Electromagnetic Radiation Explained

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(How Radio Waves Are Born)

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One of the least understood phenomena in electrical engineering is the idea that electric and magnetic fields appear to leave a radio transmitting antenna to form what we know as radio waves. Most books fall just short of explaining this process by making statements that fields snap or jump off the antenna as they expand. At the same time, books on electromagnetics present the needed laws of field behavior to explain wave propagation, but are so advanced that it can be difficult for us to relate what we are learning to radiation.

This explanation attempts to go beyond the elementary treatments, while at the same time keeping the mathematics a notch simpler than the more advanced treatments of fields. This article will attempt to give the reader a better feel for how electromagnetic fields behave to provide propagated radio signals.

My key reference in understanding this topic is a book called *Radio-Electronic Transmission Fundamentals* by B. Whitfield Griffith, Jr., 1962, re-published in 2000. Additional sources are listed in the bibliography provided at the end of this article.

A knowledge of trigonometry, calculus and vectors is assumed as well as a fairly good background in Electrical Engineering. A more qualitative explanation can be found on the next page.

Contents

A changing magnetic field will

create an electric field in space.

The whole is the summation of its parts:

The voltage, which is induced in the loop does not arise at any single point in the loop, but, rather is the summation of all the infinitesimal bits of voltage that are arising around the loop, distributed along its contour.

If the total distance around the contour of the loop is *s*, the differential element of length along the contour is said to be ds. Hence, the total voltage induced in the loop will be the dot product **E . ds**, summed or integrated once around the contour of the loop.

$$V_c = \int_c E \cdot ds$$

The total voltage around the loop is the sum of all the infinitesimal pieces of voltage around the contour of the loop. Each bit of voltage is represented by the dot product of the electric field intensity volts/meter and the segment length. (The field component, which is tangent to the loop at that point.)

Eq. 1

Now, we find the relationship of the total voltage to the magnetic flux density **B**.

Faraday's Law -

The voltage induced in a loop of wire is directly proportional to the rate of change of the magnetic flux which links or passes through that loop.

$$V = \frac{d\phi}{dt}$$

In other words, it is the time derivative of the flux linkage.

Eq. 2

Since, according to Faraday's law, this total voltage is solely dependent on the rate of change of the total flux ϕ, passing through the loop, it is important to know how the total flux is related to the density of the magnetic flux.

$$d\phi = B \cdot n\, da$$

The differential flux is the dot product of the flux density with the unit vector normal (perpendicular to) the differential area, which says that it is the component of flux which is passing perpendicularly through the element area da.

Eq. 3

The total flux can now be expressed in terms of the flux density as follows:

To obtain the total flux passing through the contour area, we sum the differential pieces by integrating both sides of

$$\phi = \int_A B \cdot n \, da$$

the equation.

Eq. 4

Recalling Faraday's law, stating that the voltage induced in the loop is proportional to the rate of change of the flux, we can differentiate the above integral with respect to time to get the voltage as related to the flux.

$$\frac{d\phi}{dt} = \frac{d}{dt} \int_A B \cdot n \, da$$

Eq. 5

Getting back to Faraday's law, if we were to hold up a ring of wire in front of us and have an expanding (increasing positively) magnetic flux passing through it, but away from us, the induced voltage would cause a current flow in a counterclockwise direction. The counterclockwise current flow, is contrary to the right-hand screw rule, therefore we consider it a negative flow. Following this, Faraday's law equation is rewritten as follows:

$$V_c = -\frac{d\phi}{dt}$$

Eq. 6

Now, substituting each side of Eq. 6 with Eq. 1 on the left side and Eq. 5 on the right side, yields the first of the field equations as shown in Eq. 7.

$$\oint_c E \cdot ds = -\frac{d}{dt} \int_A B \cdot n \, da$$

Eq. 7

The circle added to the integral symbol indicates that we are integrating around the entire closed contour. This provides a means of computing the induced voltage in a loop of arbitrary size and shape with any distribution of magnetic flux within the enclosed area. **The most important implication of this equation is that it relates an electric field with a changing magnetic flux without considering that any current carrying wire is present.**

This equation makes the statement that a changing magnetic field will create an electric field in space.

A changing electric field will create a magnetic field in space.

Biot-Savart law -

If a long, straight conductor carrying a current, it will cause a magnetic field of intensity **H** to surround it at any radial distance r, hence the Biot-Savart Law equation:

$$H = \frac{2I}{r}$$

Eq. 8

We can obtain the magnetomotive force with a relation that is analogous to that used to obtain the electromotive force as expressed in Eq. 2.

$$M = \oint_c H \cdot ds$$

The total magnitomotive force is the sum of the components of magnetic field strength tangent to the contour.

Eq. 9

If we assume that the conductor is long and straight and passes perpendicularly through the center of the contour, the solution simplifies to:

$$M = Hs$$

Eq. 10

Substituting equation 8 and the circumference of a circle for H and s respectively give us:

$$\oint_c H \cdot ds = Hs = \frac{2I}{r} 2\pi r = 4\pi I$$

Eq. 11

Note that the radius has been canceled in the equation, which means that the magnetomotive force around the contour is independent of the radius or, for that matter, even the shape of the contour. A circle is the special case where **r** is constant in a curve expressed in polar coordinates and that a non-circle is when r is a function of the angle. So, whether **r** is constant or variable with the angle, the total magnetomotive force is dependent only on the current through the conductor.

This equation tells us that a current passing through a conductor results in a magnetic field and that the strength of the magnetic field is proportional to the current. It follows that if the magnitude of the current were varying in any way, the resultant magnetic field would also vary. So, if the current were alternating in a sinusoidal fashion at some frequency, the magnetic field would also be caused to alternate at the same frequency.

So far we have shown that an alternating current through a wire or conductor results in alternating magnetic and electric fields around the conductor. So far, we have not shown that these fields radiate or "leave" the conductor on a distant journey in any way nor do they "snap," "jump," or "hop" off the antenna as many texts would have you believe.

In order for radiation to be able to occur, we have to prove that magnetic and electric fields can exist without the presence of a nearby current and that these fields will "move" through space. We will see the idea of movement of these fields through space as radio waves is really an abstraction. What really happens is more of a domino effect, which is a demonstration of "propagation."

In order to begin to understand the transition between the fields we have just described, which are referred to as conduction fields and fields that become free of the wire we must find some way to relate what happens in a conductor to what happens in space. We will start off by stating Kirchoff's law.

Kirchoff's Law -

The sum of all currents entering and leaving a node or branch point in a circuit must equal zero as illustrated by figure 1..

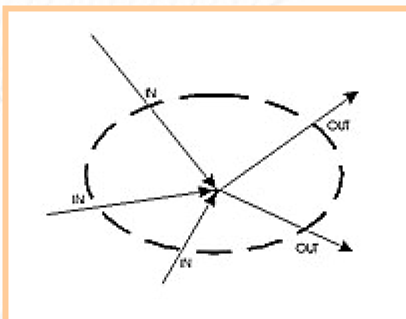


Fig. 1

Expanding this to an enclosed volume. If the dashed line in Fig. 1 represents an enclosed volume then, the sum of all the currents entering the boundary of the volume must equal the sum of all the currents passing out of the volume. Mathematically speaking, the integral of the current density over the entire volume regardless of shape or size equals zero. Current cannot be dead ended inside of a volume. What goes in, must come out.

Let us now enclose one of the plates of a capacitor with a volume as shown in Fig. 2.

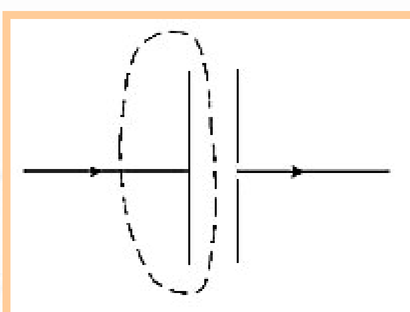


Fig. 2

The boundary of the volume passes between the plates. The arrows indicate a current entering the left capacitor lead and exiting the right capacitor lead. Since there is no conductive connection between the plates, how can we apply Kirchoff's law if current cannot actually flow out of the volume enclosed by the dotted line to get to the right capacitor plate? The answer lies in the idea of *displacement current*.

Displacement Current -

First, we introduce *dielectric displacement*. The *dielectric displacement*, designated by the letter **D**, represents the electrical strain which occurs in a dielectric medium, when an electric field is present.

$$\mathbf{B} = \mu \mathbf{H} \qquad \mathbf{D} = \epsilon \mathbf{E}$$

Eq. 12a and 12b

D is analogous to magnetic flux density **B**, hence **D** is really the electric flux density. It is related to the electric field by ϵ, which is the permittivity or dielectric constant of the material between the plates of a capacitor. The magnetic flux density B is related to the magnetic field strength **H** by μ or the permeability of the material within the magnetic field.

To explain what is happening between the plates of the capacitor, we first realize that as current flows into the capacitor, an electric charge accumulates on the plates with excess electrons on one plate and a dearth of them on the other. As the charge builds up, an electric **E** field between the plates, builds up causing the dielectric displacement or electric field density to also increase. In order to satisfy Kirchoff's law, there must be some sort of current flowing in the dielectric, proportional to the rate of change of dielectric displacement. This current has been given the name *displacement* current and we can think of it as a flowing-in (displacement) of additional flux as required as the electric flux density increases. This total displacement current is equal to the conduction current flowing into and out of the capacitor and, therefore, out of the volume with which we have surrounded the plate.

As Maxwell was aware of the displacement current, he had to decide whether it was consistent with conduction current in that it would also have a magnetic field associated with it. Maxwell, then made the assumption that there was, indeed a magnetic field associated with the displacement current. In considering this, he added an additional term into the of Ampere's Rule and the Biot-Savart equation to account for it. Equation 13 shows this new relationship.

$$\oint_c \mathbf{H} \cdot d\mathbf{s} = 4\pi I + \frac{d}{dt}\int_A \mathbf{D} \cdot \mathbf{n}\, da$$

Eq. 13

This equation takes into consideration that the area within the contour of **H . ds** integration might contain both conduction and displacement currents which would both contribute to the intensity of a magnetic field. **D . n da** is the differential electric flux across the capacitor space normal to a given point and the integral sums it up to the total flux. The rate of change of the total flux is the displacement current flowing through the contour.

We Have Radiation!

We have finally arrived at the two principal field equations of Maxwell. Since we are interested only in the field conditions in free space we drop the $4 \pi I$ term and the two field equations are expressed in Eq. 14 and 15.

$\oint_c E \cdot ds = -\frac{d}{dt} \int_A B \cdot n\, da$	**A changing magnetic field will produce and electric field.**
$\oint_c H \cdot ds = \frac{d}{dt} \int_A D \cdot n\, da$	**A changing electric field will produce a magnetic field.**

Eq. 14 and 15 **Maxwell's free space equations.**

If we make the appropriate substitutions from Eqs. 12a and 12b to Eq. 14 and 15, we have:

$\oint_c E \cdot ds = -\frac{d}{dt} \int_A \mu H \cdot n\, da$	**A changing magnetic field will produce and electric field in space.**
$\oint_c H \cdot ds = \frac{d}{dt} \int_A \epsilon E \cdot n\, da$	**A changing electric field will produce a magnetic field in space.**

Eq. 16 and 17 **Maxwell's free space equations.**

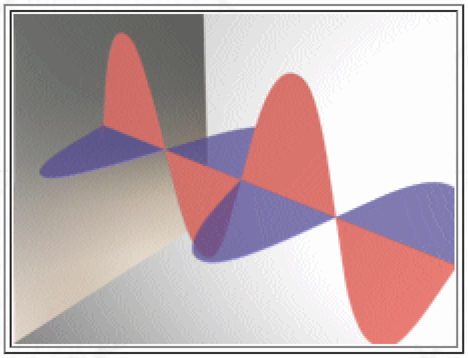
These equations are the key to electromagnetic radiation! Most important is the fact that no conduction current need exist and, therefore, no physical conductor.

The concept of radiation can be stated as follows:

If there is an alternating current in a conductor, an alternating magnetic field will be created surrounding the wire. The alternating magnetic field due to the current in the wire will create an alternating electric field in space further out from the conductor. WE HAVE LIFTOFF! The first transition from conduction fields to space fields has been made. Now, carrying it further, the alternating electric field, which was just born in space will create a magnetic (due to the corresponding displacement current in space) field further away from the conductor (according to Eq.17). The alternating magnetic field will then create another alternating electric field (according to Eq. 16). This process, which continues on away from the conductor is called electromagnetic wave propagation.

But, in order to radiate power, we must have both an electric E field

and H field in phase. Just like the initial electric field E in space, a magnetic field H is created from the electric field intensity or displacement current at the surface of the conducting wire. Both E and H fields, perpendicular to each other generate successive H and E fields, which are perpendicular to the previous pair of fields. The combination of these, in phase fields give rise to what is called the Poynting vector, which is perpendicular to both E and H fields and in the direction of propagation. The Poynting vector represents the actual power propagated in space. The magnitude of the Poynting vector is equal to the cross product of the E and H fields as in: P = E x H. It is measured in Watts per square meter and is, therefore, a power density.



The induction E and H fields close to the conductor are stored and, therefore, not radiated. They are separated by a 90^0 phase with each other. When the fields collapse, energy is returned to the system.

Radiated E and H field (shown left as radiated from a plane in space) are IN PHASE because they are delivering power to space. Energy is lost from the radiating system in this way and appears as a radiation resistance.

Radiation Resistance (electronic "friction") -

When the voltage and current are observed at the terminals of a radiating conductor or antenna, one component of alternating current is 90 degrees out of phase with the alternating voltage and another component is in phase with the alternating voltage. The component of current which is 90 degrees out of phase behaves like and, therefore is considered a reactive component. No power transfer or loss takes place due to the reactive component. The portion of current that is in phase with the alternating voltage is considered current due to power transfer. A portion of the power transferred or lost is due to the ohmic resistance of the antenna or radiator. It will be found, however, that there is an additional amount of power transferred, which the ohmic resistance can not be held accountable for. This power transfer is due to radiation. As far as the power source or transmitter is concerned, all power transfer appears as a total resistance and can be treated as so at the antenna feed point.

The energy lost can be thought of as being due to a "drag" or force acting against the motion of electrons which carry the electric charge. Part of this "drag" is due to energy transferred in collisions between atoms and the moving electrons, setting the atoms in motion, manifesting itself in the form of radiated heat. How, then is a "drag" felt, due to radiation?

In the American Radio Relay League article, "Why an Antenna Radiates" by Dr. Kenneth MacLeish, he describes the notion of *Bootstrap Forces*. Since the electric fields exist down to the surface of the electron and there is a force against charged as they accelerate through a magnetic field, the electron experiences a force or "drag" as it accelerates through it's own field! That portion of drag, due to the dynamic or radiated electric field is the force of radiation resistance. That is, the electron is pulled by it's own bootstraps! Part of the fields which drag the electron, collapse back into the conductor as it decelerates, thus returning energy to the electron in the opposite direction. This returned force is the back-emf due to inductance, which is part of the reactive component of the antenna impedance.

There are many other approaches to explaining radiation. I highly recommend another article entitled "Why an Antenna Radiates" provided on the ARRL web site on the Antenna Theory page. This article defines radiation as resulting from the acceleration of charges.

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7. "Why an Antenna Radiates" by Dr. Kenneth MacLeish, **QST magazine**.

Related Links

ARRL Technical Information Service: Why an Antenna Radiates by Kenneth Macleish
EDN Magazine: Understanding electromagnetic fields and antenna radiation takes (almost) no math
Displacement Current
How Magnetic Fields are Produced (Brigham Young University Physics 122)
Eric Weisstein's Treasure Trove of Physics
Georgia State University - Index to Hyperphysics
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Vector Calculus Web Page by Kris