… and, from this comes antennas!

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Introduction

I am fascinated by the continued confusions over the concept/meaning of "displacement current" by some members of the antenna discussion list.

Of all groups within society, antenna builders/users are the most affected by the abstraction that has come to be known as displacement current, and hence should have the greatest appreciation of its significance.

Yet, the opposite seems to be true.

Only after Maxwell developed this concept were people's minds freed enough from past prejudices about electricity and magnetism to be able to conceive of the experiments that resulted in broadcasting and receiving electromagnetic waves via antennas.

But this ongoing discussion emphasizes that electromagnetism is much more abstract than, say, mechanics.

Thus, list member “Dave” has recently written: "from what I have read displacement current does not produce a magnetic field. Only conduction current produces a magnetic field."

There is a basic truth in this. Magnetic fields can always be traced back to conduction currents SOMEWHERE.

The difficulty with a narrow application of this notion is that one will be led to "action at a distance". The magnetic field HERE may be due to conduction currents that are extremely FAR AWAY- for example, on a distant star.

Soon, one must confront questions like: if the current on the distant star changes, does the magnetic field that I experience change immediately? Or, is there a delay between cause and effect?

Experiments show that there is a delay. Changes in electricity and magnetism propagate at the speed of light (and light is an electromagnetic phenomenon!).

How can we understand a finite speed of propagation?

One way is to suppose that the phenomenon involves particles, which moves around with a finite velocity.

So, magnetism = bullets?????

Newton believed this. And nowadays, the bullet view of magnetism has been revived by quantum mechanics. But with qualifications: magnetism sometimes behaves like bullets, sometimes not... (This modern view is even more complicated than the notion of displacement current.)

However, users of antennas are more likely to be in the camp that views electricity and magnetism as a type of WAVE phenomenon.

The compelling evidence for this is usually considered to be INTERFERENCE effects. The performance of your antenna is strongly affected by interference with the "ground plane," or with other antennas...

But, once one says that electromagnetism is a wave phenomenon, one soon must confront the question: waves of what?

- Water waves are waves of water.
- Sound waves are waves of the density of the air.
- Electromagnetic waves are waves of.......??????.........

The answer given in the 1800's was: the ETHER.

But 150 years of effort resulted in frustration as to identifying any plausible "mechanical" properties of this ether.

We are left with abstract statements such as "the ether is simply the electromagnetic FIELD".

What is the field? Well, it's what used to be called the ether!

Changing the name from "ether" to "electromagnetic field" does not make this concept any more "concrete".

A field is an entity that has a value at all points in space (although, of course, that value may be zero in many places).

A slight complication is that the electromagnetic field is a VECTOR field, meaning that its value at each point includes a direction as well as magnitude.

A key role of the field is to provide an answer to the question of action at a distance.

"Real" charges and currents create nearby electric and magnetic fields.

Then those fields create more fields in the next region of space.

And those fields create more fields..........on and on until all space can be filled with fields, due to the original action of the "real" charges and currents.

All this does not happen instantaneously. The fastest that the buildup of fields can occur over a distance d is time t = d / c where c = speed of light.

This is a beautiful logical viewpoint, though somewhat abstract.

We can now say that the magnetic field that we experience is due to the distant "real currents," or due to effects of nearby fields depending on which "source" we find it more convenient to emphasize.

It is possible that a lot of the recent debate has to do with being uncomfortable with the "dual" view that electromagnetic effects can be regarded as due to

> **1. distant sources**
> ….and to:
> **2. nearby fields**

Life would be simpler if we needed only 1 view.

Perhaps this is why static electricity and static magnetism continue to enchant people. When nothing is changing, a single view suffices. For this, most people choose view 1: static electricity and static magnetism are due to distant sources, and that's all there is to it.

But an antenna discussion group must celebrate the greater richness of electromagnetism when things are changing!

In this case, both views 1 and 2 are needed. And view 2, the field view, tends to play a broader role than view 1.

The field view has vast practical utility – but one must always remember that the fields are ultimately due to "real" sources, even if they are far away.

> *In this context, I interpret a statement like "displacement current does not produce a magnetic field" as a disavowal of the concept of an electromagnetic field.*
>
> *I am skeptical that pursuit of notions like this will lead to much understanding of electromagnetism -- and the tortured nature of the e-discussions recently would seem to confirm this assessment.*

Another theme of these discussions might be interpreted as: a magnetic field is a nothing but a nonzero reading on a magnetic field meter.

Magnetic fields, therefore, can only exist in places that a magnetic field meter can be put.

> **[*Some levity:*** Some people would say that abstractions like magnetic fields exist only "inside one's head." But, magnetic fields can't exist inside one's head because a magnetic field meter can't be put there. Thus, it would be "logical" to conclude that magnetic fields don't exist at all!**]**

"Real" currents in real wires create magnetic fields -- in that when a magnetic field meter is placed near a current carrying wire, a nonzero reading is obtained.

However, by this logic there can be no magnetic field inside a real wire, because it is not possible to place a magnetic field meter there.

This is, I believe, the heart of list member Bill's objection to displacement current.

Suppose we want to do an experiment to see if there is a magnetic field inside a current carrying wire.

We must create a hole in the wire to make room for the magnetic field meter.

Since wires are small, and magnetic field meters are big, the only way to create a big enough hole in the wire is to cut the wire!

But then, the wire can no longer carry a steady current, so the magnetic field goes away. The magnetic field meter reads zero, and we have proved that there can be no magnetic field inside a wire!

Mr. Maxwell objects to this line of thought.

Suppose instead the wire carries an alternating current (of not too high a frequency). Then, if the magnetic field meter has good enough frequency response, it detects an alternating magnetic field outside the wire.

Furthermore, it we now cut the wire and place the magnetic field meter in the gap, it will still measure a nonzero magnetic field.

For this statement to have much precision, the magnetic field meter must be small, and the wire big.

To be practical, people have added some circular plates to the ends of the cut wire, making the diameter of the wire large, at least for a short distance. Then a "real" magnetic field meter can be smaller than the wire, and placed inside the gap between the two cut ends of the wire.

Now we can clarify some details. If the magnetic field meter is placed exactly along the axis of the wire it reads zero.

If the meter is moved away from the axis of the wire, but is still inside the wire (inside the large plates that we added), the strength of the field increases with distance from the axis.

When the meter is entirely outside the wire, the field falls off inversely as the distance from the axis of the wire -- just as it does if the wire had never been cut.

These experiments can be interpreted as showing that a magnetic field exists inside a current carrying wire, as well as outside it.

> [*By the way, this is exactly what is predicted by Ampere's model of magnetism as being due to electrical current. In this view, magnetic fields exist both inside and outside wires. Hence, I interpret Bill's objections as being objections to Ampere's view of STATIC magnetism, more than Maxwell's view of changing electricity and magnetism.*]

Viewpoint 1 says the magnetic field is due to "real" currents, so the magnetic field in the gap in the wire is due to currents in the wire some distance away.

This is a fine view, but too narrow, in my opinion, for antenna enthusiasts.

Viewpoint 2 says the magnetic field in the gap is due to fields in the gap. In greater detail, the magnetic field arises from CHANGING ELECTRIC FIELDS.

Maxwell worked out a prescription for this. When a changing electric field, dE/dt exists perpendicular to an area A, a magnetic field is produced of the same strength as would be due to a "real" current I_E = epsilon_0 A dE/dt.

Other than having a peculiar equation, this current is just a "real" as the "real" currents in the wire. The magnetic fields calculated using this "field theory" expression can be measured to exist with the same magnetic field meter that we have been using all along.

The effects of the current I_E = epsilon_0 A dE/dt are just as real as those due to a conduction current I.

In view of this, Maxwell gave the name "displacement current" to I_E = epsilon_0 A dE/dt. To him an electric field E was a "displacement" of the ether. Nowadays, we tend to say "electric field" where Maxwell said "displacement."

[As you may know, many people still write epsilon_0 E = D = displacement field vector. Then, we can write I_E = A dD/dt, in which case it is "natural" to call this construct the "displacement current."]

But, it would be more in tune with contemporary language to say that I_E = epsilon_0 A dE/dt is the "electric field current."

What about reciprocity?

If there is an "electric field current," shouldn't there be a "magnetic field current?"

For that matter, if there is an electric charge, shouldn't there be a magnetic charge?

People originally thought that magnetism was due to magnetic charges, not due to conduction currents (= moving ELECTRIC charges).

Magnetism was originally separate from electricity, but seemed to obey many similar laws. Just like gravity and electricity obey many similar laws, but are different phenomena.

Oersted and Ampere had the profound realization that moving electric charges produce effects that are indistinguishable from magnetism.

Ampere made the great leap to say that MAGNETIC CHARGES DON'T EXIST. All magnetism is really due to electrical charges in motion.

There are not two separate sciences, electricity and magnetism, but one unified science, electromagnetism.

But, was Ampere correct? Reciprocity would say NO!

What does Nature say?

This requires experiment. And, in the 180 years since Ampere made is conjecture, no evidence has been found for the existence of magnetic charges.

Thus far, Nature does NOT appear to be "reciprocal" in the sense of the existence of both electric and magnetic charges.

Nonetheless, there are still many "reciprocities" to be found in the combined science of electromagnetism.

Oersted and Ampere showed that changing electrical effects (i.e., a "current" = electric charges in motion) causes magnetic effects.

It was natural then to ask: can changing magnetic effects cause electrical effects?

Ampere asked himself this question and came close to answering it -- but it was Faraday would is credited with providing the answer.

I will state Faraday's discovery in a way that emphasizes its "reciprocity" with Ampere's view of magnetism.

Recall Ampere's law: The integral of the tangential component of the magnetic field around a loop equals mu_0 times the (electric) current I through the loop.

Faraday discovered that: the integral of the tangential component of the electric field around a loop equals times the magnetic current I_B through the loop.

Faraday's prescription for the "magnetic current" was I_B = - A dB/dt
where A = area of loop
B = component of magnetic field perpendicular to the loop
(If B varies over the loop, I_B = - int dArea dB/dt.)

This "current" is NOT due to the motion of magnetic charges, as might have been expected from a straightforward vision of reciprocity.

Rather, it has to do with changing magnetic fields.

So, perhaps we should expand our terminology to say that I_B = "changing magnetic field current."

But, Faraday didn't use such language. He liked to speak of the rate at which magnetic field lines cut across the loop. Some people find this language very helpful. Others find it awkward. Some of the latter note how Faraday's prescription of field lines cutting across loops is hard to apply to Faraday's own example of a homopolar generator. Even though Faraday was the first to successfully explain the homopolar generator using his notion of field lines, some people claim that he "faked" the explanation, and that a new theory of electromagnetism is needed. The web site distinti.com is an example for such thinking (which I consider to be frozen in time in the year 1830, before Faraday showed us a vision of electromagnetism that has become one of the most fruitful contributions ever to human knowledge.)

We are now in the year 1832.

It is perhaps astonishing that not until the year 1864 did anyone successfully take the spirit of "reciprocity" of Ampere and Faraday to the next step.

If I_B = - A dB/dt is a "magnetic field current" that causes electrical effects, shouldn't we expect that I_E = k A dE/dt, which is an "electric field current", should cause magnetic effects? (k is a constant to be determined experimentally.)

Perhaps because Ampere had already given a very successful vision of magnetism as due to conduction currents I, nobody took the "obvious" next step of asking if magnetism could also be due to the "electric field current" I_E.

So, the years went by until Maxwell, while translating Faraday's largely verbal explanations of electromagnetism into mathematics, saw how natural it would be to consider the effects of an "electric field current."

He realized that if the constant k were set to + epsilon_0, very beautiful predictions follow.

The combination of Faraday's law (that changing magnetic fields cause electrical effects), and the new Ampere's law (that changing electric fields, as well as moving electric charges, causes magnetic effects) implies that the resulting changes propagate at the velocity c = 1/sqrt(epsilon_0 mu_0), whose numerical value is the speed of light.

This was almost like "magic". The constants epsilon_0 and mu_0 that arise in STATIC electricity and magnetism combine to tell us a key, previously missing fact about MOVING electromagnetism, namely, how fast can the fields change.

With this, one can contemplate and construct controlled generator and receivers of electromagnetic waves across large intervening gaps → ***antennas...***

Conclusion

All this reinforces how bizarre it is that an antenna discussion group argues over whether or not "displacement currents" = "electric field currents" exist or not.

Displacement current = epsilon_0 A dE/dt

In list member Ralph’s example, E is the electric field between capacitor plates.

If E is varying sinusoidally, then dE/dt is 90 deg out of phase with E.

In further detail, E in the capacitor is proportional to the charge Q on the capacitor plates. When the capacitor is charged by an AC current, the charge Q is 90° out of phase with the charging current.

Hence, the displacement current is IN PHASE with the charging current.

The displacement current is the "extension" of the charging current into the gap of the capacitor, and so is expected to be in phase with the charging current.

It all works out as well as could possibly be desired -- as Maxwell
discovered 140 years ago.

And from this comes antennas, since, some of the AC electric and magnetic fields leak out of the capacitor and could be detected by distant observers. **–30–**

Technical note: list member Bill claims that magnetic fields inside a wire vanish because if you divide the wire up into smaller wires, the fields from neighboring wires cancel one another. This is technically incorrect. The cancellation is only partial, except on the axis of the wire, where the cancellation is complete.

A correct, elementary derivation of this follows in a line or two from Ampere's law, and a lengthy integration over the imagined smaller wires confirms this.
http://puhep1.princeton.edu/~mcdonald/examples/displacement.pdf

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BRIEF BIOGRAPHY OF AUTHOR KIRK McDONALD

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Kirk McDonald is a professor of physics at Princeton University, where his research centers on experimental elementary particle physics. Since particle accelerators are essentially boxes with antennas on their walls that radiate inwards, McDonald has long been fascinated with unusual aspects of electromagnetic waves.

As an exotic example, he was the leader of a project that demonstrated how gamma rays could interact with a laser beam to produce antimatter. Many of his other articles on electromagnetism can be viewed at his website:
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