June 2012
Volume 118
Issue 1914
£5.10

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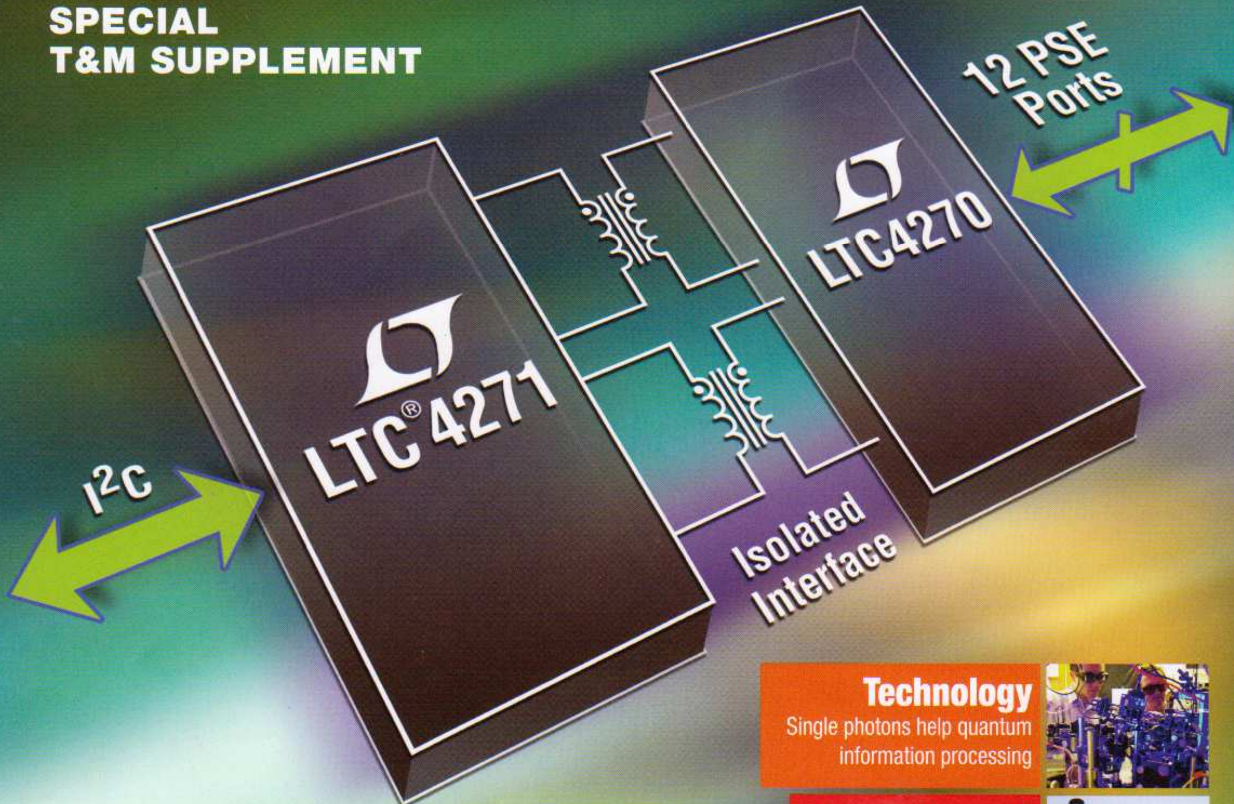

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WHAT THE READERS SAY

ANSWERING THE CATT QUESTION

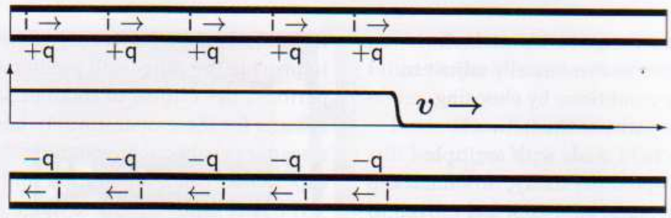

Figure 1: Illustrating the problem statement

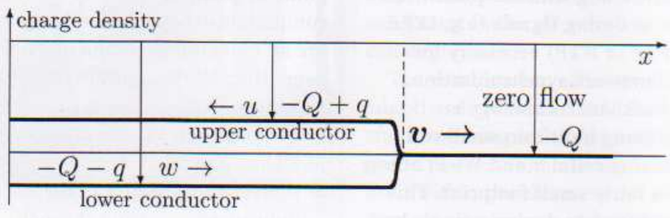

Figure 2: Densities and velocities of charges

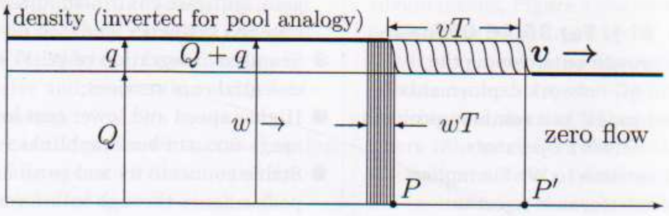

Figure 3: Relating the speed of the charges to the speed of the wavefront

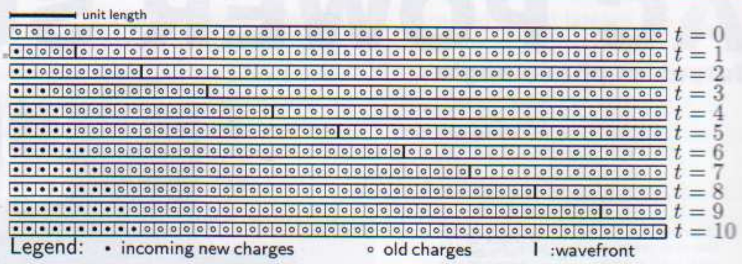

Figure 4: How the waveform travels much faster than the charges

The Catt question: At http://www.electromagnetism.demon.co.uk/cattq.htm one finds an instructive question, together with an animation that the reader may wish to view before continuing. It was posed decades ago by Ivor Catt (http://www.ivorcatt.org/).

Catt presents a reasoning (and other gedanken experiments) from which he concludes that classical electromagnetic theory is wrong and, as such, due for a thorough revision. Here we consider a less drastic approach, saving Maxwell's neck.

The question is the following: Consider an ideal transmission line formed by two parallel wires (Figure 1). A battery is connected at one end (assumed to the left in Figure 1), causing a voltage step and associated current step to travel along the line.

By Maxwell's equations, the step travels at light speed (assuming the medium is air).

When the step has travelled to a point at a certain distance from the battery, the entire line to that point is at the DC voltage determined by the battery, and hence charges ±q must be present along this entire distance. Since the electrons carrying the charges have non-zero mass and hence cannot travel at light speed (Einstein), how can the charges get there?

Approach: We assume that standard electromagnetic theory (Maxwell) correctly describes what happens when the step travels along the line and what charges ±q appear. Then, to eliminate the anomaly suggested by Catt, we have to show only how the charges can get there at the appropriate time instants without travelling at relativistic speeds.

To access a broad audience, the approach is intuitive, avoiding the usual mathematics of the telegrapher's equation and making extensive use of pictures instead. The quantitative calculations near the end, indispensable to obtain an intuitive feel for the orders of magnitude involved, require only basic arithmetic.

The answer – how the charges get there: Wires are metallic. The charges ±q are established by a shortage/excess of free electrons w.r.t. the neutral state. For a more intuitive picture, we let all symbols denote positive quantities and indicate negative polarities explicitly by a preceding minus sign. Let -Q be the charge per unit length (charge density) constituted by free electrons. We show later that this supply is huge compared to q. So most charges are already there; they just have to move to carry current. The question is: how fast?

Figure 2 shows the flow of electrons on both wires as the voltage step moves to the right. Although the free electrons are milling around locally at tremendous speeds, it is the collective (average) movement along the wire that constitutes current. This takes place at (much lower) drift velocity.

The negative battery terminal pumps electrons into the lower conductor, lowering the charge density from –Q to –Q-q. Imagining electrons as water coming from the left into a quiescent pool, it is easy to see that the rising level causes a wave that can move faster than the water particles themselves, tsunami-like. Another analogy is an elastic rod that is pushed from one side in the length direction. However slowly one pushes, the effect propagates at the speed of sound (for the material of the rod).

The (drift) velocity w of the electrons in the lower conductor can be related to the velocity v of the wavefront via Figure 3, inverting Figure 2 to exploit the intuitive pool analogy.

Consider a time duration T during which the wave moves from P to P', so PP' = vT. During that time the charge density along PP' must increase from Q to Q+q, so the charge itself must increase from Q·PP' to (Q+q)·PP'. This increase is q·PP', which equals qvT, and must be supplied by charges coming in from the left. These come at velocity w and with density Q+q, so the charge supplied during time T is (Q+q)wT. Hence (Q+q)wT = qvT, or w = vq/(Q+q).

This result is illustrated in Figure 4 for q = Q/4. To obtain a simple picture we use arbitrary units, calling them ulength, utime and ucharge. Assume that at t = 0utime the charge density Q is 4ucharge/ulength and v = 1ulength/utime. Behind (i.e. to the left of) the wavefront (thick vertical dashes), Q = 5 ucharge/ulength. Since w/v = q/(Q+q) = 1/5, charges must travel only (1/5)ulength/utime. At a density of 5ucharge/ulength, this amounts to 1ucharge/utime.

We shall see that, in reality, Q is very much larger than q, making w = vq/Q a very good approximation.

What happens in the upper conductor? There the positive terminal drains electrons from the wire, lowering the density of electrons. Quantitatively, (Q-q)uT = qvT and hence u = vq/(Q-q).

If Q is much larger than q, then u = vq/Q = w is a good approximation.

Concrete numbers: Without concrete numbers it is difficult to appreciate the extreme differences of magnitudes that enter into the picture here.

How large is Q? For instance, in copper the free electron density is $8.5{\cdot}10^{28}/m^3$ and the charge of an electron is $1.6{\cdot}10^{-19}$C (Coulomb). The 3D charge density is therefore $1.36{\cdot}10^{10}C/m^3$.

A wire of 1mm diameter has a cross-section of $0.79{\cdot}10^{-6}m^2$, so the free charge per meter length is $1.07{\cdot}10^4$C/m, which is huge. For simplicity replace the battery by a voltage source such that I = 0.107A (more about this later). Then, approximately, u = w = I/Q = $1{\cdot}10^{-5}$m/s. No hurry indeed!

Refining the numbers: Is I = 0.107A realistic? What voltage would be needed?

First, some conventions. Assume the (ideal) line has capacitance C and inductance L per unit length. The propagation velocity v along the line is given by v = 1/√(LC) and the characteristic impedance Z by Z = √(L/C).

To make further number estimates simple, we assume that the line has the same relevant numerical values as free space, namely $C = \varepsilon_0 = 8.854{\cdot}10^{-12}$F/m and $L = \mu_0 = 4\pi{\cdot}10^{-7}$H/m. This is realistic; it suffices that the ratio of the distance d between the wires and the radius r satisfies $d/r = e^{\pi} \approx 23$, which is nothing special (11.5mm wire separation for 1mm wire thickness). Then $v = 3{\cdot}10^8$m/s and Z = 377ohm. Hence the voltage source would have to deliver about 40V.

Sanity checking: Consider the following sanity check for charges along the line.

A line segment of length x starting from the battery has capacitance Cx. If the step voltage is V, the total charge when the step reaches the end is VCx, the charge budget. On the other hand, the battery current I after connection is given by I = V/Z. The travel time t is given by t = x/v. The charge delivered by the battery into the line during that time is tI. Now tI = (x/v)(V/Z) = x√(LC)·V/√(L/C) = VCx. So the charge budget is met, which constitutes a sanity check.

Final note: We have assumed that the wave (or ripple) has not reached the end of the line. The obtained results pertain to an infinite line, or a line that is loaded by a resistor with value Z at the other end. Otherwise, reflected waves appear on the line. However, this was not the issue here.

Raymond Boute

MORE OF CATT, PLEASE

"I am 19 years old [and] I find Catt Theory extremely easy to grasp; it inherently makes a lot of sense to me, and seems to do the same for others around my age"

My name is Cameron, and I am 19 years old. I find Catt Theory extremely easy to grasp. It inherently makes a lot of sense to me, and seems to do the same for others around my age that I share it.

I am not fully schooled in conventional theory, and I think this is what makes Theory C so much easier to comprehend. I have found virtually no stumbling blocks, and have yet to run into one of those situations where my studies come to a standstill while I resolve two different ways of thinking with each other.

Publishing his papers could be a huge opportunity for others like me, and I would be very grateful of you doing so.

Cameron Mercer

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July 2012
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WHAT THE READERS SAY

BEST RESPONSE TO THE CATT QUESTION

The response to the Catt Question by Raymond Boute [Letters, June] is one of the best I have seen, which both deals with the objections raised by Catt and presents an understandable model of what is really going on, without recourse to complex mathematics or arguments. I always felt there was a fundamental error by Catt, but could not quantify where it was.

The reality of the "electron gas" moving at high speeds within the copper conductor, and the influence electrons have on each other at great distances with respect to the effective electron size, was always going to mean that reality was somewhat different from the idealised model presented by Catt. Consider the effect of relatively slow average electron movement in the coils of a magnetic deflection system. These have been used for years without really understanding the process. A magnetic field is surely nothing more than the influence of one set of moving charges on another set. In permanent magnets it is the aligned spin of unpaired orbital electrons that creates a magnetic field; in conductors carrying current it is the relative drift speed of the electron gas.

Much as scientists dislike the concept of force at a distance, the influence of one set of charged particles on another is profound and happens over distances several orders of magnitude greater than the size of the particles.

I wonder therefore whether the propagation of an EM wave is nothing more that the force at a distance of one charged particle on another. Although we consider the vacuum of space to be empty, there are in fact many particles per cubic metre, many of which are charged, all of which can be affected by a movement of other charged particles. We are not able to detect EM waves except by using instruments composed of atoms and molecules, so how can we know they exist in isolation?!

I don't know whether anyone has done the experiment to time the propagation of magnetic influence, or whether it is even practically possible or not. If one could switch on the current in an electomagnet instantly, how long would it take a beam of electrons one metre away to be deflected?

The logical answer would be that it is no less than the speed of light, in that that is the speed at which the sphere of influence appears to propagate. That being the case there would be no way to determine whether a magnetic field really exists in its own right, or is simply the artefact of moving charges influencing one another. In a whole universe concept it is impossible to determine cause and effect if these movements of charges each spread their own sphere of influence at the speed of light. As soon as one intercepts or changes something in order to measure it, the sphere of influence of the measurement spreads at the speed of light changing the surrounding environment.

Scientists and engineers have over the years worked out usable models that enable us to make use of the phenomena of EM radiation and magnetic and electric charges. Raymond Boute's explanation of the transmission line problem is a good usable model. In a universe where everything has an influence on everything, there will always be room for other interpretations and we will never fully understand, but to my mind a simple model is sufficient to enable us to use the phenomena to our advantage.

Ray Lee

MIXING THEORY WITH PRACTICE

[In response to Ivor Catt's letter 'Where are They' in the Letters section of the May issue] Engineers are not trained or have as an objective the upsetting of physics, so we have lived in the dual world of "theory says" versus how things "really work". The real world and the theory world are compartmentalized. They are not allowed to influence each other. I think this is Catt's objection.

It is correct that the theory world – that is the world of platonic idealism – has always been the refuge of the elite. There was a brief period from, say, 1600s to maybe 1900s wherein the real world was supposed to be important. This may be something of a myth. The actual fact may be more along the lines that the theory world,

> *Engineers are not trained or have as an objective the upsetting of physics, so we have lived in the dual world of "theory says" versus how things "really work"*

in looking for a reason to reject the old theory, looked to the empirical world as an aid in doing away with the old theory. But once that was accomplished, the theory world ceased to dirty its hands in the facts.

Today we have a theory-driven empirical science. That is something of a contradiction, in that we are told that theories are tested. But unless there is a motivation to replace a theory the actual testing doesn't seem to be effective in changing the thinking of the theory world.

Harry Ricker

ELECTRONS AND PHOTONS

The letter by Raymond Boute in the June 2012 issue of Electronics World is very plausible. It recognizes the facts that a current pulse will propagate along a transmission line at near-light velocity and that the bulk movement of electrons along a conductor progresses at a snail's pace. However, he writes: "It is the collective (average) movement along the wire that constitutes current". He is confusing cause and effect.

Current must be caused by the movement of a physical entity, and the only entities capable of moving at the velocity of light are sub-atomic particles. We have given these particular particles the name 'photons'.

The simplest configuration which can be used to illustrate this effect is the dipole antenna. Consider a setup where a length of wire is cut at the middle and the two halves connected together via a battery and switch, as illustrated by Figure 1. When the switch closes, a step voltage is applied between the two conductors. This creates a current step which propagates to the right at velocity *v* along the right-hand conductor, whilst another step propagates to the left along the left-hand conductor at the same velocity. Figure 2 illustrates the distribution of current *Ia* after a time period of 1ns has elapsed. It is assumed that v = 300Mm/s.

But that is not the whole picture. Over the same time-period, an electromagnetic wave propagates outwards in all directions, forming the spherical wavefront shown in Figure 3. Current *Ie* is departing from the conductor into the environment. Antenna theory analyses this effect and introduces the concept of the 'radiation resistance', *Rrad*. That is, the effect of the environment can be represented by the circuit model of Figure 4.

Not all of the current departs into the environment. Most of it propagates to the end of each wire. *Ia* and *Ie* can be described as 'partial currents'.

At any instant, the wavefront intersects with a cross-section of each conductor. At the right-hand section, electrons are moving radially into the body of the conductor to leave a net positive charge on the surface. At the left-hand section, electrons move radially from the body of the conductor to the surface, to leave a net negative charge. The charged surface propagates at the same velocity as the wavefront.

There is a superabundance of electrons in the conducting material of the wires. So the electrons need not move very far to compensate for the action of the photons, which are the real charge carriers. The terms 'field propagation', 'current' and 'photon movement' have essentially the same meaning.

If a second conductor is laid alongside the first and the experiment repeated, the same thing happens. The wavefront propagates outwards. But this time it propagates along both wires in parallel. This constitutes antenna-mode current which flows along the outer surfaces of the conductors.

The second conductor also acts as a receiving antenna, where the induced current flows back towards the center. Most of the current flows out along the transmitting conductor and back along the receiver. This is the differential-mode current.

The conductor pair is now acting as a transmission line with a differential-mode current pulse following behind the antenna-mode wavefront. Most of the electrical energy is concentrated in the region between the two conductors. Since the two wires are both insulated and are close together, there is a significant amount of dielectric material in the path of the differential-mode wavefront. This is in contrast with the antenna-mode wavefront where the dielectric material is mostly air. Solid dielectric has a higher relative permittivity than air.

Since the velocity of propagation is inversely proportional to the square root of the relative permittivity, the antenna-mode current propagates at a higher velocity than the differential-mode current. This explains the phenomenon observed by Ivor Catt and reported in the January 2011 issue of Electronics World. As a short, sharp, current pulse propagates along a transmission line, it separates out into two components; one travelling faster than the other.

Ian Darney

Figure 1: Long wire configured as a dipole antenna

Figure 2: Current in conductors 1ns after switch closure

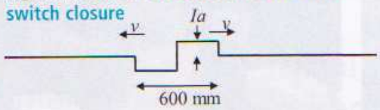


Figure 3: Wavefront 1ns after switch closure

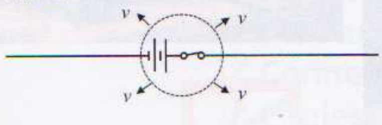
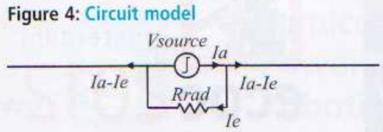


Figure 4: Circuit model



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