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Experiment 117

Laying Down the Laws

Most amateurs tend to think of *wireless* as beginning with Marconi in the mid-1890s — he transmitted a message over a distance of a bit less than 2 miles in 1895. The historically minded ham might travel farther back through the experiments and papers of well known and not so well known names such as Nikola Tesla, Heinrich Hertz, Nathan Stubblefield and Mahlon Loomis to arrive at James Clerk Maxwell's electromagnetic theory, published in 1864. Yet their work required, as Isaac Newton had characterized it, "standing upon the shoulders of giants" who explored the *terra incognita* of electricity and magnetism from the early 1600s. Who were these giants and what did they discover?

My interest in prewireless was sparked, so to speak, by a recent article in the *IEEE Antennas and Propagation Magazine* giving a chronology of how wireless communications came to be.[1] (The article may be available through your local library or from an *IEEE* member.) A huge number of discoveries and explanations of basic concepts were required before Maxwell could synthesize them into his theory of electromagnetic waves.

For many of us, our electrical education began with Ohm's law, first stated by Georg Ohm in 1827.[2] We know it today as the familiar I = E / R, but R was a brand new idea in those days. In fact, Ohm's ideas were not well received at all! From Ohm's law, we progressed through the equation for power (P = E × I) and then into circuitry such as capacitance, inductance, reactance and impedance that quickly followed. But capacitance and inductance are treated as *givens* in equations we memorize for time constants, turns ratio, resonant frequency and so forth. Where do these *proto wireless* concepts come from?

In this column, we'll begin reviewing several of the most important advances listed in the article then progress to some simple experiments you can do yourself. The goal is to more fully understand what is meant by the familiar symbols and units in the design equations and in schematics. It is one thing to memorize an equation or paragraph and quite another to experience it for yourself on the workbench!

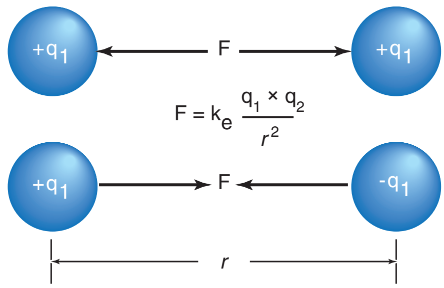

Figure 1 — Coulomb's law describes the force, F, between two electrically charged particles (q_1 and q_2). The force is proportionally weaker with the square of the distance between the particles, r. If the charges have the same polarity, the force is positive and they repel each other. If they are oppositely charged, the force is negative and attracts the particles together.

The Beginnings

There is a long history of experimentation with static electricity and magnetism leading to the invention of the capacitor in the mid 1700s. Perhaps the best known example of an early capacitor is the Leyden jar.[3] Since static electricity was fairly easy to generate, the capacitor and its ability to store electrical energy were well known by the end of the 18th century. The relationship between electricity and magnetism, however, was quite unclear and that relationship lies at the root of electromagnetic phenomena — such as wireless.

The IEEE article begins its journey to wireless with Charles-Augustin Coulomb's determination in 1785 that electric forces varied proportionately to the inverse square of distance — now known as Coulomb's law (Equation 1) as illustrated in Figure 1.

$$F = k_e \frac{q_1 q_2}{r^2} \quad \text{[Eq 1]}$$

where

F = the electric force between two particles with charges, q_1 and q_2,

r = the distance between them, and

k_e = a "constant of proportionality." It is this constant that turned out to have the most for reaching implications because it is determined solely by the properties of free space:

$$k_e = \frac{1}{4\pi\varepsilon_0} = \frac{c^2\mu_0}{4\pi} \quad \text{[Eq 2]}$$

where

c = speed of light in vacuum

ε_0 = the permittivity of free space (roughly, the ability of free space to contain electrical energy) and

μ_0 = the permeability of free space (the ability of free space to contain magnetic energy).

As it turns out, the speed of light (electromagnetic energy) traveling in free space is also determined by these two quantities:

$$c = \sqrt{\frac{1}{\varepsilon_0\mu_0}} \quad \text{[Eq 3]}$$

Not only does Coulomb's simple relationship contain the beginnings of wireless but it is also the first step in the studies of electromagnetic waves that led to relativity and its profound effects on our understanding of the universe. Coulomb did not know this at the time, of course. He only knew that he had discovered a relationship between electrical charge and electrical force.

Meanwhile (as the narrator often intones) other investigators were developing new ways of creating electricity. Up until this time, electrical experiments had to be performed with static electricity created by mechanical friction. In 1799, Alessandro Volta created an electrochemical *battery* based on chemical principles.[4] This was a major advance because experimenters then had a source not only of what Volta called the *electromotive force* (abbreviated *EMF*) but a source of

[1] Salazar-Palma, *et al*, "The Father of Radio: A Brief Chronology of the Origin and Development of Wireless Communications," *IEEE Antennas and Propagation Magazine*, Vol 53, No 6, Dec 2011, pp 83-114.

[2] **en.wikipedia.org/wiki/Ohm's_law**

[3] **en.wikipedia.org/wiki/Leyden_jar**

[4] **en.wikipedia.org/wiki/History_of_the_battery**

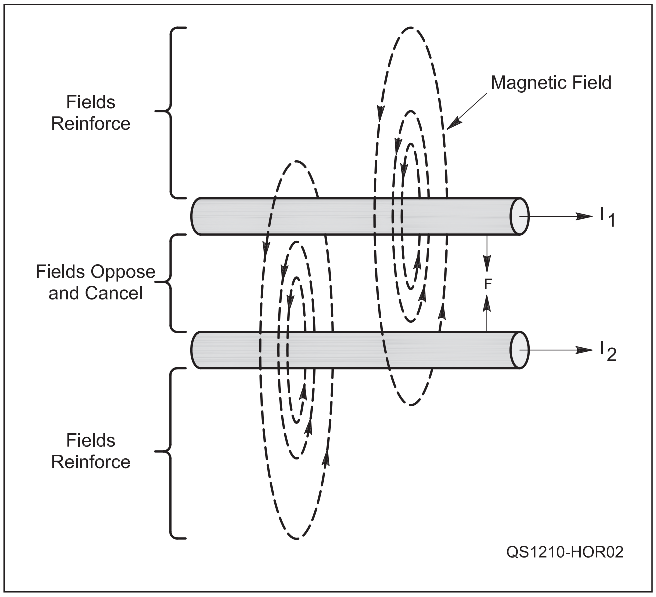

Figure 2 — Ampère's force law describes the force between two parallel, current-carrying wires. If the currents are flowing in the same direction, the fields are oriented in opposite directions between the wires, partially cancelling each other. Since the fields reinforce elsewhere, the result is a force pushing the wires together.

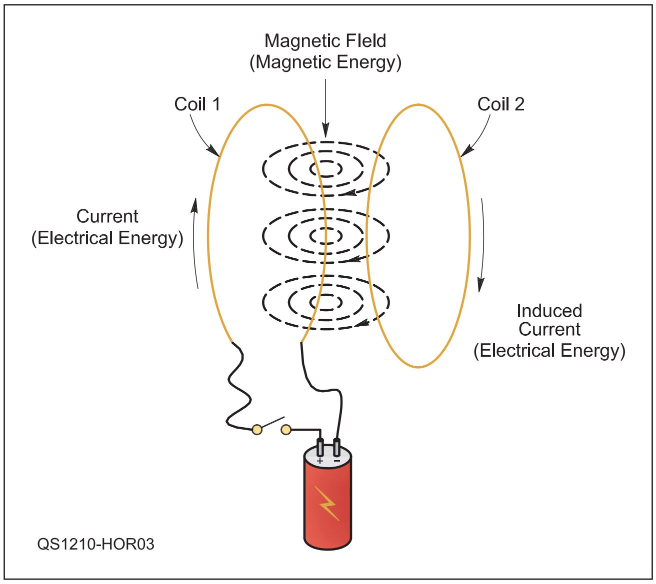

Figure 3 — Faraday demonstrated electromagnetic induction by showing how changing current in one coil induces a similar current in a second coil through a shared magnetic field. When the switch is closed, current in coil 1 will cause the current shown in coil 2. Lenz's law states that the current in coil 2 will be oriented to oppose the magnetic field from coil 1.

current they could then control and study. Prior to that current was mostly available as pulses from electrical discharges — *sparks*.

Magnetism was considered a separate phenomenon from electricity until 1820 when Hans Christian Ørsted discovered that current flowing through a wire caused a magnetic compass needle to deflect and created a circular magnetic field around the wire.[5] François Arago then demonstrated that not only did current flowing through a wire affect a magnet but that the current carrying wire itself became a magnet! Within days, André-Marie Ampère also demonstrated that parallel currents attract each other and opposing currents repel due to those magnetic fields:

$$F = 2k_a \frac{I_1 I_2}{r} \qquad \text{[Eq 4]}$$

where $k_a - k_e/4\pi$,

with similar definitions to Coulomb's law and illustrated by Figure 2. Note the similarity of Ampère's force law and Coulomb's law above.

The linkage of electricity and magnetism through the motion of electrical charge — current — led Ampère to create a theory of *electrodynamics* that is at the heart of wireless. After all, it is the continual acceleration and deceleration of electrons in our antennas that cause electromagnetic waves to be radiated. The movement of electrons in response to incoming waves allows us to hear those waves in our receivers. 1820 was a very good year!

In 1825 and 1826, Ampère published a collection of material on magnetism including what is now known as Ampère's law, the general relationship between currents and magnetic fields. This relationship was extended by Maxwell and forms one of Maxwell's equations that describe electromagnetic fields.

Getting Ready for Maxwell

Almost immediately, Ørsted's discovery and Arago's extension of it led to practical inventions. In 1821, American physicist Joseph Henry invented the *electromagnet* by winding the current carrying wire into a coil. While doing these experiments, he also discovered the need for insulation between the wires making up the coil. His experiments led to refinement of the electromagnet into the *electromagnetic telegraph* in 1831.

The really big news of that year, however, came from Michael Faraday, a self taught scientist who had been experimenting with electricity and chemistry since 1812. Faraday demonstrated *electromagnetic induction* by showing how changing currents in one circuit (later *ac current*) could induce similarly changing currents in another circuit without any direct connection between them.[6]

Figure 3 shows that in doing so, Faraday converted the electrical energy of current in the first circuit into magnetic energy in the surrounding field and back into electrical energy in the second circuit. This led Faraday to predict the existence of electromagnetic waves, as well.

Faraday refined his explanation of induction into the following formula known as Faraday's law:

$$\varepsilon = -\frac{\text{change in } \Phi_B}{\text{change in time}} \qquad \text{[Eq 5]}$$

where ε is the electromotive force (or *EMF*) and the fraction represents the change in magnetic flux (Φ_B) with time. The faster the magnetic flux changes or the larger the amount of change in one circuit, the larger the voltage that is *induced* in the other circuit.

The minus sign in the equation means that the current caused by the changing magnetic field flows in the direction that creates an *opposing* magnetic field. This is otherwise known as Lenz's law and it describes the *back EMF* we observe in motors and the *kickback voltage* in a relay coil when the relay is deenergized. If you look closely at Figure 3, you can see that the induced current flows in the opposite direction to the current caused by the battery.

In the next experiment, we will follow in the steps of Coulomb, Ampère, Ørsted and Faraday by performing some simple experiments that demonstrate the various effects they described. Is this purely a historical exercise? Not at all! These phenomena are at the heart of every radio — without them we would be wireless less.

[5]**en.wikipedia.org/wiki/Hans_Christian_%C3%98rsted**

[6]**en.wikipedia.org/wiki/Electromagnetic_induction**