wire. It is definite in amount, and the rate of transmission of energy (total) is also definite in amount.

It becomes important to find the paths along which the energy is being transmitted. First define the energy-current at a point to be the amount of energy transferred in unit time across unit area perpendicular to the direction of transmission. As the present section is argumentative and descriptive only, we cannot enter into mathematical details further than to say that if **H** be the vector magnetic force, and **E** the vector electric force, not counting impressed forces, the energy-current, as above defined, is $\mathbf{VEH}/4\pi$ (see equation (3) for definition of V). This is true universally, irrespective of the nature of the medium as to conductivity, capacity, and permeability, or as to eolotropy or isotropy, and true in transient as well as in steady states. A line of energy-current is perpendicular to the electric and the magnetic force, and is a line of pressure. We here give a few general notions.

Return to our wire from London to Edinburgh with a steady current from the battery in London. The energy is poured out of the battery *sideways* into the dielectric at a steady rate. Divide into tubes bounded by lines of energy-current. They pursue in general solenoidal paths in the dielectric, and terminate in the conductor. The amount of energy entering a given length of the conductor is the same wherever that length may be situated. The lines of energy-current are the intersections of the magnetic and electric equipotential surfaces. Most of the energy is transmitted parallel to the wire nearly, with a slight slant towards the wire in the direction of propagation; thus the lines of energy-current meet the wire very obliquely. But some of the outer tubes go out into space to an immense distance, especially those which terminate on the further end of the wire. Others pass between the wire and the earth, but none in the earth itself from London to Edinburgh, or *vice versâ*, although there is a small amount of energy entering the earth straight downwards, especially at the earth "plates." If there is an instrument in circuit at Edinburgh, it is worked by energy that has travelled wholly through the dielectric, then finding its way into the instrument, where it enters the coil and is there dissipated, or else used up by the visible motions it effects in moving parts of the instrument; which, however, is a different kind of affair from dissipation, as it involves impressed force.

Now, go into the line-wire. A tube of energy-current arriving at the surface of the wire by a long slant, at once turns round and goes straight to the axis. In passing from the battery to the wire through the dielectric the energy-current is continuous, the state being steady (or the ether machinery frictionless); but directly it reaches the conducting matter of the wire dissipation commences and the current begins to fall in strength, and on reaching the axis has fallen to nothing. Not a fraction of an erg is transmitted along the wire. Some small part of the energy leaving the battery may enter it again, but most of the dissipation in the battery itself is accounted for by the weakening of strength in tubes which are on their way to leave the battery.

Put the battery in the middle of the line; earth at both ends. Now, one half of the energy-current tubes leaving the battery sideways turn round to one section of the line, the other half to the other section. Otherwise the case is similar to the last.

When we have a double wire looped without earth, and battery at one end, most of the energy is transmitted between the wires.

In a circular circuit, with the battery at one end of a diameter, its other end is the neutral point; the lines of energy-current are distributed symmetrically with respect to the diameter.

On closing the battery circuit there is an immediate rush of energy into the dielectric, and, at the first moment, into all bodies in the neighbourhood of the battery, and wasted there in induced currents according to their conductivity. In the variable state the tubes of energy-current are themselves in motion. It takes some time to set the electric machinery going steadily. Also the energy-current is not continuous in the dielectric, for the potential energy of displacement and the magnetic energy have to be supplied at every place. But, in the end, the energy-current becomes continuous in the dielectric, goes round an external conductor instead of entering it, as it would do in the transient state, and finally reaches the conductor to which the battery is connected, penetrating which it terminates.

If we neglect the magnetic energy, as in Sir W. Thomson's original telegraph theory, against the energy of electric displacement, we can easily get a general idea of the setting up of the permanent state in a long suspended wire; a submarine cable is more complex on account of the sheath. The energy reaches the beginning of the wire first, and only reaches the end, save insignificantly, later on. But the theory indicates instantaneous setting up of current at the far end, though not in recognisable amount. This result follows from the neglect of the magnetic energy. In a dielectric medium the velocity of undisturbed propagation is $(c\mu)^{-\frac{1}{2}}$; where c is the capacity, and μ the permeability; that the magnetic energy $=0$ is equivalent to assuming $\mu=0$ everywhere, whence instantaneous transmission. The "retardation," however, arises from the setting up of the potential energy of displacement. But, strictly speaking, we must not neglect μ. It is, then, not so easy to follow the transient state without simplifications. There is an oscillatory phenomenon in the dielectric, a to-and-fro transmission of energy and pressure parallel to the wire all round it with a velocity whose possible maximum is that of undisturbed transmission. This is modified as it progresses by dissipation in the wire, and so gets wiped out. This usually occurs so rapidly that the waves are of importance only at the battery end of a long wire. The electric machinery must have mass, as well as elasticity, by reason of this phenomenon, since there is reason to believe (from Maxwell's theory of light) that it is not the air, but something between the air molecules that is the electromagnetic medium, the air merely modifying the phenomena somewhat.

In the state of steady current through a submarine cable, with an iron sheath outside the dielectric, the energy is transmitted wholly through the gutta percha or other suitable insulator (neglecting the small amount going to earth), thus going nearly parallel to the wire, practically quite parallel, except as regards the lines near the wire itself, as they all eventually meet the wire. There is no transmission in the sheath lengthwise, though there is dissipation there if it should contain, as it does sometimes, part of the return current. In the transient state there is, of course, always dissipation in the sheath more or less, besides the loss of energy to magnetise it.

Now to speak more generally. In the steady state of current due to any impressed forces, the tubes of energy-current start sideways from the places of impressed force, where energy is supplied to the electric system, and travel through definite paths, without loss in dielectric, with loss in conducting parts, to terminate finally in conducting matter; or else they may go from one place of impressed force to another with or without dissipation on the way when the current is with the impressed force at one source, and against it at the other. But with special arrangements (solenoidal) of impressed force, there is no transmission of energy in the steady state.

Since on starting a current the energy reaches the wire from the medium without, it may be expected that the electric current in the wire is first set up in the outer part, and takes time to penetrate to the middle. This I have verified by investigating some special cases.

Increase the conductivity of a wire enormously, still keeping it finite, however. Let it, for instance, take minutes to set up current at the axis. Then ordinary rapid signalling "through the wire" would be accompanied by a surface-current only, penetrating to but a small depth. The disturbance is then propagated parallel to the wire in the manner of waves, with reflection at the end, and hardly any tailing off. With infinite conductivity there can be no current set up in the wire at all. There is no dissipation; wave propagation in the medium is perfect. The wire-current is wholly superficial—an abstraction—yet it is nearly the same with very high conductivity. This illustrates the impenetrability of a perfect conductor to magnetic induction (and similarly to electric current), applied by Maxwell to the molecular theory of magnetism. Whatever state of magnetic induction and of current there may be in a perfect conductor is a fixture. If we move the conductor about in a magnetic field, superficial currents are instantaneously induced, whose only function is to ward off external induction and keep the interior state unchanged.

In a thermo-electric circuit of two metals, with one junction a little hotter than the other, there is a transmission of energy from one junction to the other through the dielectric, with a trifling amount of loss in the circuit generally. Here the source of the electric energy is heat, and the final result is heat. One junction is cooled, the other is heated, reversibly. Now, heat is the energy of molecular agitation, and at first sight the only difference is that the agitation is a little more brisk at one junction than at the other. Again, all parts of the circuit are agitating the ether. It would appear, then, that the ordinary molecular agitations set up no electric manifestations on account of their irregularity; although the electric machinery may be influenced vigorously, yet it must be done in some regularly symmetrical manner to constitute an impressed electric force. At the junctions there is a change of material, the molecules are different, and at their contact some directed quality is given to the agitations. This is very vague, no doubt, but is merely to point out that the impressed force is a symmetrical kind of radiation.

After these general remarks the temporarily interrupted mathematical treatment will be resumed.

SECTION III. RESUMPTION OF ROUGH SKETCH. EXTENSIONS.

Real transient, and suggested dissipative Magnetic Current.

As the rate of increase of the displacement in a non-conducting dielectric is the electric current, so the rate of increase of $\mathbf{B}/4\pi$ may be called the magnetic current. Let it be $\mathbf{G}$. Then

$$\mathbf{G} = \dot{\mathbf{B}}/4\pi = \mu\dot{\mathbf{H}}/4\pi. \quad \text{(Magnetic current)} \quad (12)$$

Like electric displacement currents, magnetic currents are transient only, *i.e.*, they cannot continue indefinitely in one direction, like an electric conduction current. Also, like electric currents in a dielectric, they are unaccompanied by heat generation. In ether, the electric current and the magnetic current are of equal significance.

There is probably no such thing as a magnetic conduction current, with dissipation of energy. If there be such, analogous to an electric conduction current, then let

$$\mathbf{G} = g\mathbf{H} + \mu\dot{\mathbf{H}}/4\pi. \quad \text{.........................} (13)$$

Here $g\mathbf{H}$ is the magnetic conduction current, which, added to the undoubted magnetic current as in (12), gives $\mathbf{G}$ the true magnetic current. g may be scalar, or similar to k, with rotatory ϵ. Multiply (13) by $\mathbf{H}$. Then, using (11),

$$\mathbf{HG} = \mathbf{H}g\mathbf{H} + \dot{T}. \quad \text{........................} (14)$$

Here $\mathbf{H}g\mathbf{H}$ is the rate of dissipation. Compare with (9).

Effect of g in a Closed Iron Ring.

The permanency of state of a steel magnet makes it improbable that