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Fields and Waves—Visualizing Important Electromagnetic Concepts

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This tutorial attempts to show how electromagnetic radiation occurs, from an intuitive viewpoint rather than in-depth mathematics

Electromagnetic concepts are more important than ever. Actually, for many engineers, those feared Maxwell's Equations from undergrad EM class are the new "Ohms Law." This tutorial won't attempt to derive or analyze Maxwell's Equations, but I will try to provide some intuitive explanations for some of the more important—often difficult to grasp—concepts that are embodied in their mathematics.

Engineers who need this tutorial probably know who they are. Inexperienced engineers may need additional background, but with so many traditional "non-RF" applications operating at higher frequencies, or in concert with wireless functionality, I expect many readers will be managers and marketing staff who need a better understanding of the new realm that now involves their products.

I apologize in advance to those who want more pictures to help visualize EM concepts! The visualization referenced in the title is, by necessity, largely in your imagination. It is hard to express many of the actions in the electric and magnetic domains on paper or monitor screen.

The Electromagnetic Spectrum

This may be "Science 101" to a lot of you, but it's always worthwhile to start at the beginning. Figure 1 represents the electromagnetic spectrum from very low frequencies to Gamma rays. There are two things that must be remembered from this chart:

1) The EM spectrum is a continuum of the same phenomenon. Radio waves, light waves and Gamma rays are all the same "material"—photons, which are the embodiment of radiated electromagnetic energy.

This characteristic make it obvious why all EM energy travels at the speed of light—it *is* light, or more correctly, different modes of the same thing as light.

2) The differences are in the energy level of the photons, as measured indirectly by either their frequency of vibration or wavelength (the inverse of frequency).

It can easily be grasped that it requires more energy to increase the spin or vibration of any object. Or, as an object gains more energy, that energy can be stored in its spin or vibration. The "vibration" experienced by a photon is not mechanical, but rather, is the back-and-forth transition between electricity and magnetism. So let's look at those two things separately.

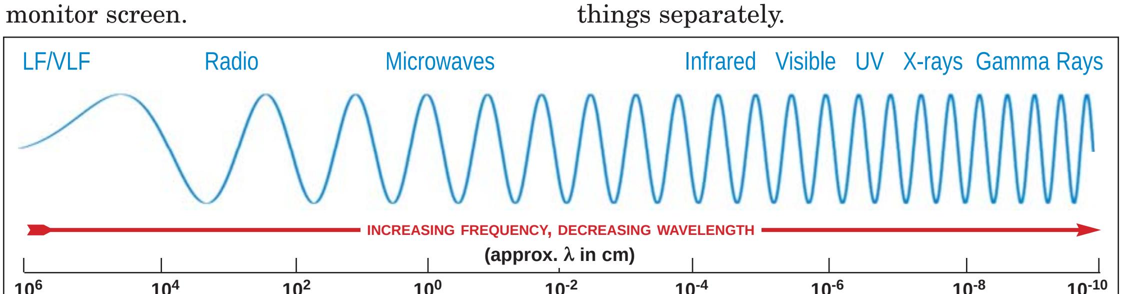

Figure 1 · The electromagnetic spectrum from low frequency to gamma rays.

Electromagnetics in Circuits

Electromagnetics is not just radiation, it also applies to the electricity that flows inside wires and circuits, and the magnetic fields that they create or interact with. The flow of electrons as electric current, the electric fields that we understand as capacitance and the magnetic fields that relate to inductance all are manifestations of electromagnetic force.

When we begin studying electricity and magnetism, we use the imperfect, but useful analogy that "pure" electricity and magnetism are EM forces that are contained within physical structures. Without this view, we would not have "DC circuits" that allow us to take the first steps toward understanding electronics. This idealized view is then continued as the first level of understanding AC circuits as well. It is only later in our engineering education that we begin to see that this simplistic viewpoint does not hold as our circuits begin to move toward the right from the left end of the chart in Figure 1.

Maxwell's Equations

In our current understanding of physics, the *electromagnetic force* is one of the four fundamental forces of nature, along with the strong and weak nuclear forces, plus gravity.

As you might expect, the description of a fundamental force requires daunting mathematics, but you may not need to delve any deeper than what you learned in undergraduate EM class. (However, you probably will need to review that same material often!) Unless you are writing EM analysis software, or some similar in-depth analytical work, what you need is a grasp of what Maxwell's equations accomplish in explaining how things work.

Maxwell's equations serve to organize the work of Ampere on magnetic fields, the work of Faraday on magnetic flux and induced EMF (electromotive force) in a conductor, and the work of Gauss on electric charge and magnetic flux within an enclosed space. The most important new concept introduced by Maxwell is *displacement current* for both the electric and magnetic fields. This is probably the point where many students become uncertain of their understanding.

First, remember how Faraday showed that current in a conductor created an associated magnetic field, and a magnetic field would induce current in a conductor. But, for the magnetic field to create that induced current, there must be *motion*. That motion can be physical, as in a motor or a fluctuation in the magnetic field, as might be created by a fluctuating current in the conductor (electromagnet) that generates the field.

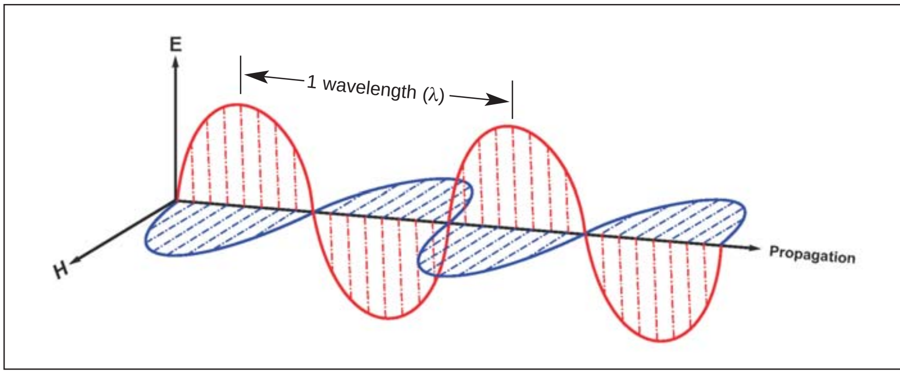

Figure 2 · EM waves a cyclic in the electric and magnetic domains, which are orthogonal. Defining the relationships between the two field types is one of Maxwell's contributions to our understanding.

What was missing was the corresponding behavior of an electric field. There are no "magnetic conductors" where we can observe "magnetic currents" induced by a moving electric field. Still, Gauss showed that electric and magnetic fields behaved the same way with regard to flux density and within bounded spaces.

Maxwell made the leap to the invisible realm of a unified electric and magnetic force, with displacement currents as the flow of energy in both the electric and magnetic fields. Because these currents operate outside conductors, they necessarily involve a radiated electromagnetic field.

We can consider electric field displacement currents as "half a capacitor," where the field goes outward from one plate, but does not require another plate to "push against." The Magnetic field displacement currents are similar—magnetic field lines of force that act outward, but do not return to the other end of the magnet as they do in our simple science experiments with a magnet and iron filings. The term *displacement* arises because the fields simply push outward—if there was a physical transmission media present (the proverbial "aether"), it would be displaced by these currents.

What happens in the creation of a radiated field is that the displacement current in a fluctuating field (electric or magnetic) induces the other, also as a displacement current. Successively, the wave cycles through electric and magnetic states as it propagates outward (Figure 2), maintaining the same rate of change (frequency) as the initiating field.

The Radiation Mechanism

Electromagnetic waves (comprised of photons) contain energy. The magnitude of that energy varies across the spectrum of Figure 1. The highest frequency (and energy) EM waves require nuclear-level effects—a nucleus may lose a neutron, and the energy that held the particle in place is radiated as a gamma ray.

Visible light and adjacent frequencies are created by shifts in energy levels of electrons as an excitation energy is applied (electrical, thermal, etc.).

Radio waves are launched by antennas, using the energy generated and amplified by electronic circuitry, with the antenna serving as the "half capacitor" plate and the "open-ended" electromagnetic transducer.

Summary

This tutorial ends here, but we will continue to examine this topic in future articles, to help you gain additional insight into the basic behavior of electromagnetic fields.