What's This Thing Called "Current"?

Electrons, Displacement, Light or What?

Douglas Brooks, President
UltraCAD Design, Inc.
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ABSTRACT

The generally accepted definition of electrical current is "the flow of electrons." But some people criticize this definition on the basis that: (1) it cannot explain how current (a signal) flows at the speed of light, (2) it cannot explain how current "flows" across the plates of a capacitor, and (3) it cannot explain how current can be induced in a conductor some distance away. This article shows that these criticisms are not valid. Electron flow, properly understood, can occur at the speed of light, and some of the component laws on which Maxwell's Equations are based are fully capable of explaining the other phenomena.

DEFINITION OF CURRENT

The usual definition of current is "the flow of electrons." This definition has been around for over a hundred years. If you do a search on Google for "flow of electrons" you will get over two million hits, most of them somehow related to this definition.

The formal definition of one amp of current is the movement of one coulomb of charge past a point (or across a surface) in one second of time. One coulomb of charge is further defined as 6.24×10^{18} electrons. The definitive measure of current would be the actual count of electrons passing by a point. We don't know how to do that, so all measures of current infer that flow by some other property of current, most commonly by a voltage drop across a known resistance or by the magnetic field the current generates around the conductor as the electrons flow.

Materials (elements) that are good conductors have a single electron in the outer (valence) shell. Copper, silver and gold are known as good conductors and they each have two very important properties in common. First, they are solids at room temperature and second, they have single electrons in their outer, or valence shells (or "bands.") These electrons are not tightly held to their parent atoms. In fact, it is not always clear which atom "owns" which of these "outer" electrons. They are often (inappropriately) referred to as "free" electrons. As electrical force is applied to a conductor, electrons tend to "jump" from one atom to the next (Figure 1), constituting the "flow." If you have a length of copper wire, it is not wrong to conceptually think about one electron popping out the far end for each electron that is injected somehow into the front end.

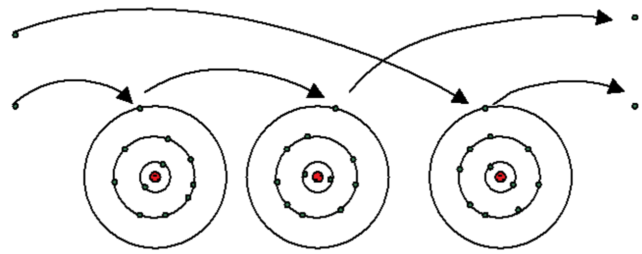

Figure 1: Single electrons in the outer, or valence, shell are free to move among similar atoms.

The "flow of electron" definition is not without its critics or without criticism. While it is true that current is the "flow of electrons," the term can be misleading if we are not careful in how we describe it. Some people (incorrectly) refer to this idea as the "fluid model" of current flow, sort of like water flowing through a pipe.

While the analogy of water flowing through a pipe is useful for illustrating some types of current concepts (such as resistance, capacitance and transmission line reflections) it is a very poor analogy in other ways. In particular, the fluid model (correctly) and the "flow of electrons" model (incorrectly) are criticized as being unable to deal with another aspect of current --- that it propagates at the speed of light. In fact, I have heard people take the absolute position that current is not the flow of electrons because electrons do not flow at the speed of light.

SIGNAL FLOW AT THE SPEED OF LIGHT

Here is where communication breaks down. When we talk about current being the flow of electrons and current flowing at the speed of light, we are not talking about the same flows! Individual electrons actually flow very slowly through a conductor, much, much slower than at the speed of light. But electrons (as a group) shift very quickly through a conductor, almost, well…. at the speed of light! We have to focus on the right thing.

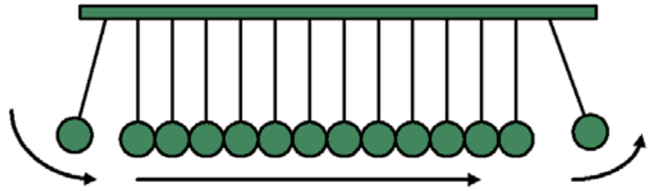

Figure 2: Electron flow causes a shift in electrons along a conductor.

Figure 2 illustrates this point. We are all familiar with this desktop toy. The falling ball at the front hits the first ball and transfers its energy to it, which then transfers energy to the second ball, and so on. The last ball in the string pops out (in the absence of friction) as far as the first ball fell. We could think of this string of balls as being extremely long. Even so, in the absence of friction, the last ball would pop out almost instantaneously, almost at the speed of light, even though the first ball is not moving nearly that fast. This is a rough analogy of what happens with electrons. And the distinction is very important.

Current flow does not mean "one electron in - same electron out." This happens very slowly as that individual electron travels through the conductor. Instead, it means "one electron in-one electron out." This can happen almost instantaneously, as Figure 2 suggests[1].

So the first criticism of the "flow of electron" definition of current, that it can't handle the idea that signals flow at the speed of light, is incorrect. It's a matter of understanding what we mean by "flow."

MAXWELL AND CURRENT FLOW

There are two other criticisms of the "flow of electron" definition that are often raised. They both go at least as far back as Maxwell. The first is that current cannot be the flow of electrons because electrons don't flow between the plates of a capacitor, and the second is that the electron flow model can't explain how electrons can be caused to flow in a completely separate conductor, in some instances very far away, from the conductor carrying the flow of electrons in the first place. Maxwell worried about these problems and postulated the existence of something he called "displacement" current, a type of current that is somehow different from electron flow and therefore can flow across various types of voids. It is interesting that calculations of displacement current always yield values and phases exactly equal to the primary current.

Maxwell made an extraordinary contribution to our industry. His equations (known, of course, as Maxwell's Equations) have endured for 130 years and are as valid today as when they were first published[2]. However, it should be noted that Maxwell was a mathematician, not a physicist. The usual expression of Maxwell's equations encompasses a set of four equations (insightful as they are) that represent four "laws" that had been formulated earlier. In layman's terms, the four laws are:

First, Charles Augustin de Coulomb has been credited with Coulomb's Law (1785) in which he stated that there are two kinds of charge, positive and negative. Like charges repel, and unlike charges attract, with forces proportional to the product of their charge and inversely proportional to the square of their distance.

Second, Carl Friedrich Gauss is generally credited with stating that every magnetic pole is actually part of a dipole that includes an equal and opposite pole. One pole cannot exist without its opposite. Magnetic force is applied along a vector with a direction that is a line along which the force acts. Magnetic force is inversely proportional to the square of the distance.

Third, André Marie Ampere is credited with Ampere's Law: An electrical current is accompanied by a magnetic field with a direction at right angles to the direction of the current flow. An extension of this law is that a changing electrical field is accompanied by a changing magnetic field. (The concept of displacement current is part of Maxwell's way of thinking about this extension of Ampere's original law.)

Finally, in 1831, Michael Faraday published Faraday's Law of Magnetic Induction: A changing magnetic field is accompanied by an electric field that is at right angles to the change of the magnetic field.

It turns out that we don't need a concept of displacement current to explain how current flows "through" a capacitor. Coulomb's Law provides enough explanation. Charges (electrons) collect on one plate of a capacitor and repel charges (electrons) from the other plate. The net effect is a shift of electrons all the way through the circuit. And if the capacitance is large enough, or the frequency high enough, the shift of electrons is effectively indistinguishable from what would happen if there were a conductor connecting the plates.

Similarly, we don't need the concept of displacement current to explain coupled currents elsewhere in the world. Ampere's (as extended) and Faraday's Laws, together, explain how an electrical current (flow, or shift, of electrons) creates an electromagnetic field. The electromagnetic field contains energy. That energy is lost to the circuit generating it. In antenna theory, we talk about an effective radiation resistance of the circuit to represent the loss. With EMI, the concept of radiation resistance is a little more subtle (the equivalent resistance becomes frequency dependent.) When we work with antenna circuits we try to maximize the transfer of energy in the field[3]. When we are dealing with EMI we try to minimize the transfer of energy. But nevertheless, if there is radiated electromagnetic energy in any form, it represents a loss of energy (however small) in the driving circuit.

The radiated energy in the electromagnetic field is radiated into space, never to return again. But if the field intersects a conductor somewhere in space, Faraday's Law explains how that intersected energy can be converted back into a current. The energy in the induced current would be a very, very small portion of the total radiated energy, but it would be non-zero nevertheless.

So the construct of displacement current is a useful construct to explain what happens when we do not have a direct conductive connection between parts of a total system. But it is a model, useful for understanding, not a necessary individual component of theory.

SUMMARY

In summary, the "flow of electron" definition of current is perfectly appropriate as long as we understand what electron flow is. No other than the Nobel Prize-winning physicist Richard Feynman confirms the electron component of current in his book QED[4].

> *In an atom with three protons in the nucleus exchanging photons with three electrons - a condition called a lithium atom - the third electron is further away from the nucleus than the other two (which have used up the available space), and exchanges fewer photons. This causes the electron to easily break away from its own nucleus under the influence of photons from other atoms. A large number of such atoms close together easily lose their individual third electrons to form a sea of electrons swimming around from atom to atom. This sea of electrons reacts to any small electrical force (photons), generating a current of electrons - I am describing lithium metal conducting electricity. Hydrogen and helium atoms do not lose their electrons to other atoms. They are "insulators."*

FOOTNOTES

1. It should be noted that current must flow in a closed loop. Thus, we cannot think about "one electron out" unless there is a path for electrons to return back to the source through that closed loop.
2. Maxwell's equations were first published in his Treatise on Electricity and Magnetism, 1873
3. The theoretical maximum amount of energy we can transfer to the field is 50% of the source power.
4. Richard P. Feynman, QED, The Strange Theory of Light and Matter, Princeton Scientific Library, 1985, p113

ABOUT THE AUTHOR

Douglas Brooks has a BS and an MS in Electrical Engineering from Stanford University and a PhD from the University of Washington. During his career has held positions in engineering, marketing, and general management with such companies as Hughes Aircraft, Texas Instruments and ELDEC.

Brooks has owned his own manufacturing company and formed UltraCAD Design Inc. in 1992. UltraCAD is a service bureau in Bellevue, WA., that specializes in large, complex, high density, high speed designs, primarily in the video and data processing industries. Brooks has written numerous articles through the years, including articles and a column for Printed Circuit Design magazine. He has been a popular high-speed design seminar leader for the past decade and has given seminars all over the United States and around the world (including Beijing and Moscow.) His recently published book (Prentice Hall, 2003) titled Signal Integrity Issues and Printed Circuit Board Design has been an instant hit. His primary objective in his speaking and writing is to make complex issues easily understandable to those without a technical background. You can visit his web page at www.ultracad.com and e-mail him at doug@ultracad.com.

For more information, call us or visit: **www.mentor.com**

Corporate Headquarters
Mentor Graphics Corporation
8005 S.W. Boeckman Road
Wilsonville, Oregon 97070 USA
Phone: 503-685-7000

Silicon Valley Headquarters
Mentor Graphics Corporation
1001 Ridder Park Drive
San Jose, California 95131 USA
Phone: 408-436-1500
Fax: 408-436-1501

Europe Headquarters
Mentor Graphics Corporation
Deutschland GmbH
Arnulfstrasse 201
80634 Munich
Germany
Phone: +49.89.57096.0
Fax: +49.89.57096.40

Pacific Rim Headquarters
Mentor Graphics (Taiwan)
Room 1603, 16F,
International Trade Building
No. 333, Section 1, Keelung Road
Taipei, Taiwan, ROC
Phone: 886-2-27576020
Fax: 886-2-27576027

Japan Headquarters
Mentor Graphics Japan Co., Ltd.
Gotenyama Hills
7-35, Kita-Shinagawa 4-chome
Shinagawa-Ku, Tokyo 140
Japan
Phone: 81-3-5488-3030
Fax: 81-3-5488-3031

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