# The Heaviside signal

## An alternative view of the transverse electromagnetic wave

by I. Catt, CAM Consultants

This article proposes a different picture of electromagnetic propagation from the familiar "rolling wave" idea in which electric and magnetic fields topple over and forward, continually changing into each other as they go. The author postulates "an unchanging slab of E x H energy current" travelling forward at the speed of light, and names it "the Heaviside signal" after a concept expressed in the writings of Oliver Heaviside. This process does not rely on a causal relationship between the electric and magnetic fields, which are seen as co-existent.

MAXWELL faced up to the paradox that whereas electric circuits, in order to function properly by allowing the passage of electric current, were thought to require a complete closed circuit of conductors, electric current still seemed to flow for a time when a capacitor (which of course is an open circuit) was placed in series with the closed loop of conductors. He "cut the Gordian knot" (according to Heaviside)[1] by postulating that a new kind of current, which he called "displacement current", leapt across the plates within the capacitor. This electric current, which was uniformly distributed in the space between the capacitor plates, could even flow through a vacuum.

Maxwell followed up this daring idea by suggesting that electromagnetic waves might exist in space. Scepticism about his postulated "displacement current" was silenced in 1887 when Hertz discovered the predicted waves in space. The classic pre-Popperian requirement of a good scientific theory seemed to have been met – the prediction of further results which are later confirmed by experiment.

There are two versions of the transverse electromagnetic wave, the "rolling wave," and what we shall call here the "Heaviside signal." We shall discuss only the wide variety of views among those who believe (with the relativists) that there is no instantaneous action at a distance.

### The rolling wave

The lack of action at a distance creates a fundamental difficulty for the wave in space if it is to be launched by a force in the direction of propagation. The key to the ability of a force to project a wave is that there is a pressure difference between two points along the line of propagation. However, knowledge of a difference in pressure between two points A and B which are separated by distance implies instantaneous knowledge at B of the pressure at A; that is, instantaneous action at a distance, which has been outlawed.

This dilemma seems to be overcome if it is postulated that the force which projects the wave is a lateral, shear, force. It seems a shear force can act at a point, and so not contradict relativity whereas a longitudinal force cannot.

The above kind of reasoning, combined with the postulation of displacement current, which seemed to flow at right angles to the direction of propagation, joined forces to create the notion of the rolling wave. The rolling wave contains alternating concentrations of magnetic energy $\frac{1}{2}\mu H^2$ and electric energy $\frac{1}{2}\epsilon E^2$ in the direction of propagation. It is useful to think of a road with alternate red trucks and white motor cars. The magnetic energy or flux (by Faraday's law of induction) generates electric energy and displacement current ahead of itself, which in turn (by the Biot-Savart Law) generates magnetic flux, or energy, ahead of *itself*. Each type of energy, or flux, topples over and forward, changing as it topples into the other kind of energy. It is as though in the road containing the alternate red trucks and white cars, first the red trucks reappear as white cars a little further ahead while at the same time the white cars turn into red trucks a little further ahead; then the trucks and cars change back again, moving forward a little with each metamorphosis. The analogy with the pendulum has been proposed. One can think of a long line of pendulums, alternate ones having potential energy and kinetic energy, and communicating their energy forward step by step with a change of type of energy at each one.

## The Heaviside signal

Opposed to the rolling wave is what we have called the Heaviside signal. The most highly developed form of this view is that at any point in space, an electromagnetic signal always contains one kind of energy only, which is equal to the product of $E$ and $H$ at that point, where

$$\frac{E}{H} = \sqrt{\frac{\mu}{\epsilon}}. \qquad \text{Energy density} = \frac{E.H}{c}$$

Further, the Heaviside signal always travels forward unchanged at the speed of light, $c = 1/\sqrt{\mu\epsilon}$, and never any slower. $E$, $H$ and c are always mutually perpendicular.

The two men most likely to understand the "Heaviside signal" point of view and to oppose the "rolling wave" were Oliver Heaviside himself, in honour of whom it has been given its name, and Poynting, the man whose name is attached to the vector $E \times H$. However, their writings show that neither man arrived at a full understanding of the Heaviside signal described in the previous paragraph.

Heaviside vacillated between the two views, the rolling wave and the Heaviside signal. He always applauded the idea of displacement current, which appears to put him on the side of the rolling wave. Further, on page 6, art. 453 of volume 3 of his "Electromagnetic Theory", when he says that the curl of $E$, not $E$ itself, is the real source of the waves, he is again arguing for the rolling wave. Curliness is obviously a bid for shear, vorticular forces, a concept intrinsic to the rolling wave. However, elsewhere he seems to stand firmly for the Heaviside signal. For instance *(ibid*, art. 451, page 4), he says, "It carries all its properties with it unchanged," which is a clear statement of the Heaviside signal. In art. 452, the mention of a "slab" of signal is strongly on the side of the Heaviside signal. Heaviside mentions the slab elsewhere in his writings. One does not conceive of slabs rolling, or generating shear forces or stresses. Almost by definition, a slab, like a slab of heavy granite, moves forward unchanged at constant velocity.

Professor Poynting, who first suggested that energy was distributed in space with a density $E \times H$, also had a partial vision of the Heaviside signal. He definitely did not know that $E$ is always perpendicular to $H$, and that the $\times$ in $E \times H$ means simply multiplication. (He had a term $\sin\theta$ for the angle between them.) Poynting was writing before the general agreement that light is electromagnetic, and so did not know that this Poynting energy $E \times H$ always moved forward (in the third dimension) at a constant speed, $1/\sqrt{\mu\epsilon}$, the velocity of light in the medium.

Poynting had a very good grasp of the direction of energy flow and its magnitude, but did not seem to understand the importance of reflections at a change of medium, which leads one to think of one energy current $E \times H$ flowing backwards along its previous path, passing through the next portion of forward travelling energy current. This superposition of forward and backward energy currents (implicit in the phrases "phase velocity" and "group velocity") has prevented a clear understanding of the electromagnetic wave.

For fifty years, technology did not give us the power to drive the medium with an electromagnetic signal. With the low power at our disposal, all we could do was resonate the medium with periodic (sinusoidal) excitation in the same way as we move a child on a swing. In a resonant medium, energy is necessarily flowing in both directions; most of the forward energy returns to aid the source on the next cycle.

Our inability to drive a medium except periodically insinuated itself into our group psyche, until we came to assert that nature *was* periodic (and even that it was sinusoidal). Implicit in this view were the wrong beliefs that

(1) electromagnetic energy is necessarily contrapuntal,
(2) $E/H = \sqrt{(\mu/\epsilon)}$ is not always true, (e.g. when two waves are passing through each other so that $H$ cancels but $E$ does not, so that $E/H = \infty$), and
(3) signals can travel slower than the speed of light $1/\sqrt{\mu\epsilon}$).

The absurdity of this third idea is easy to demonstrate if we consider a two directional highway. If all cars move at 60 m.p.h. but some ($A$ per hour) move eastwards and some ($B$ per hour) move westwards, no one would argue that the total passage of cars eastwards per hour past a reference point, that is, $(A-B)$, would help us to determine the velocity of cars by the formula

Flow of cars $= (A-B)$ per hour
Distance between cars $= L$
Therefore velocity of cars $= (A-B)L$ m.p.h.

However, this seems to be done, at least subconsciously, with phase velocity and group velocity. The very terms imply some such calculation.

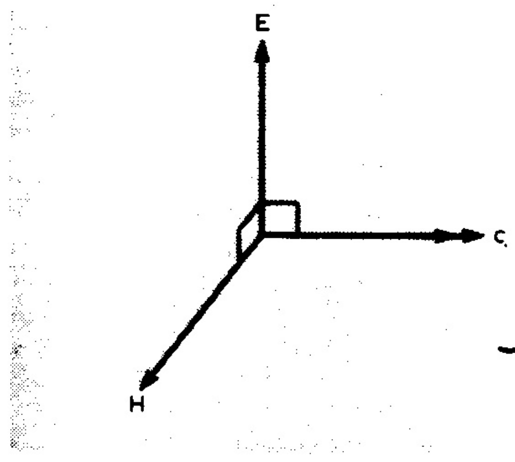
Some ten years ago the successful manufacture of high speed (1ns) logic elements capable of driving a 100 ohm load made it possible, for the first time for fifty years, to drive a medium rather than gently resonate it, as a matter of normal routine. Those driving a high speed logic step could clearly see it travelling at the speed of light for the dielectric (never any slower) and remaining unchanged on its journey. For the first time for seventy years, high speed digital engineers were privileged to see the Heaviside signal, an unchanging slab of $E \times H$ energy current guided between two conductors from one logic gate to the next. Reflections were prevented by proper termination at the destination, so that notions of phase velocity and group velocity evaporated. We saw a slab of energy launched from one point, travelling unaltered, to be absorbed by the terminating resistor at the destination.

At this point we just *had* to unburden ourselves at the theoretical level of implicit contrapuntal notions. A beautiful vision resulted, now called the Heaviside signal, of a lateral strain $E \times H$ (where $E/H = \sqrt{\mu/\epsilon}$ which by definition travelled forward at velocity $1/\sqrt{\mu\epsilon}$. As it travelled forward it filled (or probed) the space ahead of it in the same way as the ripples on the surface of a pond will fill the space (surface) as they come to it. Logic designers maintained a near constant aspect ratio in the space ahead, because whenever this slab came to a change in aspect ratio (= change of characteristic impedance, better termed characteristic resistance) some of the energy current would double back on its tracks according to the well-known laws of reflection. However, this did not lead back to the old "phase velocity" and "group velocity" notions; rather, the slab of energy current split into two slabs, one to continue forward and the other to return, both slabs continuing to probe, or fill, the space presented to them on their journeys.

The Heaviside signal offers us a dramatic simplification of our view of the fundamentals of electromagnetic theory.

## Definitions

First define energy current (= TEM wave = Poynting vector) as our primitive, where energy current is as follows:




Now $\sqrt{\mu/\epsilon}$ and $1/\sqrt{\mu\epsilon}$ can be independently defined. Let us define

(a) $\sqrt{\frac{\mu}{\epsilon}} = \frac{E}{H}$

which defines a constant of proportionality for the medium.

(b) $\frac{1}{\sqrt{\mu\epsilon}}$ = velocity of propagation c,

again a constant for the medium.

(c) Define $D = \epsilon E$, $B = \mu H$

## Derivations

$$\frac{E}{H} = \sqrt{\frac{\mu}{\epsilon}}, \quad B = \mu H$$

$$\therefore \frac{E\mu}{B} = \sqrt{\frac{\mu}{\epsilon}} \qquad (1)$$

$$\therefore \frac{E}{B} = \frac{1}{\sqrt{\mu\epsilon}} = c \qquad (2)$$

$$\therefore E = Bc \qquad (3)$$

By definition*,

$$c\frac{\partial E}{\partial x} = -\frac{\partial E}{\partial t} = -c\frac{\partial B}{\partial t} \qquad (4)$$

*See Appendix 1

$$\therefore \frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t} \qquad (5)$$

This is equation (12.5.1) in Carter (G. W. Carter, The Electromagnetic Field in its Engineering Aspects, Longmans, 1954, page 268), when he believes he is *deriving* the TEM wave, which is supposed to *result* from a causality relationship between $E$ and $B$ (Faraday's law of electromagnetic induction). Carter is clearly developing the rolling wave.

We see then that the equation $\partial E/\partial x = -\partial B/\partial t$ is a simple derivation from the definition of the Heaviside signal and is not based on $\partial B/\partial t$ *causing* $E$, as Faraday thought he had discovered.

We have shown that the passage of a TEM wave and all the mathematics that has mushroomed around it does not rely on a causality relationship (or interchange) between the electric and magnetic field. Rather, they are co-existent, co-substantial, co-eternal. The medium can only be strained in the two lateral dimensions (E and H) in fixed proportion. [In a similar way, *pressure* in a liquid in direction $x$ does not *cause* pressure in the $y$ (and $z$) direction; they co-exist.]

Faraday's great discovery in the 1830s was *not* electromagnetic induction; not a causality relationship. His great achievement was to discover that *change* was important. This started us on the road to discovering the now postulated primitive, the Heaviside signal, which can only move; it cannot stand still. Heaviside put together the main features of the new concept, but it took another century to put flesh on to the bare bones.

## Reference

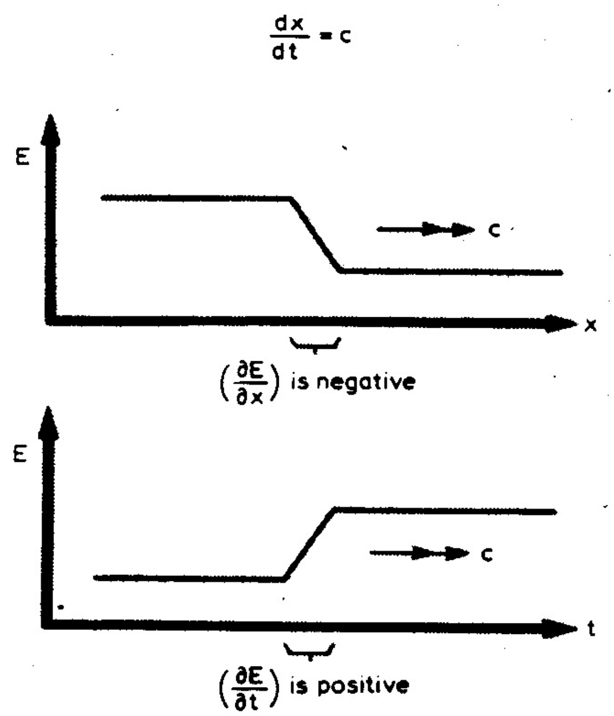

1. Oliver Heaviside, Electromagnetic Theory, 1893, London, page 28 section 30.


## Appendix 1

By convention, if a voltage step is travelling from left to right (i.e. in a positive direction) it has a positive velocity; $dx/dt$ is positive

$\frac{\partial E}{\partial t}$ is positive but $\frac{\partial E}{\partial x}$ is negative. This (reversal) problem is well known by anyone who has drawn out an oscilloscope trace on to paper with voltage and distance axes. This explains the minus sign in equation (4) in the article. When we travel, we *gain* distance while we *lose* time. However, we regard our velocity $dx/dt$ as positive.

It is strange that this ambiguity in sign convention had led to a negative sign in electromagnetic theory. This in turn intro-




duced the idea of a "Lenz's law" reluctance, or back e.m.f., in which lies nested the idea of causality,

$i \rightarrow \int H dl \quad \text{and} \frac{dB}{dt} \rightarrow v$

In fact, electric and magnetic fields have a positive relationship, and co-exist rather than cause each other.

Numerically,

$$c\left|\frac{\partial E}{\partial x}\right| = \left|\frac{\partial E}{\partial t}\right|$$

Therefore, since by convention $\partial E/\partial t$ is positive, $\partial E/\partial x$ is negative and c is positive, we must conclude that

$$c\frac{\partial E}{\partial x} = -\frac{\partial E}{\partial t}$$

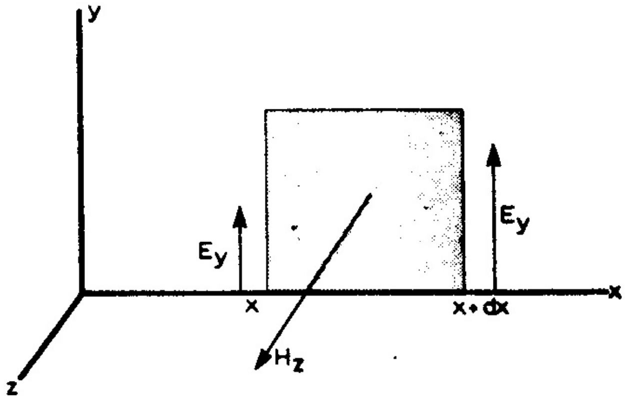
## Appendix 2: the rolling wave explained

In this article, two mutually contradictory versions of the transverse electromagnetic wave have been described and compared. These were the rolling wave and the Heaviside signal. This appendix contains the first half of a very clear description of the rolling wave taken from "Fundamentals of Electricity and Magnetism" by Arthur F. Kip, Professor of Physics, University of California, Berkeley, published by McGraw-Hill, 1962, page 320. Only enough of that description is reproduced to make his approach clear.

". . . Our demonstration involves the use of the first two Maxwell equations to show that such a postulated time and space variation of *E* gives rise to a similar time and space variation of *H* (but at right angles to *E*) and that this *H* variation acts back to cause the postulated variation in *E*. Thus, once such a wave is initiated, it is self-propagating.

"The figure below is used to show the application [of Faraday's law of induction] to the plane *E* wave, postulated to be moving along the *x* direction. A convenient closed path is drawn in the *xy* plane, around which we shall take the line integral of *E*. This is equated through [Faraday's law] to the rate of change of flux *H* through the plane bounded by the path of the line integral. Only the vertical parts of the line integral contribute since *E* is in the *y* direction, so that $E.\partial x = 0$. If we go around in a counterclockwise direction, the line integral around the path chosen becomes

$$\oint E \cdot dl = (E_y)_{x+dx}dy - (E_y)_x dy$$
$$= [(E_y)_{x+dx} - (E_y)_x]dy$$




where we are to take the values of $E_y$ at $x+dx$ and $x$, respectively. The difference between these two values of $E_y$ at the two positions is $(\partial E_y/\partial x)dx$, so we can write the line integral of Faraday's law of induction as

$$\frac{\partial E_y}{\partial x} dxdy = -\mu_0 \frac{\partial H_z}{\partial t} \; dxdy$$

Since this relationship is true for any area dxdy, we may write

$$\frac{\partial E_y}{\partial x} = -\mu_0 \frac{\partial H_z}{\partial t}$$

(This ends the extract from Kip. To get to the Carter equation we have to replace $\mu H$ by *B*, of course.)

# DISPLACEMENT CURRENT

The two articles on displacement current which have recently appeared in your magazine (December 1978, March 1979), contain the sensible suggestion that one should regard currents and charge distributions as the consequences of electromagnetic waves rather than as the sources of these waves. Apart from this, the articles are wrong in almost every detail and it is vital that this should be clearly demonstrated before undue damage is done.

The basic demolition process is simple. In Maxwell's equations for a dielectric medium we have,

$$\operatorname{div} \mathbf{D} = 0, \quad \operatorname{div} \mathbf{B} = 0,$$

$$\operatorname{curl} \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}, \quad \operatorname{curl} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

Writing $\mathbf{D} = \epsilon\mathbf{E}$ and $\mathbf{B} = \mu\mathbf{H}$ for a linear, homogeneous, isotropic medium, these equations give the wave equation for $\mathbf{E}$ (or $\mathbf{H}$),

$$\nabla^2 \mathbf{E} = \mu\epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

which means that electromagnetic waves travelling with a speed of $1/\sqrt{\mu\epsilon}$ can exist in the dielectric. The wave equation occurs due to the presence of the term $\partial\mathbf{D}/\partial t$, which Maxwell introduced and called "displacement current". Without this term the wave equation would not appear and electromagnetic waves would not exist. There is a fair amount of evidence that electromagnetic waves *do* exist, and I doubt if Catt, Davidson, and Walton would deny this. I would like to believe that they are only objecting to the name "displacement current", but if that were the case there would hardly be any point in making such a vicious attack, and after re-reading these remarkable essays a number of times I have a feeling that C, D, and W really believe that electromagnetic waves can exist without $\partial\mathbf{D}/\partial t$ occurring in the equations. A consultation with any competent mathematician should convince them that this is not so.

The above argument may not be very convincing to the non-mathematical reader and perhaps C, D, and W won't like it very much, because one gets the strong impression that these gentlemen have probably used Maxwell's equations in only the most trivial of problems. It is therefore necessary to criticise the articles in some detail. Take, for example, the simple reflection treatment given in the appendix to the first article. This applies to a uniform transmission line but not, as stated in the appendix, to a non-uniform line. For a uniform line the wave equation is

$$\frac{\partial^2 v}{\partial x^2} = LC\frac{\partial^2 v}{\partial t^2} = \mu\epsilon\frac{\partial^2 v}{\partial t^2},$$

where $L$ and $C$ are the inductance and capacitance per unit length. The error probably arises due to the following plausible but erroneous argument: "In the circular capacitor $L$ and $C$ vary with $r$,

$$L = \mu\frac{d}{2\pi r}, \quad C = \epsilon\frac{2\pi r}{d}$$

Hence the product $LC$ is still constant and equal to $\mu\epsilon$. So the wave equation for the circular capacitor will be

$$\frac{\partial^2 v}{\partial r^2} = \mu\epsilon\frac{\partial^2 v}{\partial t^2}\text{''}$$

If the wave equation is properly derived from the basic equations it will be found to be

$$\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} = \mu\epsilon\frac{\partial^2 v}{\partial t^2}$$

The reason why the reflection process described for the uniform line does not apply in this case is that there is a continuous reflection from the wave front due to the continuous variation of $Z_0$. Another serious error is that the authors regard the "radius of the input wires" to be the "input end" of the circular transmission line. If they had taken the trouble to consider the Poynting vector field, they would have discovered that the energy enters the capacitor dielectric at the outside radius, and that this outside radius is the input to the capacitor. When they take a sector of this capacitor (Fig. 1(c) of the first article) they *do* have a line supplied at the inner radius. Hence it is incorrect to regard the complete capacitor as a large number of such sectors ("pie-shaped"!) in parallel.

In the second article, and also in their reply to Mr P. I. Day's sensible letter, the authors ask "where, then, is the displacement current in the transmission line?". The answer, of course, is that in general it flows in all parts of the dielectric, but by choosing a "step" wave (a physical impossibility) they have pushed all of the displacement current into an infinitely thin sheet in the wavefront and have lost sight of it. But we haven't. A step is a very useful concept as the limiting case of, say, an exponential rise, but if the limiting process is improperly understood and causes one to lose things, it is advisable not to use it. And do I detect a rather nervous reaction to Mr Day's use of the frequency domain? Did they for one awful moment think that they saw the ghost of Maxwell's displacement current? They need not worry, it is not dead yet and *they* are certainly not capable of killing it.

These three gentlemen see fit to criticise Maxwell for lack of insight, and assert that Maxwell did not realise that displacement current was not uniformly distributed within a capacitor. In other words, that he was not capable of getting the correct solution to his own equations! And finally they praise Heaviside for "missing it only by a whisker". In fact Heaviside was never in any such danger, but I am afraid that Catt, Davidson, and Walton have dropped right in it!

May I suggest that your readers will be well advised to approach the "further reading" with great caution.

*B. Lago*
*Doxey*
*Stafford*

*The authors reply:*

Dr Lago's letter raises some interesting points which probably deserve fuller treatment than we are able to give here. We are interested that he should feel that "undue damage" can be done to Maxwell's theory through this series of articles. It would seem that he sees himself in the role of priest defending the faithful from the dangers of heretical doctrine. If this is indeed necessary then it says little for the understanding of electromagnetic theory by the faithful. Surely engineers and scientists are competent to draw their own conclusions from a public debate without such protection.

Dr Lago states "Without this term (displacement current) the wave equation would not appear and electromagnetic waves would not exist". Would that life were so simple! In fact this statement is a non-sequitur. All that he is able to state from his position is something like, "In Maxwell's theory displacement current is essential to the existence of a wave equation and hence of electromagnetic waves; therefore, if displacement current is removed, electromagnetic waves *as understood by Maxwell* would not exist". To illustrate, before Lavoisier it was thought that the process of combustion involved, or rather depended upon, the removal of a substance, 'phlogiston', from the burning material. Someone who believed the phlogiston theory would no doubt have asserted that "without phlogiston it is impossible for things to burn". But he would have been quite wrong because the argument is premised on a faulty theory. In the same way we regard the Maxwellian framework as faulty. We have no doubt that electromagnetic radiation exists and there is nothing in our articles to suggest otherwise. What we chiefly object to is the spurious causality and physical meaning given to the term $\epsilon(\partial E/\partial t)$ which is a barrier to the deeper understanding of electromagnetic processes.

We would like to assure Dr Lago that our experience in electromagnetic theory goes beyond "the most trivial problems" and one of us (DSW) lectured on electromagnetic theory in Trinity College Dublin.

Dr Lago is quite wrong to impute to us the facile misunderstanding of the pie-shaped transmission line. IC published a paper[1] in which the theory of the pie-shaped line is discussed with reference to power plane decoupling on multi-layer printed circuit boards. In this paper it is made quite clear that there is continuous reflection caused by the changing impedance seen by the step as it travels outwards to greater radii. We did in fact reference this paper at the end of the December 1978 article. In this latter article we do not claim to be treating the case of a circular capacitor in the mathematical appendix. We in fact refer to Fig. 2 which represents a uniform end-fed transmission line. This case is treated since it demonstrates the key features without requiring unnecessarily complex mathematics.

Incidentally, Dr Lago says that a zero risetime step is a "physical impossibility". This interesting statement merits further analysis. One would like to know whether he is attacking the concept or its practical realisation, i.e. is he against the Platonic ideal of a step or is he saying, as might Aristotle, that such a concept is not useful because it is not practically realisable? If the former then we assume he is also opposed to the sine wave concept since infinite time is required for its perfect realisation; if the latter then what physical principle determines the shortest risetime obtainable in practice? In the latter case the principle must precede the concept, i.e. there must be no circularity.

Finally, Dr Lago agrees with us (and Heaviside) when he states that "one should regard currents and charge distributions as the consequences of electromagnetic waves rather than as the sources of these waves." In that case is $\epsilon(\partial E/\partial t)$ a *current* and therefore an effect or a *field* and therefore a cause, or is it both!

*I. Catt, M. F. Davidson, D. S. Walton*

**Reference**

1. "Crosstalk (noise) in digital computers", I. Catt, *IEEE Trans. EC-16*, Dec. 1967, pp. 743-763.

C.A.M.

# No radio without displacement current

## An aid to understanding Maxwell's equations for wave propagation

by **D. A. Bell,** M.A., B.Sc., Ph.D., F.Inst.P., F.I.E.E.

"Faraday's conception of electric and magnetic force and their interrelations, expressed in terms of his lines of force, were fundamental. In terms of them James Clerk Maxwell developed the equations that underlie all modern theories of electromagnetic phenomena."
*Encyclopedia Britannica.*

BECAUSE displacement current forms a vital link in Maxwell's equations for wave propagation in empty space, text books often give the impression that Maxwell invented displacement current as a kind of mathematical trick to make his equations work. This is not so. In his two-volume *Electricity and Magnetism,* displacement current appears first on p.65 in volume 1, in the part dealing with electrostatics, and the idea follows from Faraday's work on lines of force. It is easy enough to think of electric and magnetic fields as stresses in a tangible medium such as insulating material or iron, but what happens when the material medium is replaced by a vacuum, leaving the fields 'hanging in space'? We no longer believe in an all-pervading ether, yet experience has long shown that light from the stars travels freely through space which is practically empty and now radio waves travel back to the earth from a vehicle which is near Jupiter. So it seems that we must accept that electromagnetic fields can exist in empty space.

But has something been slipped through in the last sentence? How did electric and magnetic fields come to be replaced by electromagnetic fields? Of course it was Maxwell who transformed "electricity and magnetism" into "electromagnetism" by setting out four equations which link together to form a closed cycle of electric field – magnetic field – electric field . . . and so on, continuing for ever as radiation if no conductors get in the way. Looked at from the experimental viewpoint, the most basic factor is electric charge, which usually is associated with a number of electrons (negative charge) or of protons (positive charge). A charge in steady motion constitutes a current, which produces a steady magnetic field. With varying motion a varying current produces a varying magnetic field which acts on an electric charge like an electric field. This looks

Professor David Bell, who joined the University of Hull in 1965 to set up its Department of Electronic Engineering, retired in September 1978. From 1949 to 1961 he was Reader in Electromagnetism in the electrical engineering department of Birmingham University, and thereafter till 1965 he was the director of AMF British Research Laboratory. He has contributed widely to the learned journals and has been writing for Wireless World throughout his career.

In early 1987, Bell refused to allow re-publication of his August '78 paper "No Radio .....". He also refused to fill the resulting space in this book by other material written by him.

The omission of Bell's paper give me the opportunity to insert some material which looks into the future.

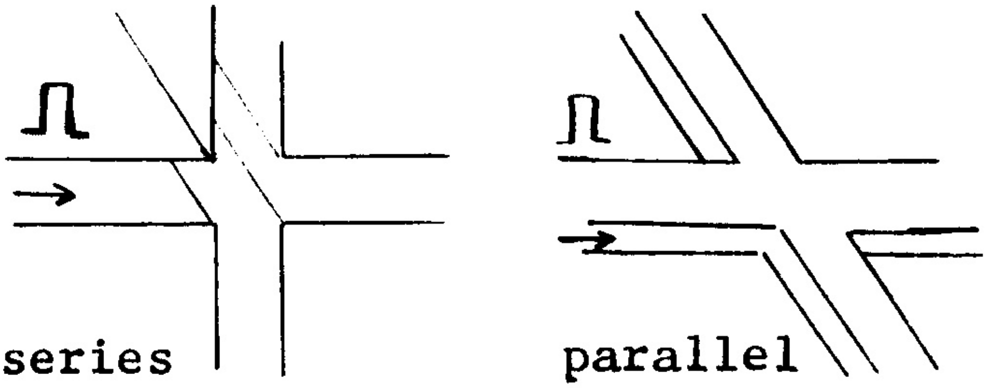
THE CRYSTAL AS ENERGY CURRENT

It might be helpful to first read my letter published on page 166 of this book.

The discussion which follows is equally valid for two situations;

1. A signal comes down some 50 ohm coaxial cable towards a branch where it enters three similar cables connected (a) in series, looking like a 150 ohm termination, or (b) in parallel, looking like a 17 ohm termination.
2. A TEM signal travels down between two wide parallel flat conductors, towards a branch

where it spreads out into three such regions (a) in series, or (b) in parallel.




In what follows, we attempt to construct a regular (i.e. crystal) shape out of mutually trapped, standing waves of energy current. We concentrate on the series case, when the pulse arriving from the left breaks up into four pulses of equal amplitude, half of the original pulse, each containing one quarter of the incident energy. However, if an identical pulse arrives at the junction at the same time, from the         the result (by superposition) is that two full sized pulses depart from the junction, one to the north, the other to the south. The rule is that

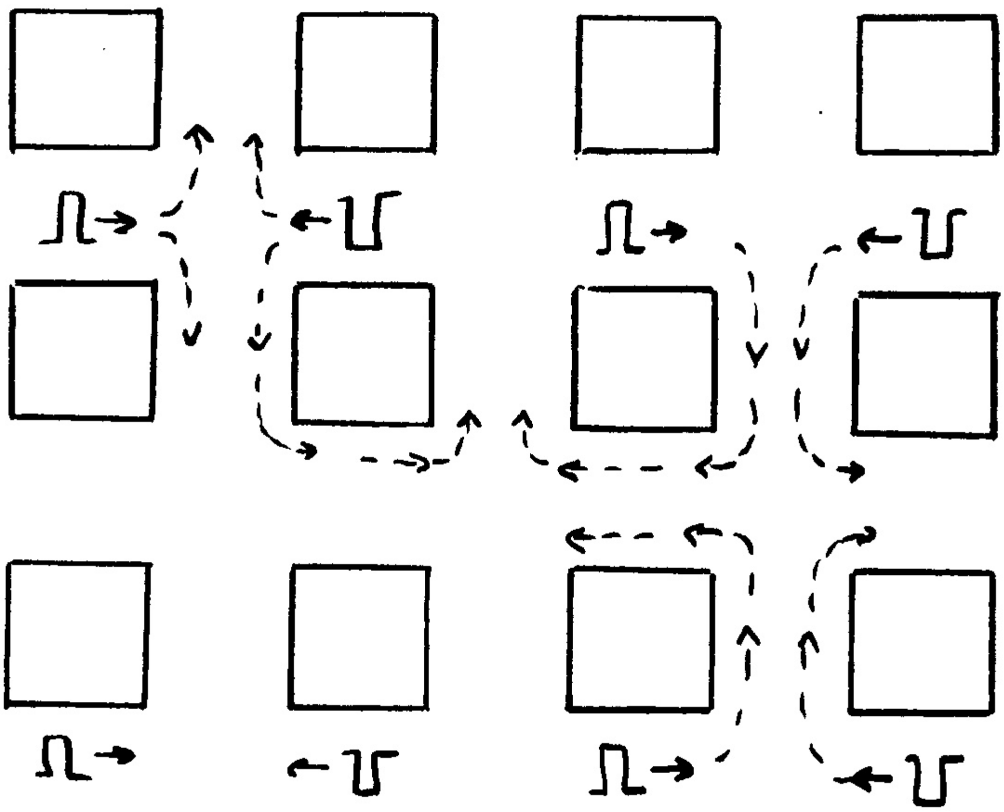
> For a series junction, similar pulses repel.

If we invert the second pulse, we find

(by the accepted laws of reflection) that dissimilar pulses hug (help) each other across the gap.

(In the case of a parallel branch, similar pulses hug, dissimilar pulses repel.)

We now attempt to build a crystal by building a regular array of such branches, and we find that a regular pattern of pulses will trap each other into a "fixed" pattern of circular flows of energy current.



Such a trapped, standing array of energy currents is fully compatible with the problem of building the edge of a crystal. Simply end the squares abruptly. Energy current reaches the edge, sees the open circuit, and reflects back into the array.

The remaining (unsolved) problems are;

(1) To build a structure which is three dimensional rather than two dimensional.

(2) To get rid of the conductors bounding the pulses. This might be achieved (a) by sending another array of pulses down inside the conductors which call for equal and opposite electric current in the conducting surfaces, or (b) by shrinking the size of the bounding conductors down to zero. (A so-called electron might be something like a concentric sphere capacitor with one sphere reduced to zero and the other increased to infinity.)

C.A.M.

## DISPLACEMENT CURRENT

Your contributors (I. Catt *et al.*, December and March issues) are not alone in their dissatisfaction with the usual textbook assertions about the magnetic fields "caused" by "displacement currents". A more satisfying viewpoint supporting theirs is presented in the book "Classical Electromagnetism via Relativity" by W. G. V. Rosser, Butterworths (1968), (see particularly Chapter 4, Appendix 2 (p.243) and Appendix 6). However, Maxwell's equations themselves remain unchallenged, only our interpretation of certain terms is in question. Both electric and magnetic fields are associated with the moving charges set in motion when a capacitor is discharged and the changing electric field in the airgap does not "cause " a contribution to the magnetic field by the Biot-Savart relation. There is then no paradox to be explained when a finite-sized capacitor is regarded as a short transmission line.

Incidentally the controversy about relativity and time signals (L. Essen, October and April issues) is touched upon by Professor Cullwick in another philosophical book on electromagnetism ("Electromagnetism & Relativity", E. G. Cullwick, Longmans (1959), see Chapter 5, p.72).

*R. W. Watford*
*St Albans*
*Herts*

*The authors reply:*

With the best will in the world, R. W. Watford's letter is based on the premise that, in the main, the body of knowledge in e-m theory and relativity is sound and coherent. He feels that all that is needed is to brew up the right mix of existing knowledge and all will be well. His contribution is to bring relativity to the rescue; a nice touch in the centenary year.

Previously, with less good will, P. I. Day brought ω to the rescue. We would prefer to leave both out. After all, ω is incompatible with relativity. (A sine wave exists at more than one point in space, which makes it unacceptable as a primitive in a relativistic universe which excludes instantaneous action at a distance.) These men have brought up two incompatible fire engines to put out the fire.

It is of the utmost practical importance that digital designers have a theoretical framework which makes them able to design and build working, reliable systems. ω has nothing to do with their problems, theoretical and practical. Also, computers do not rush past other computers at the speed of light. We must not continue to abandon high speed digital systems very late in the development cycle, as we have continually done in the past. (cf. *Computing*, 16 March 1978, page 2 and 30 March, letter.)

Maxwell's theory is pre-relativity. If someone has cobbled up a viable post-relativity Maxwell, please tell us where the ex cathedra statement of this theory is. Einstein did not do this, because he was not expert in electromagnetic theory. (*Physics Bulletin*, July 1978, page 297.) Einstein never read Heaviside, and did not have a grasp of Heaviside's concept of a transverse electromagnetic wave which travelled forward unchanged at the speed of light. Also, he never mentioned the impedance of space – a major oversight .f e-m is being considered. Einstein did not know Heaviside's concept of energy current. Neither do contemporary relativity theorists, including Cullwick. Cullwick does not know about Heaviside's contribution to electromagnetic theory. Einstein's famous gedanken experiment, performed when he was aged sixteen and restated by him fifty years later (see "Albert Einstein: Philosopher-Scientist," ed. P. Schilpp, 1949) as the cornerstone of relativity, is incompatible with the energy current concept.

We must not let the ignorance and oversights of the last half century prevent us from building a sound electromagnetic theory from the ground up, and building thereon a viable digital electronics industry.

*I. Catt, M. F. Davidson, D. S. Walton*

# DISPLACEMENT CURRENT

Messrs Catt, Davidson and Walton are perhaps right to draw attention yet again to the importance the distributed nature of real capacitors can have in real circuits (December 1978 issue). Its significance in r.f. circuits is well-known and obviously it has some slightly unexpected subtleties in high-speed pulse circuits. But I cannot see how they can claim to have excised displacement current from Electromagnetic Theory – or in their case circuit theory – in any useful way.

To begin with, Kirchhoff's "Laws" apply to ideal circuits of zero physical extent described by simple mathematical relationships between their terminal voltages and currents. No assumptions are made about their physical nature, nor is the concept of "displacement current" necessary for the development of all the richness of modern circuit theory from these basic assumptions. Nor is there any doubt about the practical usefulness of the resulting theory, for example, in successfully designing high-performance filters.

If one must, for the sake of peace of mind, equate the terminal current of a capacitor with "... a mathematical manipulation of the electric field *E* between the capacitor plates" all well and good, and no harm will come provided the limits of the approximations necessary are always borne in mind; for example, that the dimensions of the capacitor must be small compared with the wavelength of the electrical disturbance being considered. But where is the conceptual improvement in equating the terminal current to what must in the end be a mathematical manipulation of the electric *and magnetic* fields associated with a transmission line? Especially when the manipulations involved are a lot more difficult.

If, as they claim, the concept of displacement current permits the retention of Kirchhoff's laws, does their "excision" of it throw out those too? And if so, what analytical tools are left to us for circuit analysis? If their transmission-line concept *replaces* displacement current, then how so? For there is *still* no closed path in which current can flow.

In short, are we to regard this article as a warning to beware of transmission-line effects in capacitors at frequencies (or pulse widths or risetimes) where they may be important, and can we therefore take the philosophical claims with a pinch of salt? Or are we asked to change the fundamental basis of circuit and electromagnetic theory as we know it? If the latter, I find the claims made to be very unconvincing.

*John L. Haine,*
*Chelmsford,*
*Essex.*

*The authors reply:*

We find the second paragraph of Dr Haine's letter ambiguous, and so cannot reply to it except to say that "modern circuit theory" is rich, in the same way as other tall stories are rich. High-performance filters are not designed using "modern circuit theory", because inductors and capacitors are not designed using theory; they are cobbled in a haphazard, experimental way. Try talking to the "experts" in a company "designing" chokes or capacitors.

As with para. 2, we find para. 3 is back to front, or at least ambiguous.

Para 4. The answer is, yes. Traditional analytical tools have been useful in the setting and passing of examinations, but not in practical engineering problems; emphatically not in the interconnection of high speed (1ns) logic, where they have created havoc, leading to the abandonment of virtually all such projects.

Para. 5. You *are* asked to change the fundamental basis of circuit and electromagnetic theory as we know it. The need to successfully assemble high speed logic systems forces us to abandon the slovenly mess which has masqueraded as electromagnetic theory for fifty years, and build a sound theory from the ground up. The first casualty is displacement current, the bastard issue of a marriage between ignorance and nonsense. We must clear away the rubble before we begin to build.

"Our electrical theory has grown like a ramshackle farmhouse which has been added to, and improved, by the additions of successive tenants to satisfy their momentary needs, and with little regard for the future. We regard it with affection. We have grown used to the leaks in the roof. . . . But our haphazard house cannot survive for ever, and it must ultimately be replaced by a successor whose beauty is of structure rather than of sentiment." – Intermediate Electrical Theory, by H. W. Heckstall-Smith, Dent, 1932, page 283.

A lot more sludge has collected since 1935. We must dredge deep, through a century of sycophancy.

*I. Catt. M. F. Davison, D. S. Walton.*

WIRELESS WORLD, OCTOBER 1979

# DISPLACEMENT CURRENT IN A VACUUM

Whilst one may agree with the excellent logical argument via Maxwell's equations, in Professor D. A. Bell's interesting article "No radio without displacement current" in your August issue, I still find myself needing a further empirical justification of the displacement current, i.e. what is displaced in a vacuum?

Now a Dr James Dodd has recently written, in *New Scientist*, 1st March, 1979, in an article entitled "Colouring in the quark theory", that "Only naively does the vacuum live up to its name. In relativistic quantum theory it is a sea of virtual electron-positron pairs . . ." If Dr Dodd is right, could it not be that this could constitute an ether capable of displacement? Moreover, on this assumption, would it not be possible to devise a simple theory to derive an expression for the impedance of free-space, or vacuo, normally obtained in textbooks (e.g. Telecommunications, by A. T. Starr) via Ampere's Law, as 377 ohms, or 120 $\pi$ ohms? I would be very interested in your comments.

Moreover, I still cannot understand how a vacuum can offer an impedance to an electromagnetic wave, unless there is something there to do so! Perhaps someone could explain this to me.

*Peter G. M. Dawe*
*Botley*
*Oxford*

*The author replies:*
The question of intrinsic impedance of free space is fairly easily dealt with. The term 'impedance' is here merely a figure of speech, introduced because there is a close analogy with the characteristic impedance of a uniform transmission line. It merely means that in a radiated wave the ratio of electric field-strength to magnetic field-strength has a constant value which is a function only of the medium through which the wave is propagated. If the medium is free space, $E/H = 377$ and since $E$ and $H$ are measured in volts/metre and amps/metre respectively, the ratio has the dimension of ohms.

I am afraid "a sea of virtual electron-positron pairs" does not seem to me any more tangible than 'free space', especially as the word *virtual* is included. There are other aspects of physics which to me seem equally 'unreal': from Newton to Einstein it was accepted that gravitation was action-at-a-distance, and although 'curved space' can be described by good mathematics, I cannot see that it fits with any everyday experience. One can only say that much of our knowledge of the universe today can be expressed coherently in a mathematical formalism which does not correspond with everyday experience of the approximate behaviour of sizeable objects, i.e. with mechanical models.

*D. A. Bell*

# DISPLACEMENT CURRENT

In your December 1978 issue, Catt, Davidson and Walton purport to show that Maxwell's concept of displacement current is incorrect and their "true" model, which replaces a capacitor by a collection of pie-shaped transmission-lines, is correct. They argue that this dispenses with the need for displacement current, and gó on to say: "Since any capacitor has now become a transmission line, it is no more necessary to postulate displacement current in a capacitor than it is necessary to do so for a transmission line." Unfortunately, it is necessary to do so for a transmission line, or have they forgotten Kelvin's (1873) original equation:

$$-\frac{dI}{dx}=GV+C\frac{dV}{dt}$$

G being leakance and C the capacitance per unit length. The second term on the r.h.s. of this equation is the displacement current.

What they have done in their subsequent algebra is to show that the transmission line approach and the lumped capacitance approach agree very closely. In no sense have they dealt with the topic indicated in their title: "Displacement current – and how to get rid of it." It looks as if Maxwell's equations may be right after all!

*E. P. George (Professor)*
*University of New South Wales*
*Sydney, Australia*

**Reference**
Lord Kelvin, *Soc. Tel. Eng. Journ.* I (1873), 397.

*The authors reply:*
Professor E. P. George's letter raises some interesting points:

1. The reference to the Kelvin model of the transmission line is irrelevant and misleading. It is irrelevant because the point he is making could have been made by reference to the equation for a charging capacitor,

$$i=C\frac{dV}{dt}$$

In this equation one could say that the right hand side 'is' the displacement current, which it is in Maxwell's theory by definition, but not in ours. It is misleading to introduce the Kelvin model since, as was shown by Oliver Heaviside, the Kelvin model is incomplete since it does not take account of effects due to the distributed inductance of the line.

2. What we have been proposing is that Maxwell's theory is 'inside out,' since it employs **E** and **H** and, in circuit theory, leads to the concepts *C* and *L*. In our theory the travelling **E, H** signal is the primitive and the transmission line the basic circuit element. Insofar as this change of viewpoint leads to Maxwell's equations then we would consider them to be correct. In this sense therefore Professor George's statement "It looks as if Maxwell's equations may be right after all" is correct at that level.

To show how Maxwell's equations relate to our view would require more space than is proper for a note of this sort but we hope that our further article in the March issue will have helped with this point

*I. Catt, M. F. Davidson, D. S. Walton*

WIRELESS WORLD, NOVEMBER 1979

# DISPLACEMENT CURRENT

Professor Bell's article "No radio without displacement current" in the August issue raises so many issues it is difficult to know where to start. Rather than deal with the details, I will start with a consideration of the purpose of the article. The title of the article makes this clear; it is an attempt to defend Maxwell's theory against recent criticisms with particular reference to displacement current.

I understand that Aristotelians believed that a force was necessary to keep bodies in motion and that, in the absence of this force, the motion would cease. This theory led them into certain difficulties. For instance a spear, once thrown, appeared to continue to move without a force being present. The philosophers rose to this challenge magnificently with a theory that air, displaced from ahead of the spear, rushed to the rear and generated the requisite force – the theory was saved. Unfortunately they missed the simple point first noted by Newton, that it is in the nature of a moving body to continue to move.

In the same way I fear that Maxwell invented a complex explanation for a very simple phenomenon, ie that electromagnetic radiation, or energy current, moves at the speed of light – and that's all, because that is what energy current does. No mechanism invoking $E$ producing $H$ and $H$, in return, producing $E$ is required. As for the details of Bell's article – they do not stand up well to close examination.

In the first place, it is unwarranted to suggest, as Bell does, that since Maxwell *introduces* the idea of displacement current early in his treatise (the correct title, incidentally, is "A treatise on electricity and magnetism" and Bell appears to be referring to the third edition first published in 1891), this is a proof that he thought of it in connection with simple phenomena. This is just too simplistic; the way Maxwell presents his ideas cannot be taken as a guide to how he thought of them. Much has been written and many papers have been published on the genesis of Maxwell's thought and it is inadmissable for Bell to treat the subject in this superficial way. I would be happy to provide a list of references (about 20) to anyone who would like to study the development of Maxwell's thinking in detail. I suggest Joan Bromberg's paper[1] as a good start to the subject.

There are many errors of detail in the article. Perhaps I could draw attention in particular to the statement that "Maxwell . . . was at home with vectors." Vector algebra was not invented in Maxwell's time and he never used it. He made some use of Quarterninic formulation of his equations but was not consistent in its use – Maxwell, in fact, never formulated his theory in terms of four equations – this was left to Heaviside who also introduced vector calculus more or less as we know it.

The rest of Professor Bell's article can be found in any elementary textbook on electromagnetic theory; its testament, however, does nothing to establish that theory which is in the process of being replaced by a simpler formulation.

*D. S. Walton*
*CAM Consultants*
*St Albans*
*Herts*

### Reference

1. Bromberg, J. "Maxwell's Electrostatics," *American Journal of Physics* 36, 145-151 (1968).

*The author replies:*
First, Dr Walton's reference to Aristotelian philosophers is a red herring. I mentioned early speculation about the planets because Newton's theory of gravitation was based on the hypothesis that the same force accounted for objects "falling" to earth (the notorious apple!) and for planets describing *closed orbits* about the sun. It then involves the conceptual difficulty of action at a distance, unless one prefers to postulate fields of force. Incidentally Newton was *not* the first to suggest that a body in motion would so continue if undisturbed. Hobbes in his book "The Leviathan" mentions that it was a subject of discussion whether this be so or not, and himself unhesitatingly chose Newton's answer. Newton's achievement was to formulate the precise law and "prove" it by incorporating it in his complete system of mechanics which was supported by experimental evidence.

In considering the proposed alternative to Maxwell's theory of electromagnetic waves, there are two questions. First, what is an "energy current"? "Current" usually means flow of something; and "energy" seems to me entirely abstract unless qualified by some adjective such as kinetic, electrostatic etc. So what flows? Second, is there a relation, and if so why, between this "energy current" and the observable electric and magnetic effects? For example, the creation of a spark in air by a focused laser beam is consistent with the electromagnetic theory of light.

As regards the chronology of Maxwell's different uses of displacement current, the main point is that he did find use for it other than in the derivation of a wave equation. Others have since found its use in "electrostatics" convenient or even essential. (See footnote to article.) It may be that the logical train of development which I suggested is a *post hoc* rationalisation, but one cannot prove whether or not this was how Maxwell saw it.

The article by Joan Bromberg is entitled "Maxwell's Electrostatics" and details Maxwell's difficulties in arriving at a satisfactory formulation of 'displacement' in electrostatics, based largely on the concept of polarisation. So it is in agreement with the point which I was making: Maxwell regarded 'displacement' as an essential part of the description of electrical phenomena, not just as a device to facilitate the formulation of a wave equation.

Of course most of the content of my article in the August issue is to be found in standard text books. It was written on the supposition that there are many readers of *Wireless World* who have not studied a text book on electromagnetism.

*D. A. Bell*

# POYNTING VECTOR

Apparently many people find the concept of displacement current useful and some find it distasteful. Not being a member of either group I would normally be prepared to continue as a passive spectator of the fascinating correspondence which has been stimulated by the recent articles on the subject; after all, no-one is suggesting that $\partial D/\partial t$ should be struck out from Maxwell's equations, and presumably no-one is insisting that everyone must believe that there is any physical reality in a current which is said to flow in empty space where there is nothing to carry it (and nothing to be displaced). I would even leave it to others to point out that in Fig. 4 of "The history of displacement current" in your March issue the current $i$ will vary continuously between B and B′, as is the way with transmission lines, so if you want a continuous "current" you do need a displacement current, not localised at B, but distributed along the length of the transmission line.

However, the excellent iconoclasts Catt, Davidson and Walton have spurred me to action by their uncharacteristically unquestioning use of a concept/mathematical construct which is far less harmless than displacement current, namely the Poynting vector or "energy current" $\mathbf{E}\times\mathbf{H}$. A single example will show what I mean. Suppose I take a battery and connect it to a lamp by a pair of good thick metal wires. Since the electric field is negligible inside the wires the Poynting vector is too. In fact the Poynting vector is mainly localised in the space surrounding and particularly between the wires. By examining the Poynting vector one can validly draw the conclusion that energy flows from the battery to the lamp. One could even, in principle, integrate the Poynting vector over a surface containing the battery or the lamp, but not both, and calculate correctly the rate at which energy flows from the battery to the lamp, but one would be allowing oneself to be blinded by one's own



C.A.M.

mathematics to deduce from the fact that the Poynting vector is partically zero in the wires and is at a maximum between the wires that the energy flows mainly between the wires and not to any appreciable extent through them.

In case anyone does believe that even in this case the Poynting vector represents a physical energy flow I propose the following experiment. First, interpose a metal screen between the battery and the lamp, insulated from the wires themselves, but fitting as closely as possible, so as not to leave more than the tiniest space for the Poynting vector to squeeze through. Note the effect (if any) on the amount of energy which gets to the lamp. Now take away the screen and make a break (just a little one, mind) in one of the wires. Again, note the effect on the amount of energy (if any) which gets through. A similar experiment could be carried out on telegraph lines, at some inconvenience to the public. If the Poynting vector really represents a flow of energy, the screen should have more effect than the break. After all, what do we mean when we say (if we do) that the energy flows between the wires rather than through them, other than that if we wish to obstruct the flow of energy we would do better, to a first approximation at least, to insert a barrier where the energy flows than where it does not flow.

Perhaps it is time someone did a hatchet job on the Poynting vector along similar lines to that of Catt, Davidson and Walton on displacement current, with the hoped-for result being that it is cut back to its proper size, not that it is necessarily cut out completely. It may be less entertaining (surely not if the same team could be persuaded to take on the job) but the usefulness in actual practice would arguably be greater.

*C. M. K. Watts*
*Western Electric Company Ltd*
*Woodford Green*
*Essex*

*The authors reply:*
The last sentence of Mr Watts's first paragraph shows that he does not understand the mechanism for a TEM signal travelling undistorted between two perfect uniform conductors.

We should however applaud, not condemn, those who come out in the open and discuss electromagnetic theory even though their grasp of the fundamentals is weak. CAM Consultants have found that those professors and text book writers who are hiding from the present dialogue, although their professional duty would direct them otherwise, are more ignorant than Mr Watts and the other brave men who are rushing in to the vacuum. CAM Consultants challenge professors of physics and electronics to come out of the undergrowth and start *earning* their salaries by discussing the fundamentals of electromagnetic theory.

Returning to para. 2, if Mr Watts bares his chest to the sun, does he believe that the electromagnetic energy (light) burning his skin is travelling from the sun to him down conducting wires, or through a dielectric?

Paragraph 3 is very instructive. (Why must he leave the "tiniest space"? Why leave a space at all if the conductor is what it is all about?) Our book Electromagnetic Theory Vol. 2 discusses such situations thoroughly, on pages 245 and 319 and elsewhere. Referring again to his second sentence, conventional transmission line theory lets us calculate the mechanism by which energy current rapidly builds up to a high flow rate through a small gap as a result of repeated reflections. The argument somewhat resembles that in the appendix to our article in the December 1978 issue. If in his second sentence, the screen hugs the conductors for a long length (say one mile), creating a long section with very low characteristic impedance, transmission line reflection theory correctly tells us that energy flow from battery to lamp is delayed. More conventionally, this delay would be thought of as an *RC* time constant, the C being the narrow gap between conductor and screen for the very long distance. Referring to his sentence 3; once the tiny break in the conductor (which Heaviside called an obstructor) is made, energy current flows through the break and out into the vast space beyond. This space presents a rapidly increasing (characteristic) impedance, causing all the outgoing energy current to be reflected back through the break into the narrow channel through which energy was previously gliding calmly (at the speed of light) from the battery to the lamp. After the initial disturbance of the steady state caused by the breaking of the conductor (obstructor), the lines of energy current gradually, through the mechanism of reflections, settle down to a new pattern where energy (of the same amplitude as before the conductor was broken) flows out of the battery to the gap in the wire, there to be fully reflected back into the battery, in a "continual dance of energy" which Carter dismissed as absurd but CAM Consultants do not. (The Electromagnetic Field in its Engineering Aspects, by G. W. Carter, Longmans 1954, page 321.) If however the break made in the conductor is extremely narrow (and long), it will take time for its existence to become apparent. Very traditionally, this very narrow, long gap in the conductor would be regarded as a capacitor. *We* should regard it as a transmission line of very low characteristic impedance.

Dealing with his third para. in a lighter vein, one is urged to suggest that it is the "phlogiston" in a balloon material which keeps it doing its job. The absurd theory that it is the air pressure in the space inside which maintains a balloon's femininity can easily be disproved by making a tiny hole in the balloon; too small to let the air out but large enough to collapse any imagined air pressure inside. Alternatively, we can show that the goods travelling in a railway system travel *inside* the rails, or an obstruction across between the rails, *nearly* touching the rails; close enough to leave too little space for the train wheels to get through. This will prove that goods are really piped along *inside* the railway lines and it is absurd to think that the lines merely guide the flow of merchandise.

When all is said and done, however, the acid test is the question of whether the *velocity* of propagation of the energy (/electric) current is a function of the characteristics $\mu$, $\epsilon$ of the dielectric or of the conductor. When a seagull (or merely the reflection of a seagull) glides along above (/below) the surface of the water, does its speed depend on the nature of the air or of the water?

*I. Catt, M. F. Davidson, D. S. Walton*