The History Of Electromagnetism

Electromagnetism is an area of physics which involves the study of the electromagnetic force, a type of physical interaction that occurs between electrically charged particles. The electromagnetic force usually produces electromagnetic fields, such as electric fields, magnetic fields and light. The electromagnetic force is one of the four fundamental interactions (commonly called forces) in nature. The other three fundamental interactions are the strong interaction, the weak interaction and gravitation.

Until 1820, the only magnetism known was that of iron magnets and of "lodestones," natural magnets of iron-rich ore. It was believed that the inside of the Earth was magnetized in the same fashion, and scientists were greatly puzzled when they found that the direction of the compass needle at any place slowly shifted, decade by decade, suggesting a slow variation of the Earth's magnetic field.

Edmond Halley's Theories

Edmond Halley (of comet fame) ingeniously proposed that the Earth contained a number of spherical shells, one inside the other, each magnetized differently, each slowly rotating in relation to the others.

Hans Christian Oersted: Electromagnetism Experiments

Hans Christian Oersted was a professor of science at Copenhagen University. In 1820 he arranged in his home a science demonstration to friends and students. He planned to demonstrate the heating of a wire by an electric current, and also to carry out demonstrations of magnetism, for which he provided a compass needle mounted on a wooden stand.

While performing his electric demonstration, Oersted noted to his surprise that every time the electric current was switched on, the compass needle moved. He kept quiet and finished the demonstrations, but in the months that followed worked hard trying to make sense out of the new phenomenon.

However, Oersted could not explain why. The needle was neither attracted to the wire nor repelled from it. Instead, it tended to stand at right angles. In the end, he published his findings without any explanation.

Andre Marie Ampere and Electromagnetism

Andre Marie Ampere in France felt that if a current in a wire exerted a magnetic force on a compass needle, two such wires also should interact magnetically. In a series of ingenious experiments, Andre Marie Ampere showed that this interaction was simple and fundamental: parallel (straight) currents attract, anti-parallel currents repel. The force between two long straight parallel currents was inversely proportional to the distance between them and proportional to the intensity of the current flowing in each.

There thus existed two kinds of forces associated with electricity—electric and magnetic. In 1864, James Clerk Maxwell demonstrated a subtle connection between the two types of force, unexpectedly involving the velocity of light. From this connection sprang the idea that light was an electric phenomenon, the discovery of radio waves, the theory of relativity and a great deal of present-day physics.

Maxwell's Law

Originally, electricity and magnetism were considered to be two separate forces. This view changed with the publication of James Clerk Maxwell's 1873 *A Treatise on Electricity and Magnetism* in which the interactions of positive and negative charges were shown to be mediated by one force. There are four main effects resulting from these interactions, all of which have been clearly demonstrated by experiments:

1. Magnetic poles (or states of polarization at individual points) attract or repel one another in a manner similar to positive and negative charges and always exist as pairs: every north pole is yoked to a south pole.
2. Electric charges *attract* or *repel* one another with a force inversely proportional to the square of the distance between them: unlike charges attract, like ones repel.
3. An electric current inside a wire creates a corresponding circumferential magnetic field outside the wire. Its direction (clockwise or counter-clockwise) depends on the direction of the current in the wire.
4. A current is induced in a loop of wire when it is moved toward or away from a magnetic field, or a magnet is moved towards or away from it; the direction of current depends on that of the movement.

Maxwell’s Equations

Maxwell’s equations were completed in 1865, and they have a tremendous impact in our modern world. We first write down their integral forms.

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \iint_S \mathbf{B} \cdot d\mathbf{S}, \quad \text{Faraday's Law} \tag{2.1}$$

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \frac{d}{dt} \iint_S \mathbf{D} \cdot d\mathbf{S} + I, \quad \text{Ampere's Law} \tag{2.2}$$

$$\oiint_S \mathbf{D} \cdot d\mathbf{S} = Q, \quad \text{Coulomb's Law} \tag{2.3}$$

$$\oiint_S \mathbf{B} \cdot d\mathbf{S} = 0,, \quad \text{Gauss's Law} \tag{2.4}$$

The basic quantities with their units are

$$\mathbf{E} : \mathrm{V/m}, \qquad \mathbf{H} : \mathrm{A/m} \tag{2.5}$$

$$\mathbf{D} : \mathrm{C/m^2}, \qquad \mathbf{B} : \mathrm{W/m^2} \tag{2.6}$$

$$I : \mathrm{A}, \qquad Q : \mathrm{C} \tag{2.7}$$

where V is voltage, A is ampere, C is coulomb, and W is weber in the above. We can convert the above integral forms into partial differential equation form by using Stokes’ theorem and Gauss’ theorem as we did before. For example, using Stokes’ theorem, we can write

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = \iint_S (\nabla \times \mathbf{E}) \cdot d\mathbf{S} \tag{2.8}$$

Therefore, Faraday's law (2.1) becomes

$$\int_S (\nabla \times \mathbf{E}) \cdot d\mathbf{S} = -\frac{d}{dt} \iint_S \mathbf{B} \cdot d\mathbf{S} = \iint_S \left(-\frac{\partial \mathbf{B}}{\partial t}\right) \cdot d\mathbf{S} \qquad (2.9)$$

where we have exchanged the order of total time derivative and the integral, assuming that the surface integral does not change with time. After the exchange, the total time derivative becomes a partial time derivative, since B is a function of both space and time. In the limit when the area S → 0 above becomes a point-wise relationship. In other words,

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (2.10)$$

which is Faraday's law in its full glory. This equation was experimentally derived in 1831, during the height of the age of telegraphy. We can apply the same treatment to Ampere's law to get

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad (2.11)$$

The above is sometimes called the generalized Ampere's law as the original Ampere's law does not have the second term. The term $\frac{\partial \mathbf{D}}{\partial t}$ was the contribution of James Clerk Maxwell in 1865, known as the displacement current. Similarly, we can apply Gauss' divergence theorem to get

$$\nabla \cdot \mathbf{D} = \varrho \qquad (2.12)$$
$$\nabla \cdot \mathbf{B} = 0 \qquad (2.13)$$

Equations (2.10) to (2.13) constitute the four fundamental equations of electromagnetic theory, now known as Maxwell's equations. Maxwell, in addition to adding the extra term $\frac{\partial \mathbf{D}}{\partial t}$ the displacement current, to generalized Ampere's law, was the first to write these equations down lucidly and mathematically. Also the present form of what textbooks call Maxwell's equations, (2.10) to (2.13), were actually written down by his admirer, Oliver Heaviside.2 Maxwell himself first wrote down electromagnetic theory using vector potential A and scalar potential Φ. We will learn more above vector and scalar potential formulation of electromagnetic theory later.