Propagation Times

Yet Another Brain Teaser!

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Time for another quiz!

Picture in your mind two conductors. One is a simple round wire suspended in air. The other is a rectangular trace with the same cross-sectional area suspended in distilled water. The traces are far enough apart from each other and from other surfaces that any coupling is not an issue.

Now here is the question. How does the propagation time of a signal through the wire under water compare to the propagation time of a signal through the wire suspended in the air?

(a) It is faster because there is more surface area in the rectangular trace.
(b) It is the same because current (electrons) flow through copper at the speed of light.
(c) It is slower because the relative dielectric constant of the water is higher than that of the air.
(d) It doesn't flow at all, dummy, 'cause distilled water is an insulator!

OK, now, I'll give you a free "life line" and eliminate two of the options for you. Propagation time does not depend on the shape of the wire, so choice (a) is out. (And if you are thinking about "skin effect" here, we are not getting nearly that complicated in this column!) And choice (d) was thrown in there for fun. But that still leaves choices (b) and (c), and the choice between them is confusing to some people.

To see which choice is correct, we need to discuss a little about what happens when current flows. Current is the flow of electrons past a point. We don't need to get into a discussion of *how* they flow—whether each electron flows along the wire, or whether electrons jump from atom to atom. But when current flows, electrons move.

Now electrons have an electrical charge. And particles with like charges repel each other and unlike charges attract. If you were a particle outside the wire, how would you know if you should be attracted or repelled by the electrons inside the wire? You would know because charged particles have a force field associated with them that radiates outwards. It is called an electrostatic field, sometimes designated as an "E" field. This field has a force associated with it (inversely proportional to the square of the distance) and a direction (radially outwards). So, when current flows, there is an E field radiating away from the wire that flows with it.

Also, when current flows, there is a magnetic field that is generated around the wire. This field has a strength that is inversely proportional to distance and a direction that is circular around the wire. You may have seen, in school, the classic compass experiment where a wire with flowing current creates a magnetic field that causes a compass needle to move. When current is changing, this magnetic field changes along with it. And a changing magnetic field can induce a current in an adjacent wire. (This is the basic principle behind a transformer.) Therefore, as current flows through a wire, there is a magnetic field around the wire that is changing with it. We sometimes call that field (logically enough) an "H" field.

When a current flows through a wire, there must necessarily be an E field and an H field flowing along with it. Collectively we call them the *electromagnetic* field around the wire.

Sometimes this is a good thing and sometimes it is a bad thing. The E and H fields can (and do) induce currents in other conductors. When we send a signal along a broadcasting antenna, and it induces a signal in a TV, radio, cell phone, or pager receiving antenna, this is usually a good thing. This is how communication works. But when a signal flowing though a trace induces a signal in an adjacent trace, or in an FCC compliance testing antenna, that can be a bad thing. It's called crosstalk or EMI. The coupling is exactly the same phenomenon. It's just that sometimes we want to maximize it and sometimes we want to minimize it.

When current flows, the E and H fields *always* exist. And they *must all track together*. The E field cannot get out ahead of the H field or the H field get out in front of the E field. The current cannot get out ahead of the E and H fields and wait for them to catch up. The E and H fields cannot get out in front of current and wait for it to catch up.

It turns out, the issue is not how fast the electrons can travel in the copper, the issue is how fast the electromagnetic field can travel in the medium it is traveling through. For the wire suspended in air, the electromagnetic field is traveling through the air. For the trace suspended in water, the electromagnetic field is traveling through the water.

Electromagnetic fields travel at the speed of light when in a vacuum. They travel at almost exactly the same speed in air. (Normally you have to be an astronomer or concerned about atmospheric reflections of radio waves to care

This is adapted from an article that appeared in Printed Circuit Design, a CMP Media publication, August, 2000

about this difference in speed!) But electromagnetic fields travel *slower* in any *other* medium, including water. The difference in speed is inversely proportional to the square root of what is called the “relative dielectric constant”. For example, light propagates at approximately 12” per nanosecond through the air. We have the rule of thumb that signals (electromagnetic fields) travel at 6” per nanosecond in FR4 board material. The “4” in FR4 relates to the relative dielectric coefficient. The square root of 4 is 2, Hence, the signals travel at ½ the speed of light on our FR4 circuit boards! How ‘bout that!

The relative dielectric coefficient of distilled water is approximately 80. The square root of 80 is almost 9. So the propagation speed of the signal in the wire through the air is almost 9 times faster than that for the wire suspended in water. The speed has nothing to do with the material of the conductor. It has everything to do with the physical characteristic of the medium around the wire.

The answer is (c).