Does Faraday Allow Superposition?

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The speed of an electric current has always been a matter for discussion. This went nowhere while it was not realised that the energy delivered from a battery to a lamp travelled at the speed of light. Linking this with the fact that electrons travelling at the speed of light would have infinite mass, a crisis for electricity which became clearer with the advent of pulses in digital electronics was evaded for half a century.

1. Does It Exist?

Everyone, including Einstein, believes that electromagnetic theory is central to today's physics, and that it is mathematical. There is general lack of grasp of a central feature of electromagnetic theory. This feature is, extraordinarily, what happens when a battery is connected via two conductors to a lamp, and the lamp lights. With the rapid introduction of digital electronics in 1960, I had to think more deeply about this process, because I was dealing with exactly the same thing when I delivered a logic signal from one logic gate to the next.

When a battery is connected to a lamp, or when a logic gate is connected to another, the signal advances at the speed of light. We definitely know that energy, or power, is delivered. We should not assume that surrounding paraphernalia, charge and current, definitely exist. If we insisted on this, then we would have had to stick with caloric and phlogiston in earlier times. You will agree that those who insisted on retaining caloric or phlogiston as physically real were major obstructers of scientific advancement.

Although a cloud cannot exist without edges, the edges of a cloud do not exist. They have no volume, mass or density. Although a cube cannot exist without edges, the edges of a cube do not exist. A cube, for instance of copper, does exist. It is physically real. It has mass and volume. It cannot exist without edges, but its edges do not exist. The same goes for electric charge and electric current, which we find on the edge of the energy, or power, or TEM Wave, which is travelling from battery to lamp. We can do impressive mathematical gyrations with the edge of a cube, which equals the cube root of a cube's volume. Also, the surface of a cube is a more sophisticated mathematical manipulation of a cube's volume; six times the square of the cube root of its volume. Thus, we should avoid being impressed by the extraordinarily complex mathematics – Maxwell's Equations, divs, dels, curls, integrals, differentials and so forth, which create electric charge and current from the very real energy travelling from battery to lamp. Generally, a Maxwell equation says that something which is real equals the non-existent mathematical manipulation of the something which is real. We know the energy is real, because the lamp lights. Charge and current are merely extrapolations. Like caloric and phlogiston, they may or may not exist.

In 1976, I suddenly realized that the electric current did not exist. Although it was published in 1982 [1], no professor or text book writer has admitted since then that he has heard of the assertion, that when a battery lights a lamp, electric current is not involved.

Only six years later I asked for information about, not the current, but the charge involved in the process of a battery lighting a lamp. This question is called "The Catt Question" [2]. After some years I succeeded in getting contradictory answers from accredited experts, who then went silent for decades. Their bosses, including Lord Rees, refuse to investigate the fact that they do not discuss their differences, and do not inform their students that there is a contradiction in their teaching.

Last year I came across a much clearer fatal flaw in classical theory, which was published in an unrefereed journal [3]. Now in this paper, I present an even simpler, even clearer fatal flaw.

In my 1979 book [4] I wrote; "Text book writers and lecturers generally repeat what they do not grasp. Tragically, they do not even realize that there is a large subject which they do not understand, fondly believing that their sometimes skilful manipulation of meaningless mathematical symbols *is* the subject… We have to try to move [them] from their present theory, which they do not grasp…" They assert that the subject is mathematical. A Google search for "mathematics is the language of science" gives us 50 million hits. Electromagnetism being the "crowning glory" of mathematical science, we don't have to understand it, only manipulate it mathematically.

The real fundamentals, which involve trivial mathematics, are missing from the text books. Thus, the first part of this paper has to be an exegesis of the relevant classical, and false, theory, which I believed when I published in two unrefereed journals, in Britain and the USA, in 1969. Text books do not discuss them. They are also not to be found on the www. I discuss the problem of "TEM Wave, a lost concept" at [5].

2. Signal Transmission in Digital Systems

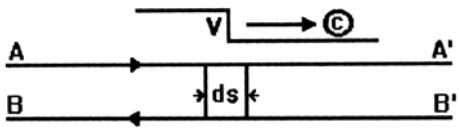

Fig. 1. A TEM Wave travels down between two parallel conductors.

All the literature treats a transmission line as a series of infinitesimally small inductors and capacitors; this article presents the more realistic approach where at no time do we have to consider infinitesimally small segments of line.

When the output of a logic gate switches from false to true, it raises the voltage difference between the output pin of the gate and the reference through a voltage v, which is called the signal

amplitude of the gate. It is important to think of the signal as being a differential mode signal between the front end of the signal line and the reference, which serves as the return path. This reference might be called "ground". This change in voltage difference between the signal line and the reference line does not appear instantaneously at the point further down the signal line because there is capacitance between the signal line and the reference line. This means that, before the new logic level (voltage difference) can be established between the signal line and the reference line at all points, an amount of charge $+q$ must have been delivered by the gate to the signal line, and an equal and opposite charge must have been removed from the reference line by the gate, where $q = Cv$, C being the capacitance between the signal line and the reference line. We might suppose that if the logic gate could instantaneously deliver that amount of charge $+q$ to the signal line and remove it from the reference line, the signal would appear without delay at the far end. Unfortunately this is not so, because of inductance.

We know that movement of electrical charge is accompanied by the appearance of magnetic flux. Change of rate of flow of electric charge down the line, (which is necessary if we are suddenly to transfer a charge q to the line) involves change of flux $d\Phi/dt$, which, by Faraday's law, creates an induced back e.m.f. which tends to oppose the change of current.

So, if we try to introduce a charge $+q$ instantaneously into the line, we get an infinite $d\Phi/dt$ and so an infinite back e.m.f.

This means that, in order to drive instantaneously the voltage drop between signal line and reference line through a voltage change v, we would need an infinite driving voltage for a short time to overcome the back e.m.f.

An alternative way of explaining why the signal cannot travel instantaneously is to say that, as the electric charge travels down the line, energy appears around the line in the form of magnetic and electric flux. By the principle of conservation of energy, this energy must have been supplied by the only available source–the logic gate. Now the gate can (ideally) support voltage and current instantaneously.

However, $p = vi$ is power, but not energy – power requires a third dimension, time, to give the full dimensions of energy. So, in the absence of infinite voltage or infinite current, time is necessary for the signal to develop throughout the length of the signal line. Note that in this discussion the geometry of signal wire and reference was not specified.

3. Logic Signal Transmission Down a Uniform Transmission Line

Let us assume that a logic swing v is introduced at AB between the signal line A and the ground line B (Fig. 1) at time t_0. We can expect the logic swing to propagate down to the right, so that later, at time t_1, the signal has reached a point in the centre. Let us suppose that the capacitance per unit length is C_L. This means that, if a steady potential difference v exists between the lines, the charge per unit length q_L on each line would be $q_L = C_L v$. Let the self-inductance per unit length of the pair of lines be L_L. This term L_L means that, if a steady current $+i$ were flowing down AA′ and a steady current $-i$ were flowing back along B′B, the magnetic flux passing through a surface AA′B′B bounded by the two wires would be $\Phi = L_L i$ per unit length of the pair of lines.

Since the cross-sectional geometries and the surrounding dielectric of the pair of lines AB does not vary along their length, it is reasonable to assume that the signal travels at a constant velocity c. We know that the impedance which the pair of lines AB presents to an impressed signal v_{AB} is not infinite, so there must be a current as well as a voltage in the signal. If a current $+i$ is flowing down line A and a current $-i$ is flowing back along line B, we have a magnetic flux field as shown by the dotted lines in Fig. 2; and this results in a net flux passing between the pair of lines AB.

Then in time Δt, the signal will have travelled a distance $\Delta l = c\Delta t$, and the flux passing through the surface AA′B′B will have increased by

$$\Delta\Phi = L_L c\Delta t\, i \tag{1}$$

Now Faraday's Law of Induction says that, if the flux through a loop increases steadily at the rate $\Delta\Phi/\Delta t$ an e.m.f. is induced equal to $-\Delta\Phi/\Delta t$. By Lenz's law this opposes the original signal, and it can be called a back e.m.f.

Apart from the original signal v introduced across AB, this back e.m.f. is the only voltage around the loop AA′B′B. By Kirchhoff's second law, the sum of the voltages around the loop equals zero, or impressed voltage v + back e.m.f. = 0.

$$v + \left(-d\Phi/dt\right) = 0 \tag{2}$$

Therefore, from Eq. (1),

$$v = d\Phi/dt = L_L ic \tag{3}$$

This gives us the first important relationship between voltage, current and velocity

$$\frac{v}{i} = L_L c \tag{4}$$

The second relationship will be derived from the principle of conservation of charge. We know that a current i is entering the line at A. So, in time Δt, the total charge in the line A will have increased by

$$\Delta q = i\Delta t \tag{5}$$

During time Δt, the signal will have advanced a distance $\Delta l = c\Delta t$, and this new section of line will have been charged up through a voltage v.

The charge absorbed over distance $\Delta l = c\Delta t$ is given by:

$$\Delta q = \Delta C\, v = C_L c\Delta t\, v \tag{6}$$

By the principle of conservation of charge this must be equal to the charge introduced into the line, $i\Delta t$ in Eq. (5). Therefore

$$i\Delta t = C_L c\Delta t\, v \tag{7}$$

This gives us the second important relationship between voltage, current and velocity:

$$\frac{v}{i} = \frac{1}{cC_L} \tag{8}$$

Now, if we divide Eq. (4) by Eq. (8), eliminating v and i, we find

$$c = \pm \frac{1}{\sqrt{L_L C_L}} \tag{9}$$

This means that *all signals, whatever their amplitude, travel at the same velocity*, $c = 1/\sqrt{L_L C_L}$.

If we multiply Eq. (4) by Eq. (8), we eliminate c to get

$$\frac{v}{i} = \pm \sqrt{\frac{L_L}{C_L}} \tag{10}$$

This means that the ratio between v and i is a constant for the line. This constant has been called the characteristic impedance Z of the line.

(Independently developed and published in 1969 by me in [6], the above occurs in only one text book in the 20th century, by Arthur F. Kip, 1962 [7].)

4. The Transverse Electromagnetic Wave (TEM)

For an animation of a Transverse Electromagnetic Wave (TEM) in the form of a voltage/current step travelling between a conductor and ground, see [8].

The Transverse Electromagnetic (TEM) wave contains electric and magnetic fields at right angle to each other and at right angle to the direction of propagation.

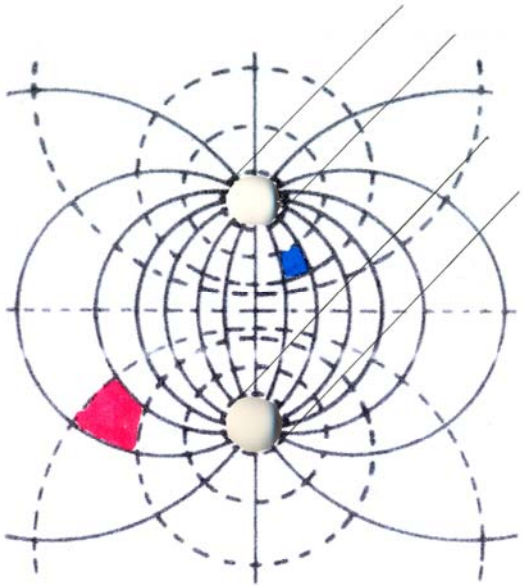

Fig. 2. Curvilinear squares. Field pattern when a TEM Wave travels down between two parallel conductors.

When a voltage is injected between two conductors, the voltage signal with its accompanying electric current travels down between the two conductors at the speed of light. There is electric field between the conductors represented by solid lines terminating in electric charge on the surface of each conductor. The electric current causes magnetic field surrounding the conductors represented by dotted lines. Thus the four features of the signal travelling down between the two conductors are electric charge, electric field, electric current and magnetic field. This field pattern was published in only one text book during the 20th century.

For more than seventy years it has been known that two fundamental TEM modes, travelling at the speed of light, can exist on a pair of conducting strips above a ground plane or between parallel ground planes. One mode is called the Even coupled-strip Mode, because the strips are at the same potential and carry equal currents in the same direction.

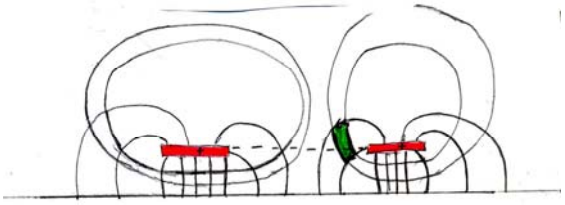

Fig. 3. Even Mode

The other mode is called the Odd coupled-strip Mode, because the strips are at equal but opposite potentials and carry equal currents in opposite directions. 40 years ago, beginning with Faraday's Law of Induction, I proved that these were the only possible modes. For proof, see [9].

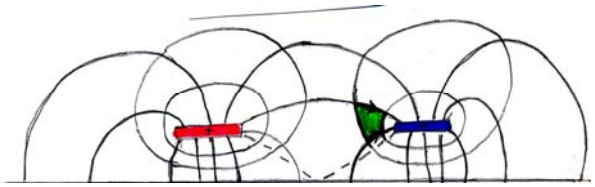

Fig. 4. Odd Mode

A voltage plane is like a mirror, with the field lines parallel with it and at right angles to it. So it is easier to remove the ground plane and consider four conductors. The proof of the two modes still applies.

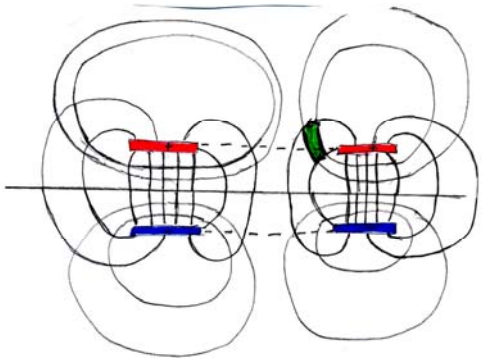

Fig. 5. Even Mode with image.

The Even Mode is as though the two conductors are shorted together.

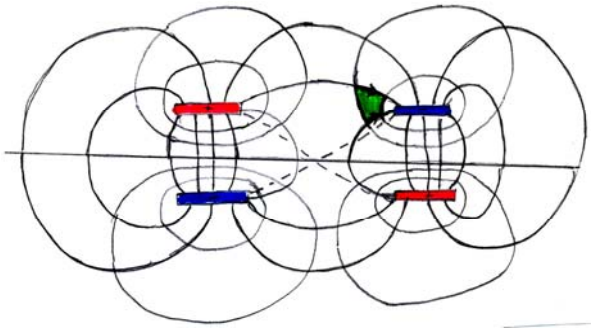

Fig. 6. Odd Mode with image.

The Odd Mode is as though the conductors are shorted together diagonally.

My proof of the two modes also applies to conductors buried between ground planes.

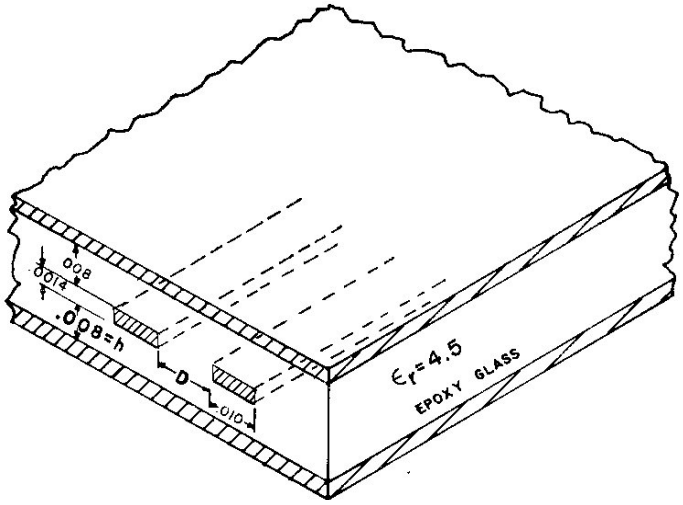

Fig. 7. Buried Conductors (Stripline).

Fig. 8. Active, left hand line. At the start, at 3 metres and at 6 metres.

Fig. 9. Passive, right hand line

For at least seventy years there was a failure to consider the implications (or initially even the possibility) of superposition, with two modes together. This resulted when I injected a voltage step into the left hand active conductor, as seen in the first trace in Fig. 8, resulting in a smaller voltage step in the right hand passive conductor, Fig. 9. The result was a superposition of the two modes, where the passive conductor was positive for the Even Mode but negative for the Odd Mode. In the Even Mode, the passive conductor had electric current travelling into the paper towards the right, but in the Odd Mode, electric current travelling out of the paper towards the left. Under Oersted, each current caused its own magnetic field. The superposition represented a third, (according to classical theory and my proof) illegal mode. Unlike Even and Odd Mode, it lacked symmetry.

A difficulty has remained unnoticed for more than seventy years, and unnoticed by me for forty years. This is that Oersted assumes a single electric current around a loop creating a single magnetic field within the loop. It does not allow two electric currents in opposite directions each creating its own magnetic field, which is what we see here in the passive line. Further, even before Oersted, classical theory does not allow two electric currents in opposite directions down a single wire.

It is helpful to look at the case of surface conductors, Fig. 10, where the two modes resulting from the injection of a single voltage spike travel at different velocities, and separate out, see Figs. 10 and 11. The signal arriving first further down the line is the Odd Mode, because more of it travels in the faster air than the slower Even Mode, more of which travels in the slower epoxy glass.

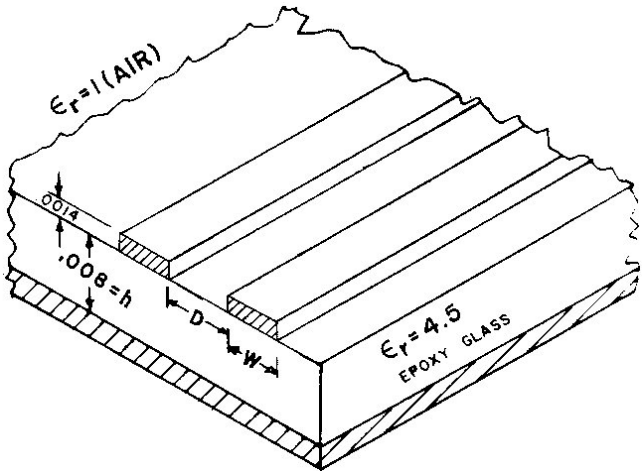

Fig. 10. Surface lines (Microstrip).

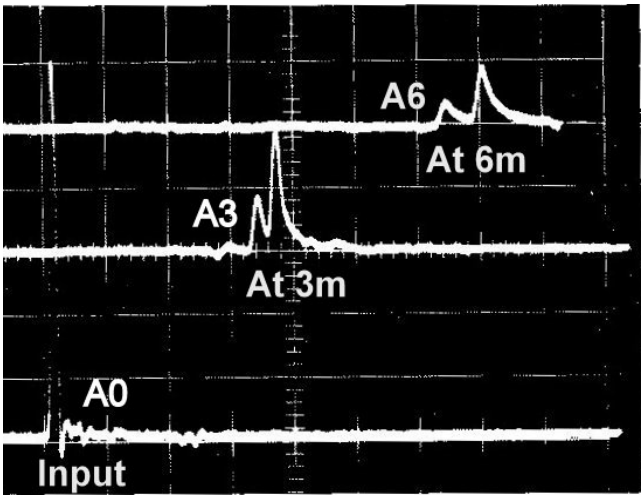

Fig. 11. Active, left hand surface line

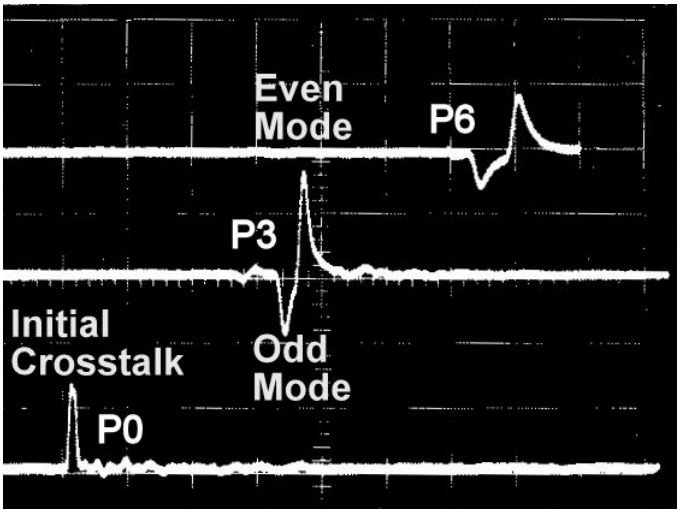

Fig.12. Passive, right hand surface line

The paradox is resolved by "Theory C", which I stumbled on in 1976. This is that when a battery is connected to a lamp via two wires and the lamp lights, electric current is not involved; the energy travels in the dielectric at the speed of light. The conductors, which Heaviside called "obstructors", guide the energy, just as rails guide a train, and nothing travels inside the rails. In the same way as a small amount of field enters the conductors, so the rails indent slightly. This discovery has been ignored for 35 years. My first attempt to get attention paid to the misalliance between electric charge/current and electromagnetic field was in 1982 with "The Catt Anomaly" about classical theory [10]. Thirty years later I published "The end of electric charge ..." [3], which first failed to get a proper acceptance or rejection from the three leading peer reviewed journals, and on which no relevant professor will comment. Now, above, we have an even clearer, simpler exegisis.

5. Conclusion

Electricity is not fit for purpose. Electromagnetic theory is massively simplified, and is no longer a dual theory, with electricity on the one hand and field on the other. We exclude electricity. Electromagnetic theory is the Jewel in the Crown of Science. With this article, have we finally reached the point where the layman understands that there appear to be fatal flaws in classical theory, while the accredited expert refuses to understand or comment? If so, we have reached the end of The Enlightenment, with implications reaching far beyond electromagnetic theory.

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