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Chapter 9

ELECTROMAGNETISM

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In ancient times, it was known that, after being rubbed, amber could attract feathers and other light objects. It was also known that iron was attracted by some mineral from the province of Magnesia in Greece. The magnetic compass, an invaluable aid to navigation, is the oldest practical application of magnetism, but its origins are unknown.

In 1600, Sir William Gilbert (1540-1603), a contemporary of Kepler and Galileo and physician to Queen Elizabeth I, published his book "On the Great Magnet of the Earth", which made him famous throughout Europe. He had spent 17 years experimenting with magnetism and, to a lesser extent, with electricity. He correctly concluded that the Earth acts as a huge magnet, which explains why the needle of a magnetic compass always points toward the North. He also showed that many common materials, when rubbed, behaved like amber. From the Greek word for amber, he called such materials "electrons", from which the word electricity was later derived.

CHARGES AT REST

An amber rod that has been rubbed is said to have become (electrically) "charged", or to have acquired an (electrical) "charge". Many other substances - such as rubber, glass and most crystals - can be charged by rubbing.

If two charged amber rods are brought close together without touching, they repel one another. The same happens with two (charged) glass rods. However, if we bring close together an amber rod and a glass rod, they attract one another. Thus, there are two types of electric charges, which are called positive and negative. Matter is normally neutral because it contains equal amounts of opposite charges that cancel one another.

All matter contains huge numbers of electrically charged particles that are extremely small and close together. In an ordinary piece of matter, the balancing of positive and negative charges is so nearly perfect that it is difficult to observe any electrical force. That is why rubbing was so important in the early observations of electrical effects: it causes a separation of positive and negative charges, altering their precise balance and revealing the presence of a "net" (positive or negative) charge. Like mass, charge cannot be created nor destroyed.

In 1785, a French physicist, Charles Augustin de Coulomb, formulated the law that describes the "electrostatic" force between two stationary *net* charges:

- Its magnitude is directly proportional to the product of the two (net) charges, and inversely proportional to the square of their distance.
- Its direction is along the line connecting the two charges.
- It is a repulsive force (away from the other charge), if the two charges have the same sign; it is an attractive force (toward the other charge), if the two charges have opposite signs.

In spite of the striking similarity between Coulomb's law and Newton's law of gravitation, there are very substantial differences between the electrostatic and gravitational forces:

- The electrostatic force is enormously more powerful than the gravitational force.
- Since charge can be either positive or negative, the electrostatic force can be either attractive or repulsive. On the other hand, only attractive gravitational forces have ever been observed.
- Gravitational forces are felt even at enormous distances throughout the universe because they never cancel out. On the other hand, even powerful electrostatic forces are not felt at all, if they cancel out. Two people standing at arm's length from one another feel no force between them. Yet, if the positive and negative charges contained in their bodies were equally out of balance by just one percent, the repelling force between the two bodies would be large enough to lift a weight equal to that of the entire earth! [1]

FARADAY AND FIELDS

Michael Faraday (British, 1791-1867) was a self-taught scientist with no formal education and only a limited knowledge of mathematics. Yet, he became one of the greatest experimental physicists of all times. He was born near London of a very poor family. After he became an apprentice to a bookbinder at age 14, in the hours after work, he would read some of the books brought in for rebinding.

His great opportunity came at age 21, when a customer gave him tickets for a series of lectures by the renowned chemist Sir Humphrey Davy. After attending the lectures, Faraday expanded the careful notes he had taken, and bound them into a book, which he sent to Davy with a letter asking for a job. Davy advised him not to give up a skilled trade for something in which there was neither money nor opportunity for advancement. A few months later, however, when one of his laboratory assistants had to be dismissed, Davy remembered Faraday and offered him a job. Thus began one of the most illustrious careers in the history of science, with many important contributions first in chemistry and then in physics.

As a reward for his lifetime devotion to science, Queen Victoria granted him the use of a house, and offered him a knighthood. Faraday gratefully accepted the house, but refused the knighthood. He wanted to remain, he said, plain Mr. Faraday to the end.

The Electric Field

Faraday - who relied on mental visualization, rather than mathematical abstraction - introduced one of the most important ideas in physics, the concept of *field*, as an aid to visualize the effects of charges on other charges.

Coulomb's law carries the same action-at-a-distance implication of Newton's law of gravitation, an implication that Faraday, like many others, strongly rejected. He proposed, instead, that a charge placed at some point creates a field of influence that extends throughout space. A small test charge placed at some other point is affected by the "field value" that exists there, and not by some action-at-a-distance from the first charge.

If we have a number of charges at various points, they create a single field that represents the combined effect of all the charges. By definition, the electric field at any point is the force per *positive* unit charge. The force acting on a charge at that point is then the value of the charge times the electric field.

As proposed by Faraday and illustrated by the two examples in **Figure 9.1**, an electric field can be depicted by drawing "field lines", or "lines of force". Where the lines of forces are more concentrated, the forces are stronger. As charges change or move, the whole pattern of lines of forces changes accordingly.

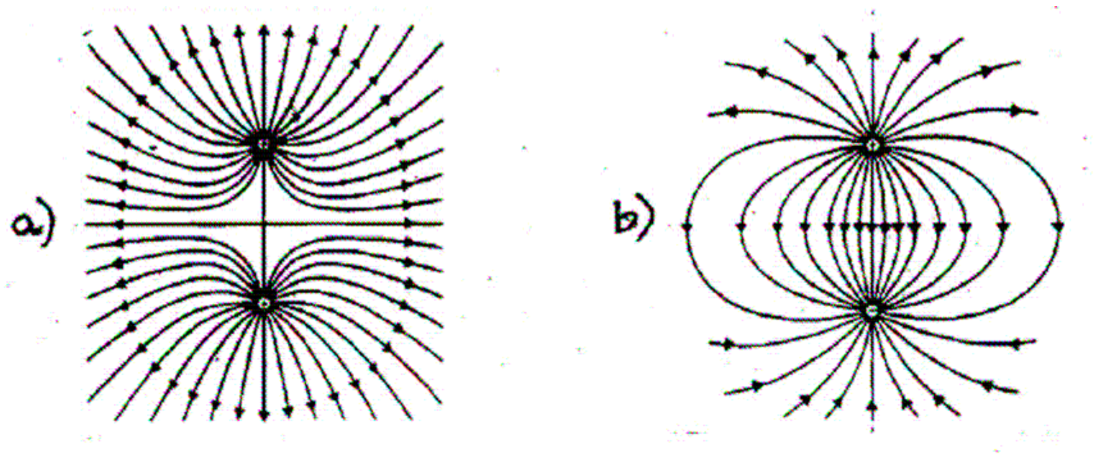

Figure 9.1 - Two examples of electric fields created by two equal charges.

In a), both charges are positive; in b), the upper charge is positive; the lower is negative. A small positive test charge placed at any point in a field will be impelled in the direction of the field line passing through that point. (The test charge is assumed to be small enough not to alter the pre-existing field.) The field varies in value and direction from point to point.

The Magnetic Field

Magnetic forces were first observed in connection with natural magnets. Magnets, like the familiar horseshoe magnet, have two end regions, called the "poles", where the magnetic forces are strongest. The two poles of a magnet are not alike. If a magnet is suspended by a thread, it will align itself with the earth's magnetic field, one pole pointing to the North, the other to the South. Two like poles (both north or both south) always repel one another, whereas opposite poles always attract one another.

The influence exerted by a magnet can also be described in terms of a "field" in the surrounding space. This magnetic field can be depicted by means of field lines, or lines of force, as illustrated in **Figure 9.2**.

To explain electric and magnetic effects, even gravity, Faraday used mental pictures of lines of forces reaching out through empty space and interacting with one another. He viewed atoms not as tiny lumps of solid matter, but as centers of concentration of forces.

MORE ABOUT THE ATOM

It will be easier to discuss the discoveries in electromagnetism that unfolded in the 1700's and 1800's, if we take now a peek at the internal structure of the atom, which was not discovered until the late 1800's and early 1900's.

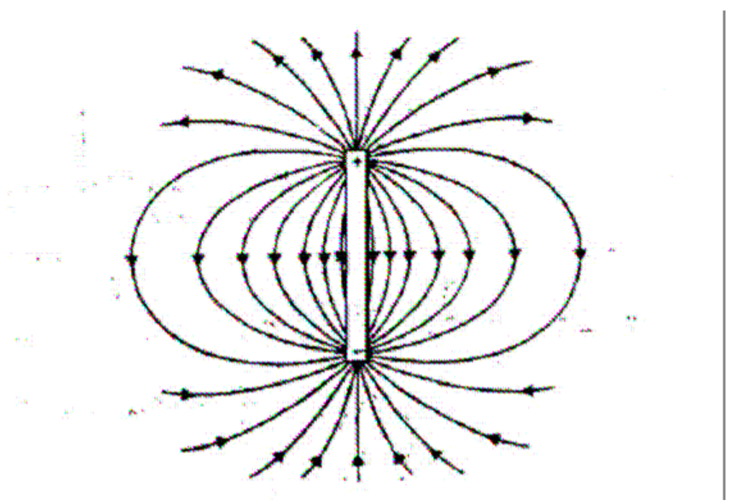

Figure 9.2 - Magnetic field due to a bar magnet

A small test magnet placed at any point in the magnetic field created by the bar magnet above will orient itself in the direction of the field line passing through that point.

In a familiar experiment, iron filings scattered around the bar magnet on a horizontal plane will arrange themselves in the pattern of the field lines depicted above.

In the classical atomic theory of matter, the atom was the ultimate indivisible particle. Actually, it has a complex internal structure. For the time being, it will be helpful to view the atom as if it were a tiny planetary system with a positively charged nucleus around which orbit a number of much lighter particles, called "electrons", all with identical negative charges. The positive charge of the nucleus always equals the combined negative charge of all its orbiting electrons, thus making the atom neutral (zero net charge).

Between the nucleus and an electron, there are both gravitational and electrical forces of attraction. The electrical force, however, is a billion billion billion billion times larger than the gravitational force. So dominant at the cosmic scale, the gravitational force is totally dwarfed by the electrical force at the atomic scale.

"The force that holds the atoms together, and the chemical forces that hold molecules together, are really electrical forces acting in regions where the balance [between positive and negative charges] is not perfect, or where the distances are very small."[2] Within a sample of matter, atoms are held together by electrical bonds. Several types of such bonds can be formed, depending on the nature of the atoms involved. In materials called "insulators", all the electrons are restrained from straying from their parent nuclei.

In materials called "conductors", instead, one or more "free electrons" from each atom are able to move about, whereas the remaining electrons are kept bonded to their parent nuclei. The positive nuclei and their captive electrons are fixed in a 3-dimensional grid.

The "free electrons" are repelled by surrounding negative charges; at the same time, they are attracted by the surrounding positive nuclei. As a result, moving in all directions, they experience many collisions, almost continuously changing direction.

CHARGES IN MOTION

Electric Current

By definition, any motion of net charge constitutes an electric "current". Of particular interest is the flow of a current through a metal wire. The current is defined as the amount of charge that passes through the cross section of the wire in a unit time. A unit of measure for current is the familiar "ampere" or "amp", named after the French physicist Andre-Marie Ampere (1775-1836). One ampere of current corresponds to the flow of about ten billion billion free electrons per second through the cross section of the wire.

An external source of energy is required to maintain a net flow of free electrons; it is called a source of "EMF" or "electromotive force". It performs a function analogous to that of a mechanical pump in a closed loop of water pipes. The operation of the pump can be characterized by the volume of water it can displace per unit time (whose electrical counterpart is the electric current), and by the pressure differential the pump can establish between its inlet and outlet. The electrical counterpart of the latter is called "voltage", which is measured in "volts", named after the Italian physicist Alessandro Volta (1745-1820).

In the presence of a source of EMF, an electric field is established along the wire affecting the motion of the free electrons. A consistent drift is now superimposed on their random motion. In spite of the many collisions and resulting changes in direction, more electrons cross in one direction than in the other, and a net current flows through the wire. Because of all the many collisions, part of the energy supplied by the source of EMF is dissipated in the form of heat.

The most common sources of EMF are batteries and generators. The battery was invented in 1800 by Alessandro Volta. It remained the main source of current until the first practical electric generator was built in the late 1860's.

Magnetic Effects of Currents

After the invention of the battery, the availability of a source of continuous current led to important discoveries. A major turning point occurred in 1820, when a Danish physicist, Hans Christian Oersted, announced that electric currents have *magnetic* effects. He made this discovery during a class demonstration to his students when, by accident, he placed a wire that carried current near a magnetic compass, and was surprised to see the needle swing to a direction perpendicular to the wire.

Here was an unprecedented case of magnetism without a magnet! What makes the discovery all the more intriguing is that a stationary charge, however large, has no effect on a magnetic needle. A charge must be *moving* in order to create a magnetic field. The larger the charge, and the faster its motion, the stronger the magnetic field it creates.

After Oersted's discovery, the magnetic effects of an electric current were studied by Ampere and others. (By the age of 12, Ampere had mastered all the mathematics then known.)

As an example, **Figure 9.3** shows the magnetic field that is produced near the middle of a long straight wire carrying current. At any point, it is proportional to the current, and inversely proportional to the perpendicular distance to the wire.

Induced Currents

When it became known that an electric current produces magnetism, it seemed natural to expect that magnetism, in turn, should produce a current somehow. It would have been of enormous practical importance to find a way of producing a current other than by the use of a battery.

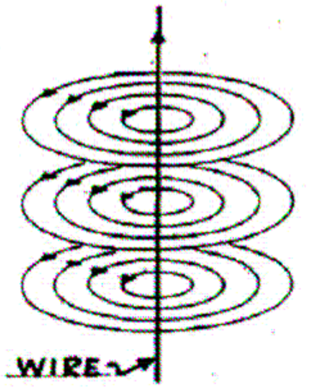

Figure 9.3 - Magnetic field lines due to a current through a straight wire

A magnetic field coils itself around a wire-carrying current, as shown above. For a circuit of a different shape, for instance, a circular loop, the magnetic lines of force will coil around the wire in a doughnut-like pattern.

If the vertical wire above goes through a perpendicular plane with iron filings scattered on it, they will arrange themselves along the lines of force.

Faraday worked on and off for 10 years trying to prove that magnetism could induce a current. He finally succeeded in 1831.The underlying principle of Faraday's discovery can be stated qualitatively as follows: *a changing magnetic field produces a changing electric field.* The electric field can be produced not only along a conducting wire, where it can cause a flow of current, but also in empty space, even in the absence of wires and charges.

Before, we saw that a charge will induce a magnetic field, *but only if it is moving*. Now, we see that a magnetic field will induce a current, *but only if it is changing*.

When Faraday first announced his discovery, he was asked "What is the use of it?" Faraday replied: "What is the use of a new-born baby?" That baby grew to create our modern electric power industry with its dams, power plants, transformers, miles and miles of high-tension wires etc.

MAXWELL AND ELECTROMAGNETIC RADIATION

James Clerk Maxwell (1831-1879) ranks alongside Newton and Einstein for the fundamental nature of his contributions. He is best known for his brilliant mathematical theory of electromagnetic radiation.

The circumstances of Maxwell's life were quite different from those of Faraday's. He was born in Edinburgh, Scotland, the son of a lawyer. When he was only 8, his mother died at 48 of abdominal cancer, the very disease that would claim his own life at exactly the same age. In 1854, he obtained a mathematics degree from Trinity College in Cambridge.

In 1860, at the age of 29, he was appointed to the professorship of natural philosophy (as physics was still called) at King's College in London. During the next five years, he developed his theory of electromagnetic radiation. In 1865, he retired to his family estate, devoting most of his energies to writing his "Treatise on Electricity and Magnetism", which was published in 1873. In the preface, he stated that his major task was to put Faraday's intuitive ideas about fields into mathematical form.

When Maxwell died in 1879, unlike Newton, he received no public honors, and was buried quietly in a small churchyard. Although his theory of electromagnetic radiation "remains for all time one of the greatest triumphs of human intellectual endeavor", he is still unknown to many people.

Maxwell's Equations

Maxwell wrote a number of equations to state in mathematical form what was known at the time about electricity and magnetism. In overly simplified fashion, we can summarize it as follows:

- Electric charges, which may be positive or negative, create an electric field.
- A current (a charge in motion) produces a magnetic field.
- A changing magnetic field induces a changing electric field.

Could a changing electric field, in turn, induce a changing magnetic field? Maxwell theorized that it could, and added accordingly one more term to his equations. Maxwell's modified equations predicted that a changing current (a charge in accelerated motion) initiates the propagation of an electromagnetic wave. The process involved can be summarized, *approximately*, as follows:

- At a transmitting source, a changing current induces a changing magnetic field.
- A changing *magnetic* field induces a changing *electric* field.
- Conversely, a changing *electric* field induces a changing *magnetic* field, which then induces a changing *electric* field, and so on.

The electric and magnetic fields work their way through space - "pushing" each other along. As a result, an electromagnetic wave propagates through space, and is capable of inducing a current at some distant receiver, concluding a chain of events initiated by the changing current at the transmitting source.

Electromagnetic radiation is produced whenever a charge is in accelerated motion (i.e., its speed and/or direction changes). A charge that is oscillating back and forth, for instance, or moving along some closed loop, radiates electromagnetic energy.

Let us assume that a changing current has set in motion the propagation of an electromagnetic wave. If the current were to stop flowing, the waves initially created would continue to spread. The electromagnetic field at some point in space depends only on the field in the *immediate* neighborhood

If the current at the transmitter alternates continuously in sinusoidal fashion, it generates a continuous train of electric and magnetic waves. The waves represent changing values of a magnetic and an electric field propagating in some direction. At any point, the electric field and the magnetic field are perpendicular to one another and to the direction of propagation.

From his equations, Maxwell was able to calculate a propagation speed for electromagnetic waves. He found that it agreed very closely with the speed of light, which led him to conclude that light itself is an electromagnetic phenomenon.

Electromagnetic radiation appears in a wide variety of forms, which are all electromagnetic waves of different frequencies, all traveling in free space at the speed of light. They include, in increasing order of frequency, radio- and TV-broadcast waves, microwaves, radar waves, infrared light, visible light, ultraviolet light, X-rays, and gamma rays.

What we call (visible) light consists of electromagnetic waves whose frequencies range between 500 million million cycles per second for red light, and 1000 million million cycles per second for violet light. The corresponding wavelengths are 0.00008 cm. for red light, and 0.00004 cm. for violet light. Note that red light and violet light, for instance, differ only in frequency (or wavelength): color is something that happens in our minds.

As the frequencies of electromagnetic waves go higher and higher, to one million million million million cycles per second and more, the associated wave lengths become shorter and shorter[4], down to one thousand-million-millionth of a centimeter and less!

To understand how such very high frequencies (and very short wavelengths) can be generated, we have to look to the very rapid motions of

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[4] You may remember that the speed of wave propagation is equal to wavelength x frequency. Since all electromagnetic waves travel in free space at the same speed, the lower their wavelength, the higher their frequency, and vice versa.

charges within atoms, or even within their nuclei.

Experimental Verification of Maxwell's Theory

It was not until about 1887, eight years after Maxwell's death, that the German physicist Heinrich Hertz announced that he had been able to produce electromagnetic waves of the type predicted by Maxwell. Between 1885 and 1889, he generated electromagnetic waves in the laboratory, and studied their behavior. He confirmed experimentally that their speed is equal to that of light, and that they behave just as light does, except that they are not visible. For instance, they can be reflected as well as refracted. Light was indeed a special case of electromagnetic radiation.

Electromagnetic waves, which can travel great distances, can be used to transmit information (send signals), if they are modified in some fashion. One way is to transmit shorter and longer bursts in some telegraphy code of dots and dashes.

In 1901, the Italian inventor Guglielmo Marconi succeeded in receiving signals transmitted by means of electromagnetic waves across the Atlantic Ocean. Signals for the letter s in Morse telegraphy code (three dots) travelled a distance of 2,000 miles from England to Newfoundland, in Canada.

This achievement created an enormous international sensation, and launched the development of radio communications, radio and TV broadcasting, radar etc., all born from Maxwell's equations.