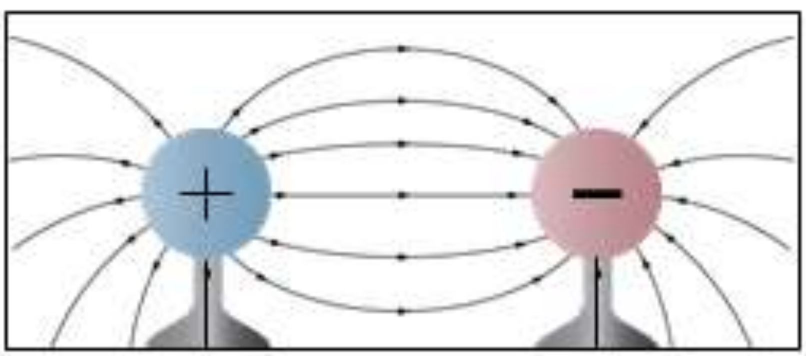
Fundamental of Electricity and Electronics



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Introduction to Electricity and Electronics

This chapter addresses the fundamental concepts that are the building blocks for advanced electrical knowledge and practical troubleshooting. Some of the questions addressed are: How does energy travel through a copper wire and through space? What is electric current, electromotive force, and what makes a landing light turn on or a hydraulic pump motor run? Each of these questions requires an understanding of many basic principles. By adding one basic idea on top of other basic ideas, it becomes possible to answer most of the interesting and practical questions about electricity or electronics.

Our understanding of electrical current must begin with the nature of matter. All matter is composed of molecules. All molecules are made up of atoms, which are themselves made up of electrons, protons, and neutrons.

General Composition of Matter

Matter

Matter can be defined as anything that has mass and has volume and is the substance of which physical objects are composed. Essentially, it is anything that can be touched. Mass is the amount of matter in a given object. Typically, the more matter there is in an object the more mass it will have. Weight is an indirect method of determining mass but not the same. The difference between mass and weight is that weight is determined by how much something or the fixed mass is pulled by gravity. Categories of matter are ordered by molecular activity. The four categories or states are: solids, liquids, gases, and plasma. For the purposes of the aircraft technician, only solids, liquids, and gases are considered.

Element

An element is a substance that cannot be reduced to a simpler form by chemical means. Iron, gold, silver, copper, and oxygen are examples of elements. Beyond this point of reduction, the element ceases to be what it is.

Compound

A compound is a chemical combination of two or more elements. Water is one of the most common compounds and is made up of two hydrogen atoms and one oxygen atom.

The Molecule

The smallest particle of matter that can exist and still retain its identity, such as water (H_2O), is called a molecule. A molecule of water is illustrated in Figure 10-1. Substances composed of only one type of atom are called elements. But most substances occur in nature as compounds, that is, combinations of two or more types of atoms. It would no longer retain the characteristics of water if it were compounded of one atom of hydrogen and two atoms of oxygen. If a drop of water is divided in two and then divided again and again until it cannot be divided any longer, it will still be water.

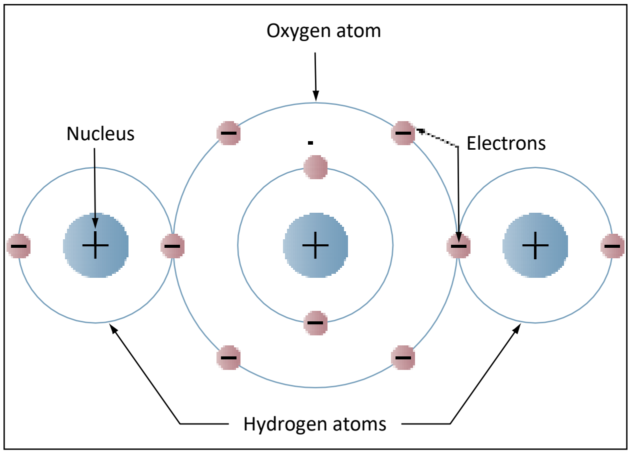


Figure 10-1. A water molecule.

The Atom

The atom is considered to be the most basic building block of all matter. Atoms are composed of three sub-atomic particles. These three sub-atomic particles are: protons, neutrons, and electrons. These three particles will determine the properties of the specific atoms. Elements are substances composed of the same atoms with specific properties. Oxygen is an example of this. The main property that defines each element is the number of neutrons, protons, and electrons. Hydrogen and helium are examples of elements. Both of these elements have neutrons, protons, and electrons but differ in the number of those items. This difference alone accounts for the variations in chemical and physical properties of these two different elements. There are over a 100 known elements in the periodic table, and they are categorized according to their properties on that table. The kinetic theory of matter also states that the particles that make up the matter are always moving. Thermal expansion is considered in the kinetic theory and explains why matter contracts when it is cool and expands when it is hot, with the exception of water/ice.

Electrons, Protons, and Neutrons

At the center of the atom is the nucleus, which contains the protons and neutrons. The protons are positively charged particles, and the neutrons are a neutrally charged particle. The neutron has approximately the same mass as the proton. The third particle of the atom is the electron that is a negatively charged particle with a very small mass compared to the proton. The proton's mass is approximately 1,837 times greater than the electron. Due to the proton and the neutron location in the central portion of the atom (nucleus) and the electron's position at the distant periphery of the atom, it is the electron that undergoes the change during chemical reactions. Since a proton weighs approximately 1,845 times as much as an electron, the number of protons and neutrons in its nucleus determines the overall weight of an atom. The weight of an electron is not considered in determining the weight of an atom. Indeed, the nature of electricity cannot be defined clearly because it is not certain whether the electron is a negative charge with no mass (weight) or a particle of matter with a negative charge.

Hydrogen represents the simplest form of an atom, as shown in Figure 10-2. At the nucleus of the hydrogen atom is one proton and at the outer shell is one orbiting electron. At a more complex level is the oxygen atom, as shown in Figure 10-3, which has eight electrons in two shells orbiting the nucleus with eight protons and eight neutrons. When the total positive charge of the protons in the nucleus equals the total negative charge of the electrons in orbit around the nucleus, the atom is said to have a neutral charge.

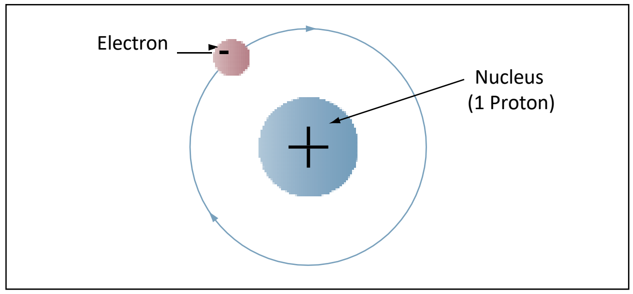


Figure 10-2. Hydrogen atom.

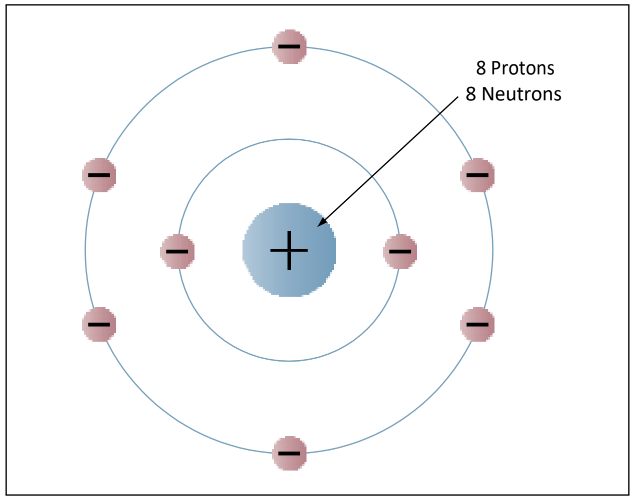


Figure 10-3. Oxygen atom.

Electron Shells and Energy Levels

Electrons require a certain amount of energy to stay in an orbit. This particular quantity is called the electron's energy level. By its motion alone, the electron possesses kinetic energy, while the electron's position in orbit determines its potential energy. The total energy of an electron is the main factor, which determines the radius of the electrons orbit.

Electrons of an atom will appear only at certain definite energy levels (shells). The spacing between energy levels is such that when the chemical properties of the various elements are cataloged, it is convenient to group several closely spaced permissible energy levels together into electron shells. The maximum number of electrons that can be contained in any shell or sub-shell is the same for all atoms and is defined as Electron Capacity = $2n^2$. In this equation n represents the energy level in question. The first shell can only contain two electrons; the second shell can only contain eight electrons; the third, 18 and so on until we reach the seventh shell for the heaviest atoms, which have six energy levels. Because the innermost shell is the lowest energy level, the shell begins to fill up from the shell closest to the nucleus and fill outward as the atomic number of the element increases. However, an energy level does not need to be completely filled before electrons begin to fill the next level. The Periodic Table of Elements should be checked to determine an element's electron configuration.

Valence Electrons

Valence is the number of chemical bonds an atom can form. Valence electrons are electrons that can participate in chemical bonds with other atoms. The number of electrons in the outermost shell of the atom is the determining factor in its valence. Therefore, the electrons contained in this shell are called valence electrons.

Ions

Ionization is the process by which an atom loses or gains electrons. Dislodging an electron from an atom will cause the atom to become positively charged. This net positively charged atom is called a positive ion or a cation. An atom that has gained an extra number of electrons is negatively charged and is called a negative ion or an anion. When atoms are neutral, the positively charged proton and the negatively charged electron are equal.

Free Electrons

Valence electrons are found drifting midway between two nuclei. Some electrons are more tightly bound to the nucleus of their atom than others and are positioned in a shell or sphere closer to the nucleus, while others are more loosely bound and orbit at a greater distance from the nucleus. These outermost electrons are called "free" electrons because they can be easily dislodged from the positive attraction of the protons in the nucleus. Once freed from the atom, the electron can then travel from atom to atom, becoming the flow of electrons commonly called current in a practical electrical circuit.

Electron Movement

The valence of an atom determines its ability to gain or lose an electron, which ultimately determines the chemical and electrical properties of the atom. These properties can be categorized as being a conductor, semiconductor or insulator, depending on the ability of the material to produce free electrons. When a material has a large number of free electrons available, a greater current can be conducted in the material.

Conductors

Elements such as gold, copper and silver possess many free electrons and make good conductors. The atoms in these materials have a few loosely bound electrons in their outer orbits. Energy in the form of heat can cause these electrons in the outer orbit to break loose and drift throughout the material. Copper and silver have one electron in their outer orbits. At room temperature, a piece of silver wire will have billions of free electrons.

Insulators

These are materials that do not conduct electrical current very well or not at all. Good examples of these are: glass, ceramic, and plastic. Under normal conditions, atoms in these materials do not produce free electrons. The absence of the free electrons means that electrical current cannot be conducted through the material. Only when the material is in an extremely strong electrical field will the outer electrons be dislodged. This action is called breakdown and usually causes physical damage to the insulator.

Semiconductors

This material falls in between the characteristics of conductors and insulators, in that they are not good at conducting or insulating. Silicon and germanium are the most widely used semiconductor materials. For a more detailed explanation on this topic refer to Page 10-101 in this chapter.

Metric Based Prefixes Used for Electrical Calculations

In any system of measurements, a single set of units is usually not sufficient for all the computations involved in electrical repair and maintenance. Small distances, for example, can usually be measured in inches, but larger distances are more meaningfully expressed in feet, yards, or miles. Since electrical values often vary from numbers that are a millionth part of a basic unit of measurement to very large values, it is often necessary to use a wide range of numbers to represent the values of such units as volts, amperes, or ohms. A series of prefixes which appear with the name of the unit have been devised for the various multiples or submultiples of the basic units. There are 12 of these prefixes, which are also known as conversion factors. Four of the most commonly used prefixes used in electrical work with a short definition of each are as follows:

Mega (M) means one million (1,000,000).
Kilo (k) means one thousand (1,000).
Milli (m) means one-thousandth ($^1/_{1,000}$).
Micro (µ) means one-millionth ($^1/_{1,000,000}$).

One of the most extensively used conversion factors, kilo, can be used to explain the use of prefixes with basic units of measurement. Kilo means 1,000, and when used with volts, is expressed as kilovolt, meaning 1,000 volts. The symbol for kilo is the letter "k". Thus, 1,000 volts is one kilovolt or 1kV. Conversely, one volt would equal one-thousandth of a kV, or $^1/_{1,000}$ kV. This could also be written 0.001 kV.

Similarly, the word "milli" means one-thousandth, and thus, 1 millivolt equals one-thousandth ($^1/_{1000}$) of a volt.

Figure 10-4 contains a complete list of the multiples used to express electrical quantities, together with the prefixes and symbols used to represent each number.

Static Electricity

Electricity is often described as being either static or dynamic. The difference between the two is based simply on whether the electrons are at rest (static) or in motion (dynamic). Static electricity is a build up of an electrical charge on the surface of an object. It is considered "static" due to the fact that there is no current flowing as in AC or DC electricity. Static electricity is usually caused when non-conductive materials such as rubber, plastic or glass are rubbed together, causing a transfer of electrons, which then results in an imbalance of charges between the two materials. The fact that there is an imbalance of charges between the two materials means that the objects will exhibit an attractive or repulsive force.

Number	Prefix	Symbol
1,000,000,000,000	tera	t
1,000,000,000	giga	g
1,000,000	mega	M
1,000	kilo	k
100	hecto	h
10	deka	dk
0.1	deci	d
0.01	centi	c
0.001	milli	m
0.000001	micro	µ
0.000000001	nano	n
0.000000000001	pico	p

Figure 10-4. Prefixes and symbols for multiples of basic quantities.

Attractive and Repulsive Forces

One of the most fundamental laws of static electricity, as well as magnetics, deals with attraction and repulsion. Like charges repel each other and unlike charges attract each other. All electrons possess a negative charge and as such will repel each other. Similarly, all protons possess a positive charge and as such will repel each other. Electrons (negative) and protons (positive) are opposite in their charge and will attract each other.

For example, if two pith balls are suspended, as shown in Figure 10-5, and each ball is touched with the charged glass rod, some of the charge from the rod

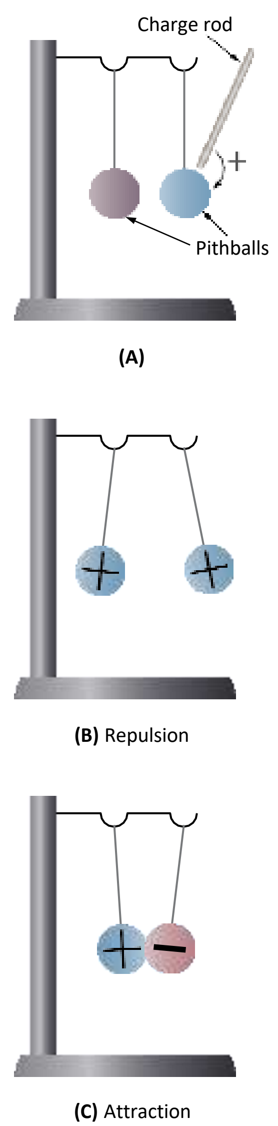


Figure 10-5. Reaction of like and unlike charges.

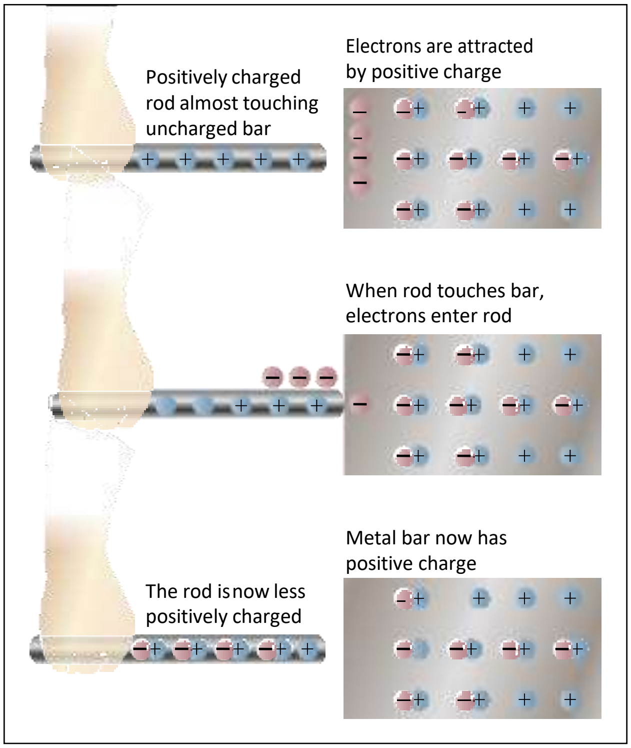


Figure 10-6. Charging by contact.

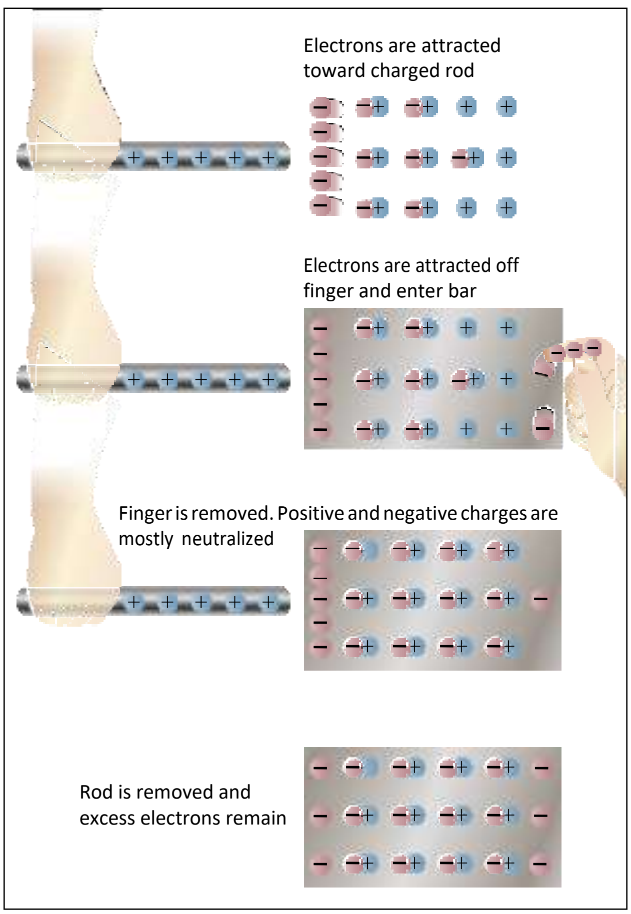


Figure 10-7. Charging a bar by induction.

is transferred to the balls. The balls now have similar charges and, consequently, repel each other as shown in part B of Figure 10-5. If a plastic rod is rubbed with fur, it becomes negatively charged and the fur is positively charged. By touching each ball with these differently charged sources, the balls obtain opposite charges and attract each other as shown in part C of Figure 10-5.

Although most objects become charged with static electricity by means of friction, a charged substance can also influence objects near it by contact. This is illustrated in Figure 10-6. If a positively charged rod touches an uncharged metal bar, it will draw electrons from the uncharged bar to the point of contact. Some electrons will enter the rod, leaving the metal bar with a deficiency of electrons (positively charged) and making the rod less positive than it was or, perhaps, even neutralizing its charge completely.

A method of charging a metal bar by induction is demonstrated in Figure 10-7. A positively charged rod is brought near, but does not touch, an uncharged metal bar. Electrons in the metal bar are attracted to the end of the bar nearest the positively charged rod, leaving a deficiency of electrons at the opposite end of the bar. If this positively charged end is touched by a neutral object, electrons will flow into the metal bar and neutralize the charge. The metal bar is left with an overall excess of electrons.

Electrostatic Field

A field of force exists around a charged body. This field is an electrostatic field (sometimes called a dielectric field) and is represented by lines extending in all directions from the charged body and terminating where there is an equal and opposite charge.

To explain the action of an electrostatic field, lines are used to represent the direction and intensity of the electric field of force. As illustrated in Figure 10-8, the intensity of the field is indicated by the number of lines per unit area, and the direction is shown by arrowheads

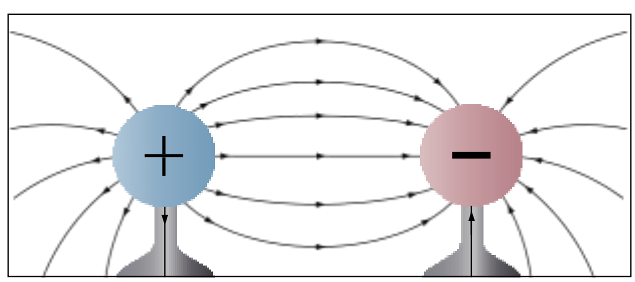


Figure 10-8. Direction of electric field around positive and negative charges.

on the lines pointing in the direction in which a small test charge would move or tend to move if acted upon by the field of force.

Either a positive or negative test charge can be used, but it has been arbitrarily agreed that a small positive charge will always be used in determining the direction of the field. Thus, the direction of the field around a positive charge is always away from the charge, as shown in Figure 10-8, because a positive test charge would be repelled. On the other hand, the direction of the lines about a negative charge is toward the charge, since a positive test charge is attracted toward it.

Figure 10-9 illustrates the field around bodies having like charges. Positive charges are shown, but regardless of the type of charge, the lines of force would repel each other if the charges were alike. The lines terminate on material objects and always extend from a positive charge to a negative charge. These lines are imaginary lines used to show the direction a real force takes.

It is important to know how a charge is distributed on an object. Figure 10-10 shows a small metal disk on which a concentrated negative charge has been placed. By using an electrostatic detector, it can be shown that the charge is spread evenly over the entire surface of the disk. Since the metal disk provides uniform resistance everywhere on its surface, the mutual repulsion of electrons will result in an even distribution over the entire surface.

Another example, shown in Figure 10-11, is the charge on a hollow sphere. Although the sphere is made of conducting material, the charge is evenly distributed over the outside surface. The inner surface is completely neutral. This phenomenon is used to safeguard operating personnel of the large Van de Graaff static generators used for atom smashing. The safest area for the operators is inside the large sphere, where millions of volts are being generated.

The distribution of the charge on an irregularly shaped object differs from that on a regularly shaped object. Figure 10-12 shows that the charge on such objects is not evenly distributed. The greatest charge is at the points, or areas of sharpest curvature, of the objects.

ESD Considerations

One of the most frequent causes of damage to a solid-state component or integrated circuits is the electro-

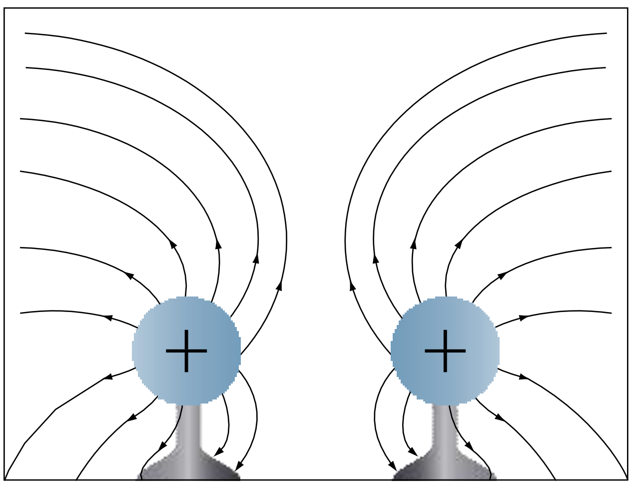


Figure 10-9. Field around two positively charged bodies.

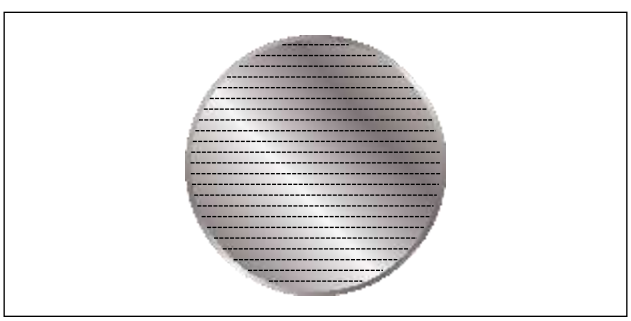


Figure 10-10. Even distribution of charge on metal disk.

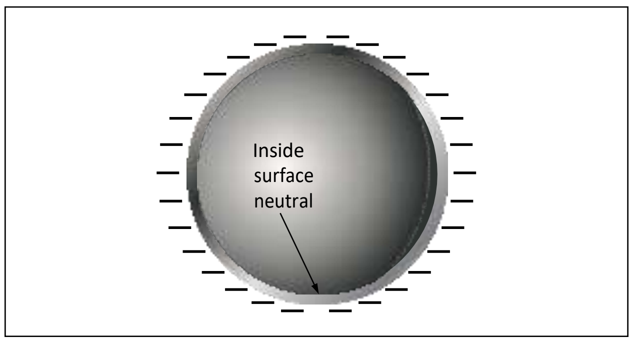


Figure10-11. Charge on a hollow sphere.

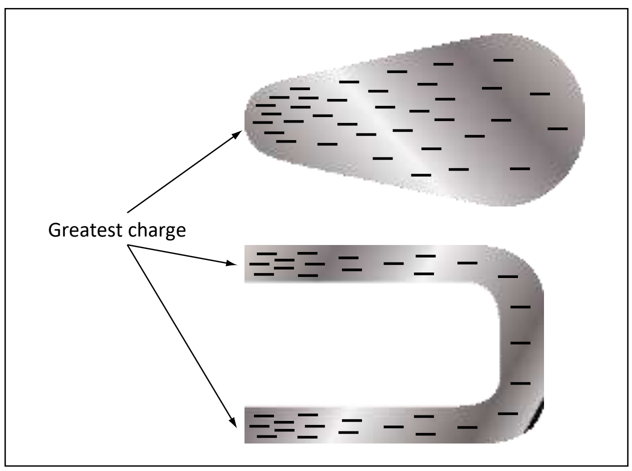


Figure 10-12. Charge on irregularly shaped objects.

static discharge (ESD) from the human body when one of these devices is handled. Careless handling of line replaceable units (LRUs), circuit cards, and discrete components can cause unnecessarily time consuming and expensive repairs. This damage can occur if a technician touches the mating pins for a card or box. Other sources for ESD can be the top of a toolbox that is covered with a carpet. Damage can be avoided by discharging the static electricity from your body by touching the chassis of the removed box, by wearing a grounding wrist strap, and exercising good professional handling of the components in the aircraft. This can include placing protective caps over open connectors and not placing an ESD sensitive component in an environment that will cause damage. Parts that are ESD sensitive are typically shipped in bags specially designed to protect components from electrostatic damage.

Other precautions that should be taken with working with electronic components are:

1. Always connect a ground between test equipment and circuit before attempting to inject or monitor a signal.
2. Ensure test voltages do not exceed maximum allowable voltage for the circuit components and transistors.
3. Ohmmeter ranges that require a current of more than one milliampere in the test circuit should not be used for testing transistors.
4. The heat applied to a diode or transistor, when soldering is required, should be kept to a minimum by using low-wattage soldering irons and heat-sinks.
5. Do not pry components off of a circuit board.
6. Power must be removed from a circuit before replacing a component.
7. When using test probes on equipment and the space between the test points is very close, keep the exposed portion of the leads as short as possible to prevent shorting.

Magnetism

Magnetism is defined as the property of an object to attract certain metallic substances. In general, these substances are ferrous materials; that is, materials composed of iron or iron alloys, such as soft iron, steel, and alnico. These materials, sometimes called magnetic materials, today include at least three nonferrous materials: nickel, cobalt, and gadolinium, which are magnetic to a limited degree. All other substances are considered nonmagnetic, and a few of these nonmagnetic substances can be classified as diamagnetic since they are repelled by both poles of a magnet.

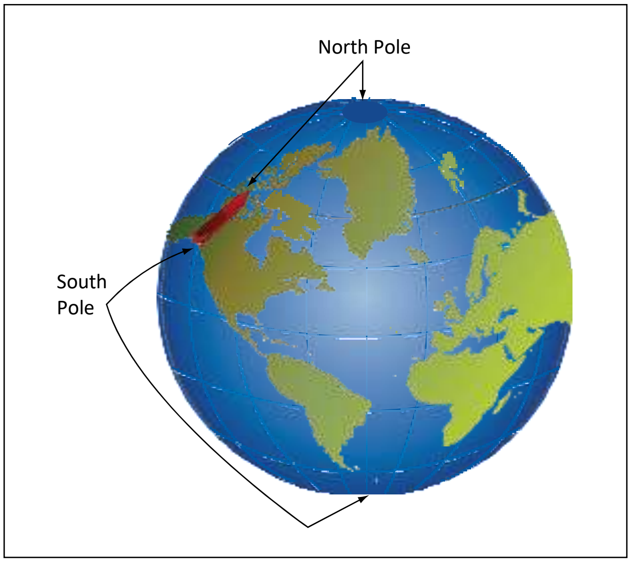


Figure 10-13. One end of magnetized strip points to the magnetic north pole.

Magnetism is an invisible force, the ultimate nature of which has not been fully determined. It can best be described by the effects it produces. Examination of a simple bar magnet similar to that illustrated in Figure 10-13 discloses some basic characteristics of all magnets. If the magnet is suspended to swing freely, it will align itself with the earth's magnetic poles. One end is labeled "N," meaning the north seeking end or pole of the magnet. If the "N" end of a compass or magnet is referred to as north seeking rather than north, there will be no conflict in referring to the pole it seeks, which is the north magnetic pole. The opposite end of the magnet, marked "S" is the south seeking end and points to the south magnetic pole. Since the earth is a giant magnet, its poles attract the ends of the magnet. These poles are not located at the geographic poles.

The somewhat mysterious and completely invisible force of a magnet depends on a magnetic field that surrounds the magnet as illustrated in Figure 10-14. This field always exists between the poles of a magnet, and will arrange itself to conform to the shape of any magnet.

The theory that explains the action of a magnet holds that each molecule making up the iron bar is itself a tiny magnet, with both north and south poles as illustrated in Figure 10-15A. These molecular magnets each possess a magnetic field, but in an unmagnetized state,

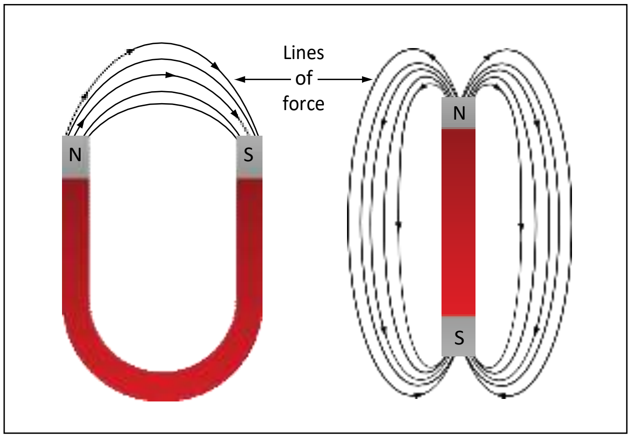


Figure 10-14. Magnetic field around magnets.

the molecules are arranged at random throughout the iron bar. If a magnetizing force, such as stroking with a lodestone, is applied to the unmagnetized bar, the molecular magnets rearrange themselves in line with the magnetic field of the lodestone, with all north ends of the magnets pointing in one direction and all south ends in the opposite direction. This is illustrated in Figure 10-15B. In such a configuration, the magnetic fields of the magnets combine to produce the total field of the magnetized bar.

When handling a magnet, avoid applying direct heat, or hammering or dropping it. Heating or sudden shock will cause misalignment of the molecules, causing the strength of a magnet to decrease. When a magnet is to be stored, devices known as "keeper bars" are installed to provide an easy path for flux lines from one pole to the other. This promotes the retention of the molecules in their north-south alignment.

The presence of the magnetic force or field around a magnet can best be demonstrated by the experiment illustrated in Figure 10-16. A sheet of transparent material, such as glass or Lucite™, is placed over a bar magnet and iron filings are sprinkled slowly on this transparent shield. If the glass or Lucite is tapped lightly, the iron filings will arrange themselves in a definite pattern around the bar, forming a series of lines from the north to south end of the bar to indicate the pattern of the magnetic field.

As shown, the field of a magnet is made up of many individual forces that appear as lines in the iron filing demonstration. Although they are not "lines" in the ordinary sense, this word is used to describe the individual nature of the separate forces making up the entire magnetic field. These lines of force are also referred to as magnetic flux.

They are separate and individual forces, since one line will never cross another; indeed, they actually repel one another. They remain parallel to one another and resemble stretched rubber bands, since they are held in place around the bar by the internal magnetizing force of the magnet.

The demonstration with iron filings further shows that the magnetic field of a magnet is concentrated at the ends of the magnet. These areas of concentrated flux are called the north and south poles of the magnet. There is a limit to the number of lines of force that can be crowded into a magnet of a given size. When a magnetizing force is applied to a piece of magnetic material, a point is reached where no more lines of force can be induced or introduced. The material is then said to be saturated.

The characteristics of the magnetic flux can be demonstrated by tracing the flux patterns of two bar magnets with like poles together, as shown in Figure 10-17. The two like poles repel one another because the lines of force will not cross each other. As the arrows on the individual lines indicate, the lines turn aside as the two like poles are brought near each other and travel in a

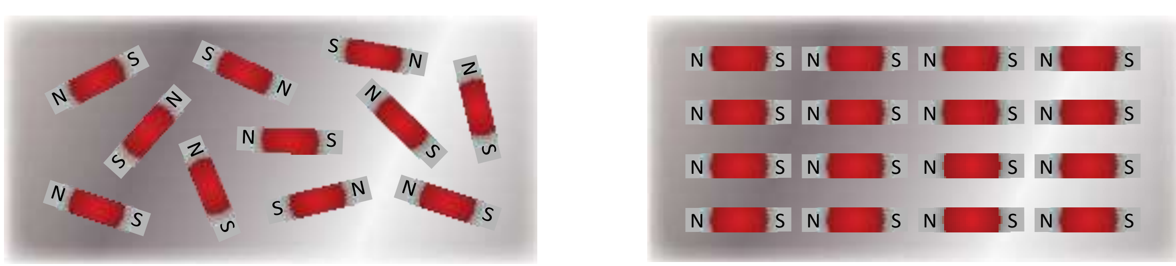


Figure 10-15. Arrangement of molecules in a piece of magnetic material.

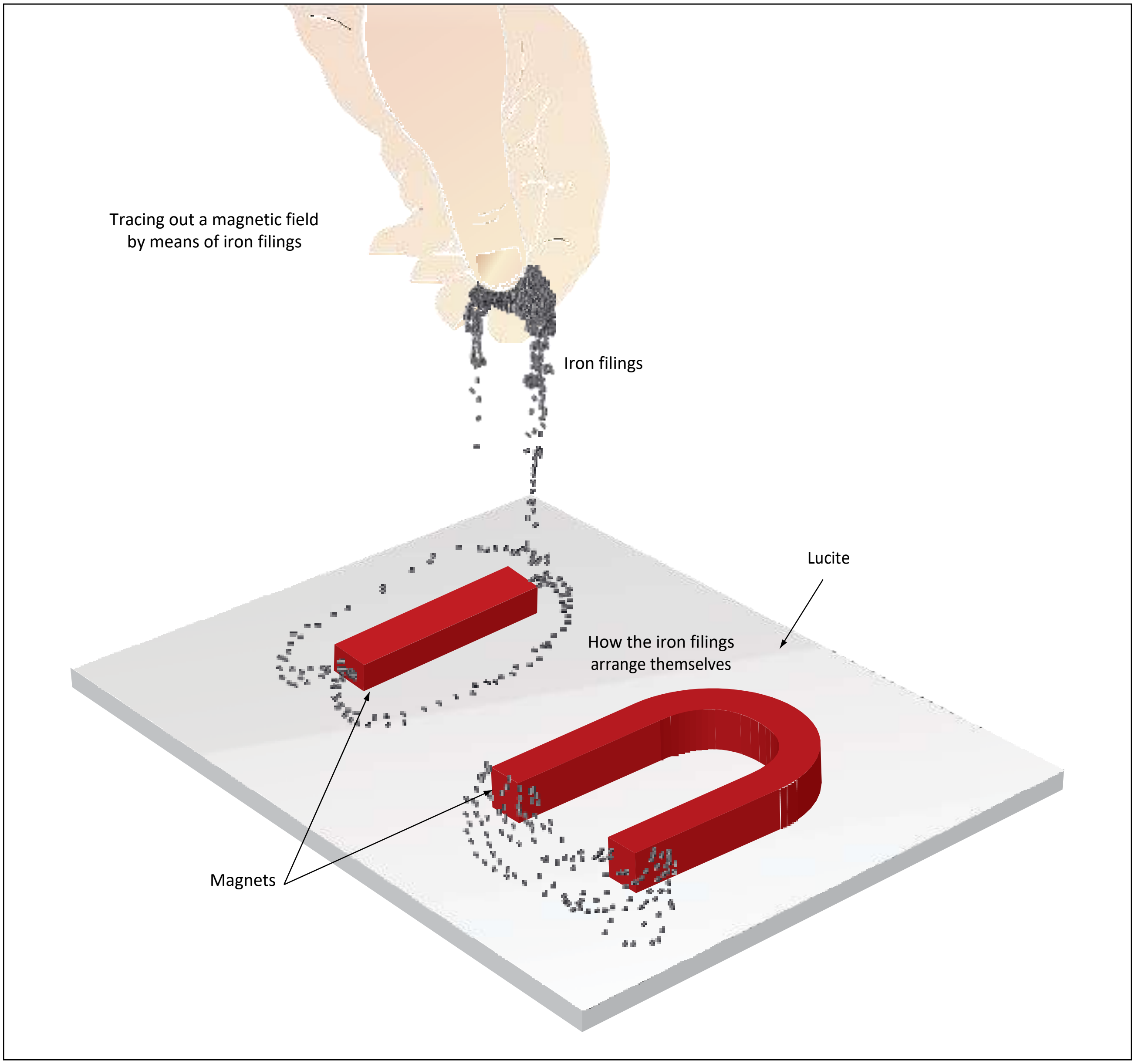


Figure 10-16. Tracing out a magnetic field with iron filings.

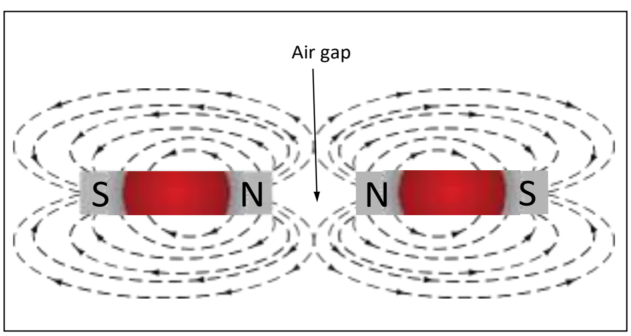


Figure 10-17. Like poles repel.

path parallel to each other. Lines moving in this manner repel each other, causing the magnets as a whole to repel each other.

By reversing the position of one of the magnets, the attraction of unlike poles can be demonstrated, as shown in Figure 10-18.

As the unlike poles are brought near each other, the lines of force rearrange their paths and most of the flux leaving the north pole of one magnet enters the south pole of the other. The tendency of lines of force to repel each other is indicated by the bulging of the flux in the air gap between the two magnets.

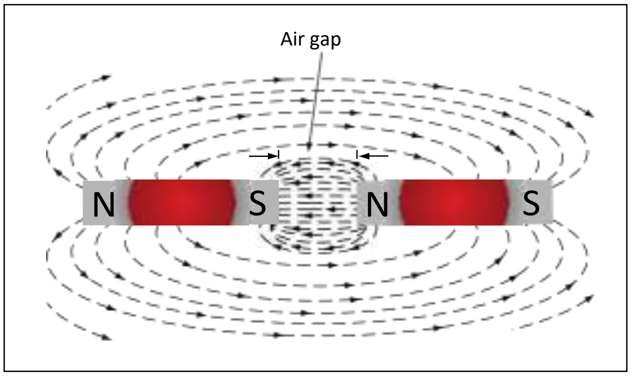


Figure 10-18. Unlike poles attract.

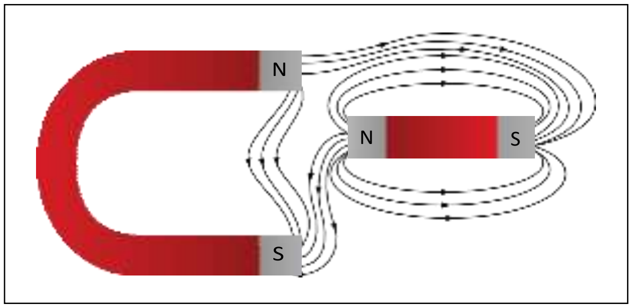


Figure 10-19. Bypassing flux lines.

To further demonstrate that lines of force will not cross one another, a bar magnet and a horseshoe magnet can be positioned to display a magnetic field similar to that of Figure 10-19. The magnetic fields of the two magnets do not combine, but are rearranged into a distorted flux pattern.

The two bar magnets may be held in the hands and the north poles brought near each other to demonstrate the force of repulsion between like poles. In a similar manner, the two south poles can demonstrate this force. The force of attraction between unlike poles can be felt by bringing a south and a north end together. These experiments are illustrated in Figure 10-20.

Figure 10-21 illustrates another characteristic of magnets. If the bar magnet is cut or broken into pieces,

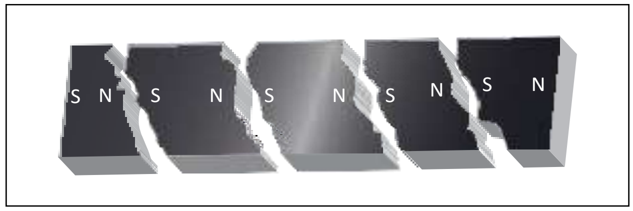


Figure 10-21. Magnetic poles in a broken magnet.

each piece immediately becomes a magnet itself, with a north and south pole. This feature supports the theory that each molecule is a magnet, since each successive division of the magnet produces still more magnets.

Since the magnetic lines of force form a continuous loop, they form a magnetic circuit. It is impossible to say where in the magnet they originate or start. Arbitrarily, it is assumed that all lines of force leave the north pole of any magnet and enter at the south pole.

There is no known insulator for magnetic flux, or lines of force, since they will pass through all materials. However, they will pass through some materials more easily than others.

Thus it is possible to shield items such as instruments from the effects of the flux by surrounding them with a material that offers an easier path for the lines of force. Figure 10-22 shows an instrument surrounded by a path of soft iron, which offers very little opposition to magnetic flux. The lines of force take the easier path, the path of greater permeability, and are guided away from the instrument.

Materials such as soft iron and other ferrous metals are said to have a high permeability, the measure of the ease with which magnetic flux can penetrate a material. The permeability scale is based on a perfect vacuum with a rating of one. Air and other nonmagnetic materials are so close to this that they are also considered to have a rating of one. The nonferrous metals with a permeability greater than one, such as nickel and cobalt, are called paramagnetic. The term

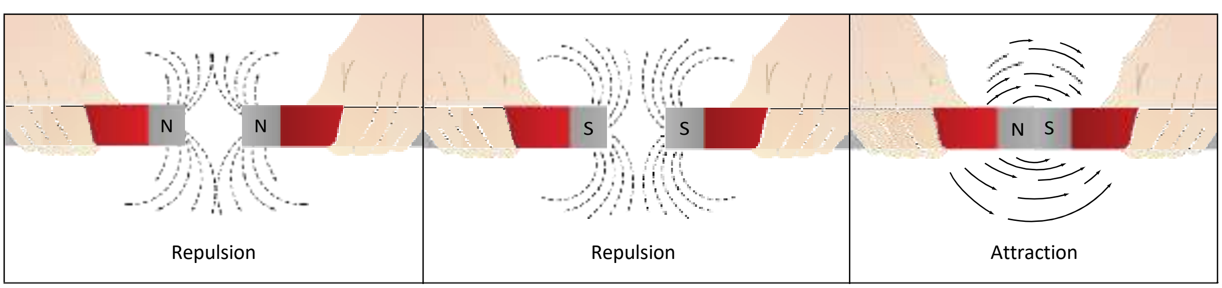


Figure 10-20. Repulsion and attraction of magnet poles.

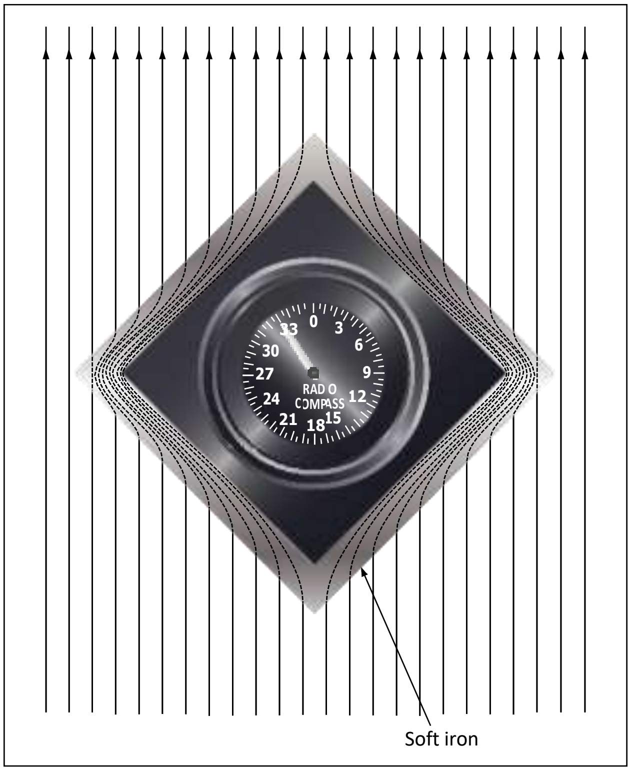


Figure 10-22. Magnetic shield.

ferromagnetic is applied to iron and its alloys, which have by far the greatest permeability. Any substance, such as bismuth, having a permeability of less than one, is considered diamagnetic.

Reluctance, the measure of opposition to the lines of force through a material, can be compared to the resistance of an electrical circuit. The reluctance of soft iron, for instance, is much lower than that of air. Figure 10-23 demonstrates that a piece of soft iron placed near the field of a magnet can distort the lines of force, which follow the path of lowest reluctance through the soft iron.

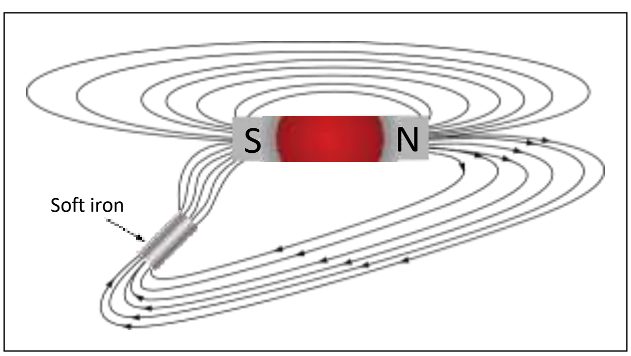


Figure 10-23. Effect of a magnetic substance in a magnetic field.

The magnetic circuit can be compared in many respects to an electrical circuit. The magnetomotive force, causing lines of force in the magnetic circuit, can be compared to the electromotive force or electrical pressure of an electrical circuit. The magnetomotive force is measured in gilberts, symbolized by the capital letter "F." The symbol for the intensity of the lines of force, or flux, is the Greek letter phi, and the unit of field intensity is the gauss. An individual line of force, called a maxwell, in an area of one square centimeter produces a field intensity of one gauss. Using reluctance rather than permeability, the law for magnetic circuits can be stated: a magnetomotive force of one gilbert will cause one maxwell, or line of force, to be set up in a material when the reluctance of the material is one.

Types of Magnets

Magnets are either natural or artificial. Since naturally occurring magnets or lodestones have no practical use, all magnets considered in this study are artificial or manmade. Artificial magnets can be further classified as permanent magnets, which retain their magnetism long after the magnetizing force has been removed, and temporary magnets, which quickly lose most of their magnetism when the external magnetizing force is removed.

Modern permanent magnets are made of special alloys that have been found through research to create increasingly better magnets. The most common categories of magnet materials are made out of Aluminum-Nickel-Cobalt (Alnicos), Strontium-Iron (Ferrites, also known as Ceramics), Neodymium-Iron-Boron (Neo magnets), and Samarium-Cobalt. Alnico, an alloy of iron, aluminum, nickel and cobalt, and is considered one of the very best. Others with excellent magnetic qualities are alloys such as Remalloy™ and Permendur™.

The ability of a magnet to hold its magnetism varies greatly with the type of metal and is known as retentivity. Magnets made of soft iron are very easily magnetized but quickly lose most of their magnetism when the external magnetizing force is removed. The small amount of magnetism remaining, called residual magnetism, is of great importance in such electrical applications as generator operation.

Horseshoe magnets are commonly manufactured in two forms. [Figure 10-24] The most common type is made from a long bar curved into a horseshoe shape, while a variation of this type consists of two bars connected by a third bar, or yoke.

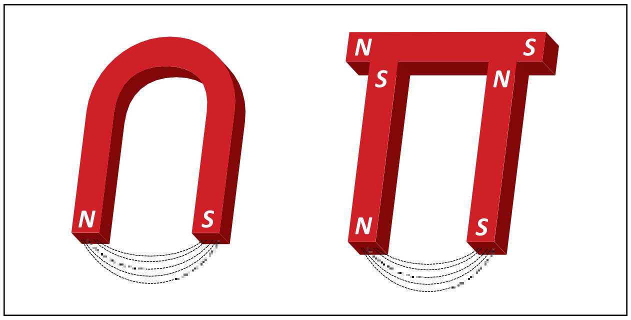


Figure 10-24. Two forms of horseshoe magnets.

Magnets can be made in many different shapes, such as balls, cylinders, or disks. One special type of magnet is the ring magnet, or Gramme ring, often used in instruments. This is a closed loop magnet, similar to the type used in transformer cores, and is the only type that has no poles.

Sometimes special applications require that the field of force lie through the thickness rather than the length of a piece of metal. Such magnets are called flat magnets and are used as pole pieces in generators and motors.

Electromagnetism

In 1820, the Danish physicist, Hans Christian Oersted, discovered that the needle of a compass brought near a current carrying conductor would be deflected. When the current flow stopped, the compass needle returned to its original position. This important discovery demonstrated a relationship between electricity and magnetism that led to the electromagnet and to many of the inventions on which modern industry is based.

Oersted discovered that the magnetic field had no connection with the conductor in which the electrons were flowing, because the conductor was made of nonmagnetic copper. The electrons moving through the wire created the magnetic field around the conductor. Since a magnetic field accompanies a charged particle, the greater the current flow, and the greater the magnetic field. Figure 10-25 illustrates the magnetic field around

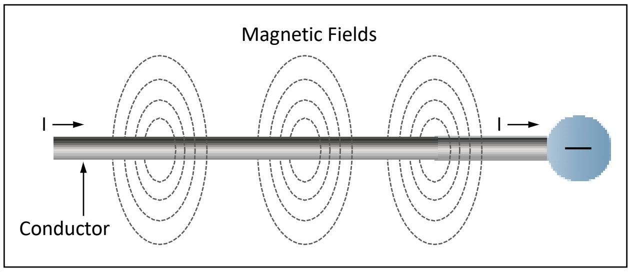


Figure 10-25. Magnetic field formed around a conductor in which current is flowing.

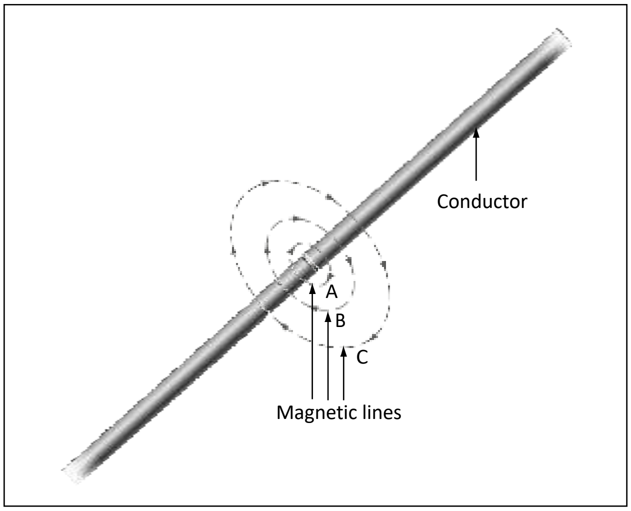


Figure 10-26. Expansion of magnetic field as current increases.

a current carrying wire. A series of concentric circles around the conductor represent the field, which if all the lines were shown would appear more as a continuous cylinder of such circles around the conductor.

As long as current flows in the conductor, the lines of force remain around it. [Figure 10-26] If a small current flows through the conductor, there will be a line of force extending out to circle A. If the current flow is increased, the line of force will increase in size to circle B, and a further increase in current will expand it to circle C. As the original line (circle) of force expands from circle A to B, a new line of force will appear at circle A. As the current flow increases, the number of circles of force increases, expanding the outer circles farther from the surface of the current carrying conductor.

If the current flow is a steady nonvarying direct current, the magnetic field remains stationary. When the current stops, the magnetic field collapses and the magnetism around the conductor disappears.

A compass needle is used to demonstrate the direction of the magnetic field around a current carrying conductor. Figure 10-27 View A shows a compass needle positioned at right angles to, and approximately one inch from, a current carrying conductor. If no current were flowing, the north seeking end of the compass needle would point toward the earth's magnetic pole. When current flows, the needle lines itself up at right angles to a radius drawn from the conductor. Since the compass needle is a small magnet, with lines of force extending from south to north inside the metal, it will turn until the direction of these lines agrees with the direction of the lines of force around the conductor. As

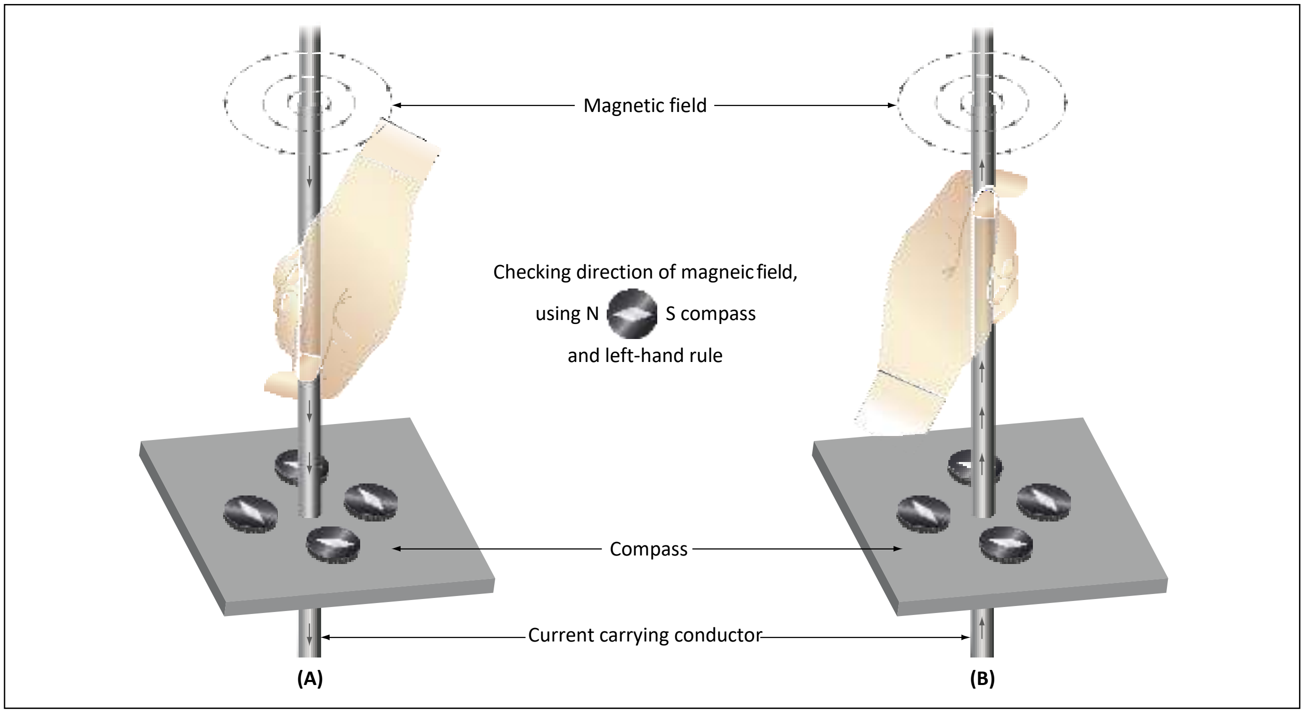


Figure 10-27. Magnetic field around a current-carrying conductor.

the compass needle is moved around the conductor, it will maintain itself in a position at right angles to the conductor, indicating that the magnetic field around a current carrying conductor is circular. As shown in View B of Figure 10-27, when the direction of current flow through the conductor is reversed, the compass needle will point in the opposite direction, indicating the magnetic field has reversed its direction.

A method used to determine the direction of the lines of force when the direction of the current flow is known, is shown in Figure 10-28. If the conductor is grasped in the left hand, with the thumb pointing in the direction of current flow, the fingers will be wrapped around the conductor in the same direction as the lines of the magnetic field. This is called the left-hand rule.

Although it has been stated that the lines of force have direction, this should not be construed to mean that the lines have motion in a circular direction around the conductor. Although the lines of force tend to act in a clockwise or counterclockwise direction, they are not revolving around the conductor.

Since current flows from negative to positive, many illustrations indicate current direction with a dot symbol on the end of the conductor when the electrons are flowing toward and a plus sign when the current is flowing away from the observer. [Figure 10-29]

When a wire is bent into a loop and an electric current flows through it, the left-hand rule remains valid. [Figure 10-30]

If the wire is coiled into two loops, many of the lines of force become large enough to include both loops. Lines of force go through the loops in the same direc-

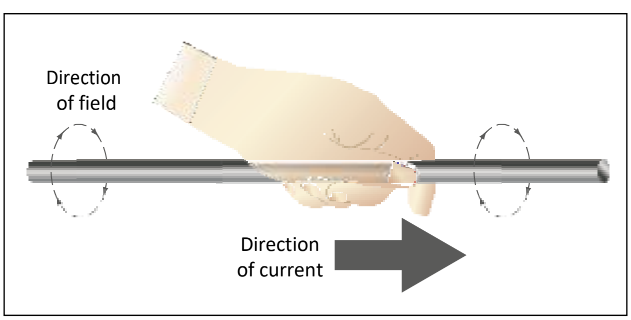


Figure 10-28. Left-hand rule.

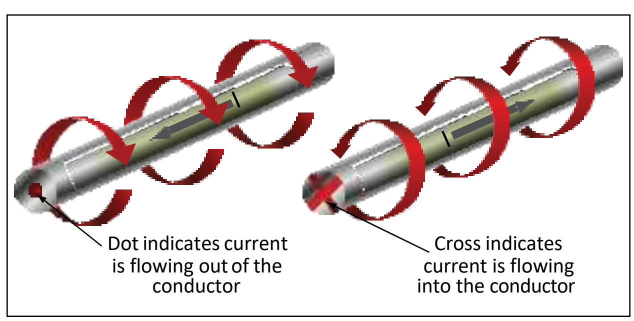


Figure 10-29. Direction of current flow in a conductor.

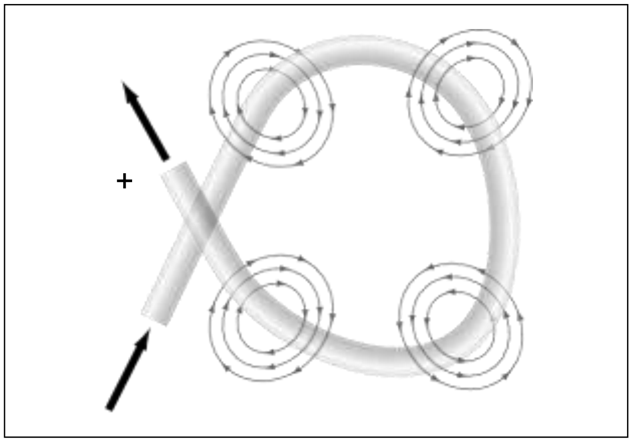


Figure 10-30. Magnetic field around a looped conductor.

tion, circle around the outside of the two coils, and come in at the opposite end. [Figure 10-31]

When a wire contains many such loops, it is called a coil. The lines of force form a pattern through all the loops, causing a high concentration of flux lines through the center of the coil. [Figure 10-32]

In a coil made from loops of a conductor, many of the lines of force are dissipated between the loops of the coil. By placing a soft iron bar inside the coil, the lines of force will be concentrated in the center of the coil, since soft iron has a greater permeability than air. [Figure 10-33] This combination of an iron core in a coil of

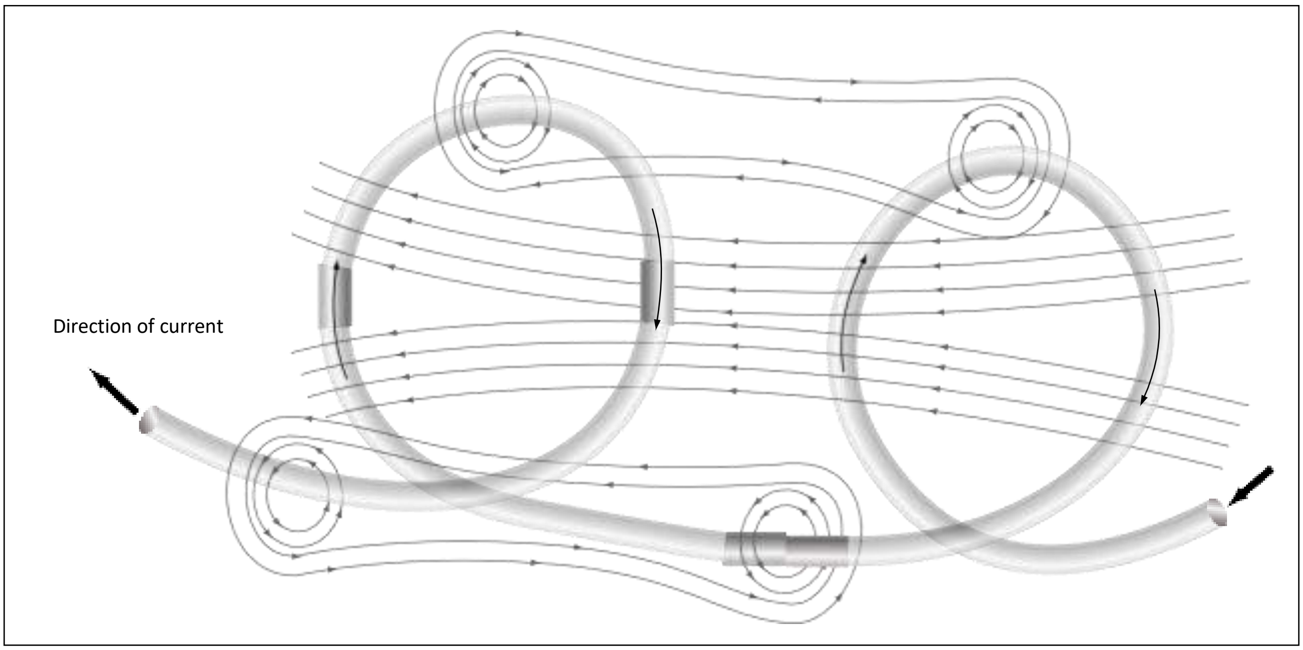


Figure 10-31. Magnetic field around a conductor with two loops.

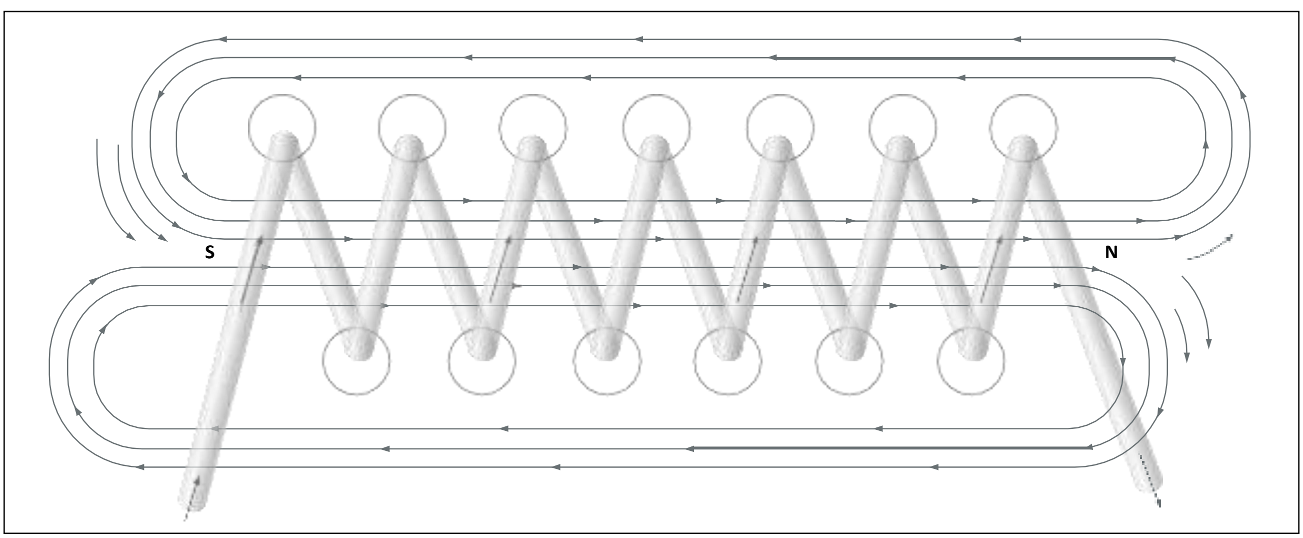


Figure 10-32. Magnetic field of a coil.

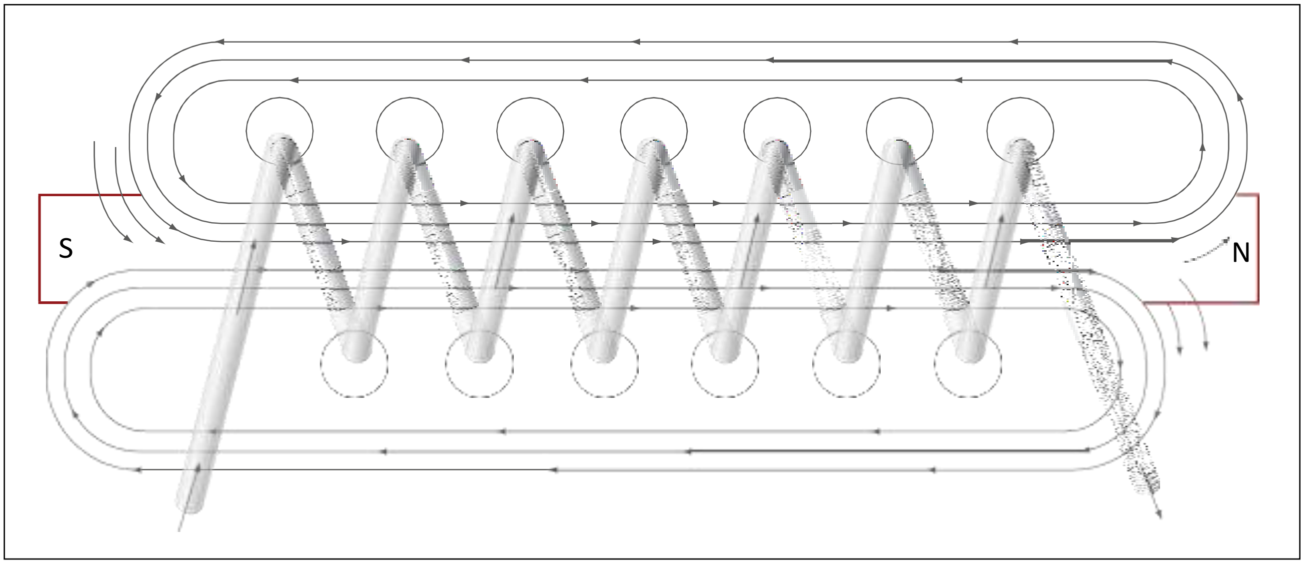


Figure 10-33. Electromagnet.

wire loops, or turns, is called an electromagnet, since the poles (ends) of the coil possess the characteristics of a bar magnet.

The addition of the soft iron core does two things for the current carrying coil. First, the magnetic flux is increased, and second, the flux lines are more highly concentrated.

When direct current flows through the coil, the core will become magnetized with the same polarity (location of north and south poles) as the coil would have without the core. If the current is reversed, the polarity will also be reversed.

The polarity of the electromagnet is determined by the left-hand rule in the same manner as the polarity of the coil without the core was determined. If the coil is grasped in the left hand in such a manner that the fingers curve around the coil in the direction of electron flow (minus to plus), the thumb will point in the direction of the north pole. [Figure 10-34]

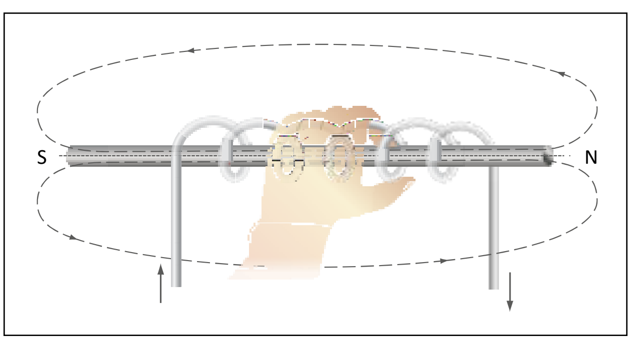


Figure 10-34. Left-hand rule applied to a coil.

The strength of the magnetic field of the electromagnet can be increased by either increasing the flow of current or the number of loops in the wire. Doubling the current flow approximately doubles the strength of the field, and in a similar manner, doubling the number of loops approximately doubles magnetic field strength. Finally, the type metal in the core is a factor in the field strength of the electromagnet.

A soft iron bar is attracted to either pole of a permanent magnet and, likewise, is attracted by a current carrying coil. The lines of force extend through the soft iron, magnetizing it by induction and pulling the iron bar toward the coil. If the bar is free to move, it will be drawn into the coil to a position near the center where the field is strongest. [Figure 10-35]

Electromagnets are used in electrical instruments, motors, generators, relays, and other devices. Some

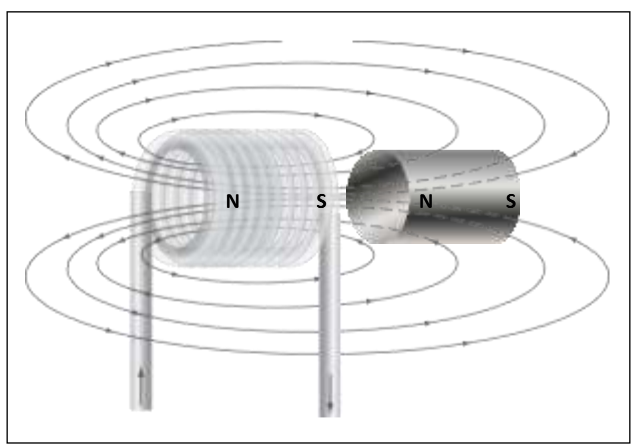


Figure 10-35. Solenoid with iron core.

electromagnetic devices operate on the principle that an iron core held away from the center of a coil will be rapidly pulled into a center position when the coil is energized. This principle is used in the solenoid, also called solenoid switch or relay, in which the iron core is spring-loaded off center and moves to complete a circuit when the coil is energized.

Conventional Flow and Electron Flow

Today's technician will find that there are two competing schools of thought and analytical practices regarding the flow of electricity. The two are called the conventional current theory and the electron theory.

Conventional Flow

Of the two, the conventional current theory was the first to be developed and, through many years of use, this method has become ingrained in electrical texts. The theory was initially advanced by Benjamin Franklin who reasoned that current flowed out of a positive source into a negative source or an area that lacked an abundance of charge. The notation assigned to the electric charges was positive (+) for the abundance of charge and negative (−) for a lack of charge. It then seemed natural to visualize the flow of current as being from the positive (+) to the negative (−).

Electron Flow

Later discoveries were made that proved that just the opposite is true. Electron flow is what actually happens where an abundance of electrons flow out of the negative (−) source to an area that lacks electrons or the positive (+) source.

Both conventional flow and electron flow are used in industry. Many textbooks in current use employ both electron flow and conventional flow methods. From the practical standpoint of the technician, troubleshooting a system, it makes little to no difference which way current is flowing as long as it is used consistently in the analysis.

Electromotive Force (Voltage)

Unlike current, which is easy to visualize as a flow, voltage is a variable that is determined between two points. Often we refer to voltage as a value across two points. It is the electromotive force (emf) or the push or pressure felt in a conductor that ultimately moves the electrons in a flow. The symbol for emf is the capital letter "E."

Across the terminals of the typical aircraft battery, voltage can be measured as the potential difference of 12 volts or 24 volts. That is to say that between the two terminal posts of the battery, there is an electromotive force of 12 or 24 volts available to push current through a circuit. Relatively free electrons in the negative terminal will move toward the excessive number of positive charges in the positive terminal. Recall from the discussion on static electricity that like charges repel each other but opposite charges attract each other. The net result is a flow or current through a conductor. There cannot be a flow in a conductor unless there is an applied voltage from a battery, generator, or ground power unit. The potential difference, or the voltage across any two points in an electrical system, can be determined by:

Where

$$E = \frac{\mathcal{e}}{Q}$$

E = potential difference in volts

$\mathcal{e}$ = energy expanded or absorbed in joules (J)

Q = Charge measured in coulombs

Figure 10-36 illustrates the flow of electrons of electric current. Two interconnected water tanks demonstrate that when a difference of pressure exists between the two tanks, water will flow until the two tanks are equalized. The illustration shows the level of water in tank A to be at a higher level, reading 10 psi (higher potential energy) than the water level in tank B, reading 2 psi (lower potential energy). Between the two tanks, there is 8-psi potential difference. If the valve in the interconnecting line between the tanks is opened, water will flow from tank A into tank B until the level of water (potential energy) of both tanks is equalized.

It is important to note that it was not the pressure in tank A that caused the water to flow; rather, it was the difference in pressure between tank A and tank B that caused the flow.

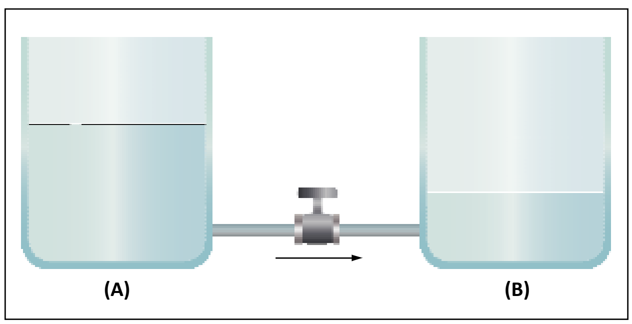


Figure 10-36. Difference of pressure.

This comparison illustrates the principle that electrons move, when a path is available, from a point of excess electrons (higher potential energy) to a point deficient in electrons (lower potential energy). The force that causes this movement is the potential difference in electrical energy between the two points. This force is called the electrical pressure or the potential difference or the electromotive force (electron moving force).

Current

Electrons in motion make up an electric current. This electric current is usually referred to as "current" or "current flow," no matter how many electrons are moving. Current is a measurement of a rate at which a charge flows through some region of space or a conductor. The moving charges are the free electrons found in conductors, such as copper, silver, aluminum, and gold. The term "free electron" describes a condition in some atoms where the outer electrons are loosely bound to their parent atom. These loosely bound electrons can be easily motivated to move in a given direction when an external source, such as a battery, is applied to the circuit. These electrons are attracted to the positive terminal of the battery, while the negative terminal is the source of the electrons. The greater amount of charge moving through the conductor in a given amount of time translates into a current.

$$\text{Current} = \frac{\text{Charge}}{\text{Time}}$$

Or

$$I = \frac{Q}{t}$$

Where:
I = Current in Amperes (A)
Q = Charge in Coulombs (C)
t = time

The System International unit for current is the Ampere (A), where

$$1\text{ A} = 1\frac{\text{C}}{\text{s}}$$

That is, 1 ampere (A) of current is equivalent to 1 coulomb (C) of charge passing through a conductor in 1 second(s). One coulomb of charge equals 6.28 billion billion electrons. The symbol used to indicate current in formulas or on schematics is the capital letter "I."

When current flow is one direction, it is called direct current (DC). Later in the text, we will discuss the form of current that periodically oscillates back and forth within the circuit. The present discussion will only be concerned with the use of direct current.

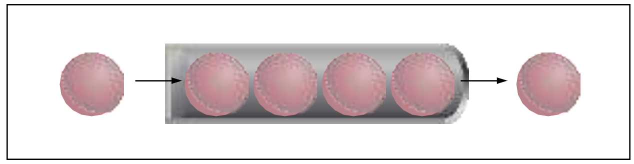


Figure 10-37. Electron movement.

The velocity of the charge is actually an average velocity and is called drift velocity. To understand the idea of drift velocity, think of a conductor in which the charge carriers are free electrons. These electrons are always in a state of random motion similar to that of gas molecules. When a voltage is applied across the conductor, an electromotive force creates an electric field within the conductor and a current is established. The electrons do not move in a straight direction but undergo repeated collisions with other nearby atoms. These collisions usually knock other free electrons from their atoms, and these electrons move on toward the positive end of the conductor with an average velocity called the drift velocity, which is relatively a slow speed. To understand the nearly instantaneous speed of the effect of the current, it is helpful to visualize a long tube filled with steel balls as shown in Figure 10-37. It can be seen that a ball introduced in one end of the tube, which represents the conductor, will immediately cause a ball to be emitted at the opposite end of the tube. Thus, electric current can be viewed as instantaneous, even though it is the result of a relatively slow drift of electrons.

Ohm's Law (Resistance)

The two fundamental properties of current and voltage are related by a third property known as resistance. In any electrical circuit, when voltage is applied to it, a current will result. The resistance of the conductor will determine the amount of current that flows under the given voltage. In most cases, the greater the circuit resistance, the less the current. If the resistance is reduced, then the current will increase. This relation is linear in nature and is known as Ohm's law.

By having a linearly proportional characteristic, it is meant that if one unit in the relationship increases or decreases by a certain percentage, the other variables in the relationship will increase or decrease by the same percentage. An example would be if the voltage across a resistor is doubled, then the current through the resistor doubles. It should be added that

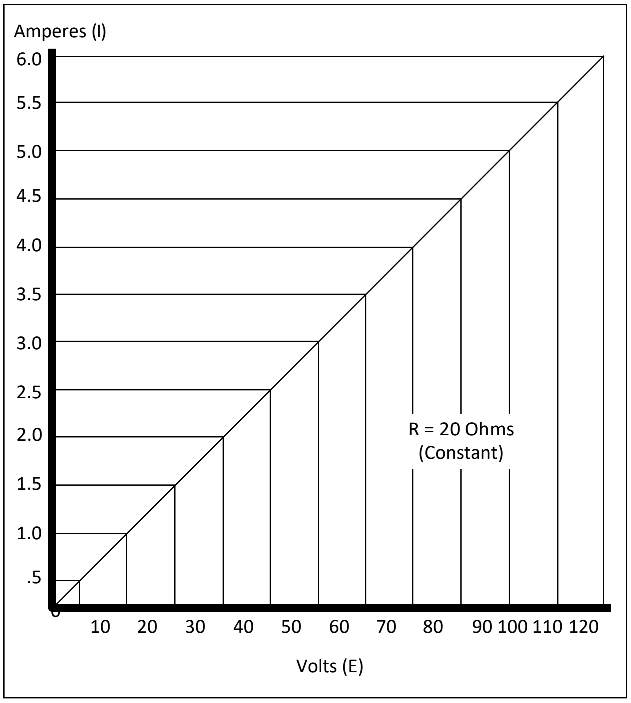


Figure 10-38. Voltage vs. current in a constant-resistance circuit.

this relationship is true only if the resistance in the circuit remains constant. For it can be seen that if the resistance changes, current also changes. A graph of this relationship is shown in Figure 10-38, which uses a constant resistance of 20Ω. The relationship between voltage and current in this example shows voltage plotted horizontally along the X axis in values from 0 to 120 volts, and the corresponding values of current are plotted vertically in values from 0 to 6.0 amperes along the Y axis. A straight line drawn through all the points where the voltage and current lines meet represents the equation $I = E/20$ and is called a linear relationship.

If $E = 10V$

Then $\frac{10V}{20\Omega} = 0.5A$

If $E = 60V$

Then $\frac{60V}{20\Omega} = 3A$

If $E = 120V$

Then $\frac{120V}{20\Omega} = 6A$

Ohm's law may be expressed as an equation, as follows:

Equation 1

$$I = \frac{E}{R}$$

I = Current in amperes (A)
E = Voltage (V)
R = Resistance (Ω)

Where I is current in amperes, E is the potential difference measured in volts, and R is the resistance measured in ohms. If any two of these circuit quantities are known, the third may be found by simple algebraic transposition. With this equation, we can calculate current in a circuit if the voltage and resistance are known. This same formula can be used to calculate voltage. By multiplying both sides of the equation 1 by R, we get an equivalent form of Ohm's law, which is:

Equation 2

$$E = I (R)$$

Finally, if we divide equation 2 by I, we will solve for resistance,

Equation 3

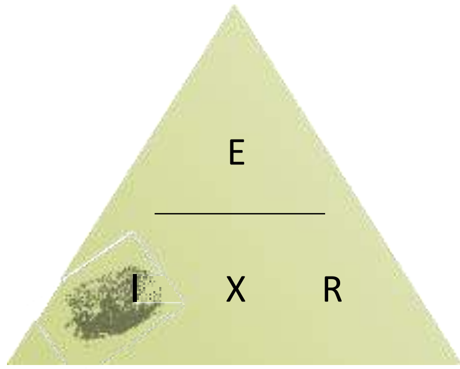
$$R = \frac{E}{I}$$

All three formulas presented in this section are equivalent to each other and are simply different ways of expressing Ohm's law.

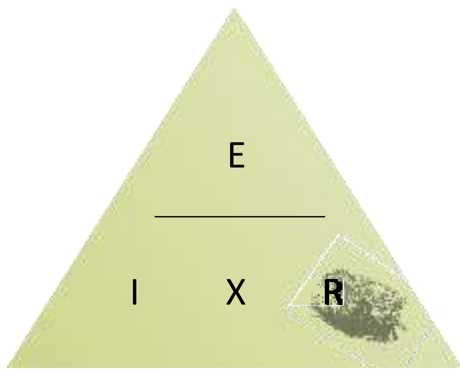
The various equations, which may be derived by transposing the basic law, can be easily obtained by using the triangles in Figure 10-39.

The triangles containing E, R, and I are divided into two parts, with E above the line and I × R below it. To determine an unknown circuit quantity when the other two are known, cover the unknown quantity with a thumb. The location of the remaining uncovered letters in the triangle will indicate the mathematical operation to be performed. For example, to find I, refer to Figure 10-39A, and cover I with the thumb. The uncovered letters indicate that E is to be divided by R, or $I = E/R$. To find R, refer to Figure 10-39B, and cover R with the thumb. The result indicates that E is to be divided by I, or $R = E/I$. To find E, refer to Figure 10-39C, and cover E with the thumb. The result indicates I is to be multiplied by R, or E = I × R.

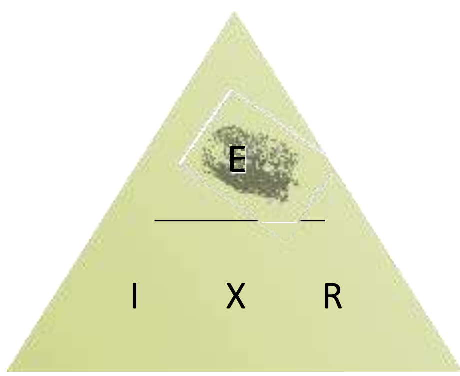
This chart is useful when learning to use Ohm's law. It should be used to supplement the beginner's knowledge of the algebraic method.



(A)
To find I (amperes), place thumb over I
and divide E by R as indicated



(B)
To find R (ohms), place thumb over R
and divide as indicated



(C)
To find E (volts), place thumb over E
multiply as indicated

Figure 10-39. Ohm's law chart.

Resistance of a Conductor

While wire of any size or resistance value may be used, the word "conductor" usually refers to materials that offer low resistance to current flow, and the word "insulator" describes materials that offer high resistance to current. There is no distinct dividing line between conductors and insulators; under the proper conditions, all types of material conduct some current. Materials offering a resistance to current flow midway between the best conductors and the poorest conductors (insulators) are sometimes referred to as "semiconductors," and find their greatest application in the field of transistors.

The best conductors are materials, chiefly metals, which possess a large number of free electrons; conversely, insulators are materials having few free electrons. The best conductors are silver, copper, gold, and aluminum; but some nonmetals, such as carbon and water, can be used as conductors. Materials such as rubber, glass, ceramics, and plastics are such poor conductors that they are usually used as insulators. The current flow in some of these materials is so low that it is usually considered zero. The unit used to measure resistance is called the ohm. The symbol for the ohm is the Greek letter omega (Ω). In mathematical formulas, the capital letter "R" refers to resistance. The resistance of a conductor and the voltage applied to it determine the number of amperes of current flowing through the conductor. Thus, 1 ohm of resistance will limit the current flow to 1 ampere in a conductor to which a voltage of 1 volt is applied.

Factors Affecting Resistance

1. The resistance of a metallic conductor is dependent on the type of conductor material. It has been pointed out that certain metals are commonly used as conductors because of the large number of free electrons in their outer orbits. Copper is usually considered the best available conductor material, since a copper wire of a particular diameter offers a lower resistance to current flow than an aluminum wire of the same diameter. However, aluminum is much lighter than copper, and for this reason as well as cost considerations, aluminum is often used when the weight factor is important.
2. The resistance of a metallic conductor is directly proportional to its length. The longer the length of a given size of wire, the greater the resistance. Figure 10-40 shows two wire conductors of different lengths. If 1 volt of electrical pressure is applied across the two ends of the conductor that is 1 foot in length and the resistance to the movement of free electrons is assumed to be 1 ohm, the current flow is limited to 1 ampere. If the same size conductor is doubled in length, the same electrons set in motion by the 1 volt applied now find twice the resistance;

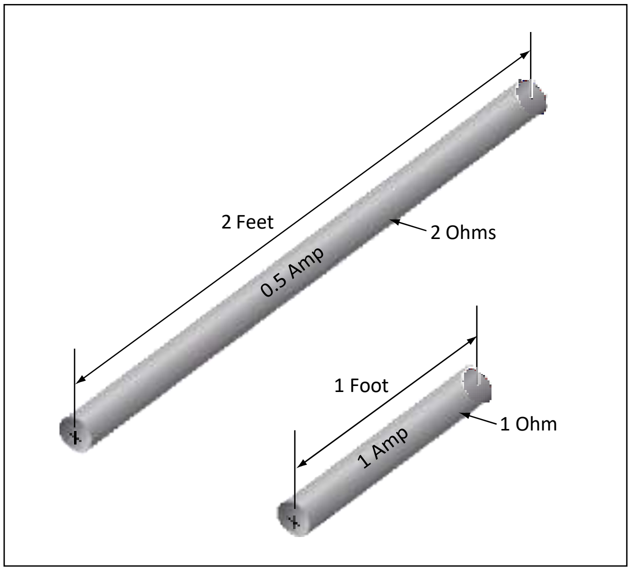


Figure 10-40. Resistance varies with length of conductor.

consequently, the current flow will be reduced by one-half.

3. The resistance of a metallic conductor is inversely proportional to the cross-sectional area. This area may be triangular or even square, but is usually circular. If the cross-sectional area of a conductor is doubled, the resistance to current flow will be reduced in half. This is true because of the increased area in which an electron can move without collision or capture by an atom. Thus, the resistance varies inversely with the cross-sectional area of a conductor.
4. The fourth major factor influencing the resistance of a conductor is temperature. Although some substances, such as carbon, show a decrease in resistance as the ambient (surrounding) temperature increases, most materials used as conductors increase in resistance as temperature increases. The resistance of a few alloys, such as constantan and Manganin™, change very little as the temperature changes. The amount of increase in the resistance of a 1 ohm sample of a conductor, per degree rise in temperature above 0° Centigrade (C), the assumed standard, is called the temperature coefficient of resistance. For each metal, this is a different value; for example, for copper the value is approximately 0.00427 ohm. Thus, a copper wire having a resistance of 50 ohms at a temperature of 0 °C will have an increase in resistance of 50 × 0.00427, or 0.214 ohm, for each degree rise in temperature above 0 °C. The temperature coefficient of resistance must be considered where there is an appreciable change in temperature of a conductor during operation. Charts listing the temperature coefficient of resistance for different materials are available. Figure 10-41 shows a table for "resistivity" of some common electric conductors.

Conductor Material	Resistivity (Ohm meters @ 20 °C)
Silver	1.64×10^{-8}
Copper	1.72×10^{-8}
Aluminum	2.83×10^{-8}
Tungsten	5.50×10^{-8}
Nickel	7.80×10^{-8}
Iron	12.0×10^{-8}
Constantan	49.0×10^{-8}
Nichrome II	110×10^{-8}

Figure 10-41. Resistivity table.

The resistance of a material is determined by four properties: material, length, area, and temperature. The first three properties are related by the following equation at T = 20 °C (room temperature):

$$R = \frac{(\rho \times l)}{A}$$

Where

R = resistance in ohms

ρ = Resistivity of the material in circular mil-ohms per foot

l = Length of the sample in feet

A = area in circular mils

Resistance and Its Relation to Wire Sizing

Circular Conductors (Wires/Cables)

Because it is known that the resistance of a conductor is directly proportional to its length, and if we are given the resistance of the unit length of wire, we can readily calculate the resistance of any length of wire of that particular material having the same diameter. Also, because it is known that the resistance of a conductor is inversely proportional to its cross-sectional area, and if we are given the resistance of a length of wire with unit cross-sectional area, we can calculate the resistance of a similar length of wire of the same material with any cross-sectional area. Therefore, if we know the resistance of a given conductor, we can calculate the resistance for any conductor of the same material at the same temperature. From the relationship:

$$R = \frac{(\rho \times l)}{A}$$

It can also be written:

$$\frac{R_1}{R_2} = \frac{1_1}{1_2} = \frac{A_1}{A_2}$$

If we have a conductor that is 1 meter long with a cross-sectional area of 1 mm^2 and has a resistance of 0.017 ohm, what is the resistance of 50m of wire from the same material but with a cross-sectional area of 0.25 mm^2?

$$\frac{R_1}{R_2} = \frac{1_1}{1_2} = \frac{A_1}{A_2}$$

$$R^2 = 0.017\Omega \times \frac{50m}{1m} \times \frac{1mm^2}{0.25mm^2} = 3.4\Omega$$

While the System International (SI) units are commonly used in the analysis of electric circuits, electrical conductors in North America are still being manufactured using the foot as the unit length and the mil (one thousandth of an inch) as the unit of diameter. Before using the equation $R = {}^{(\rho \times l)}/_{A}$ to calculate the resistance of a conductor of a given AWG size, the cross-sectional area in square meters must be determined using the conversion factor 1 mil = 0.0254 mm. The most convenient unit of wire length is the foot. Using these standards, the unit of size is the mil-foot. Thus, a wire has unit size if it has a diameter of 1 mil and length of 1 foot.

In the case of using copper conductors, we are spared the task of tedious calculations by using a table as shown in Figure 10-42. Note that cross-sectional dimensions listed on the table are such that each decrease of one gauge number equals a 25 percent increase in the cross-sectional area. Because of this, a decrease of three gauge numbers represents an increase in cross-sectional area of approximately a 2:1 increase. Likewise, change of ten wire gauge numbers represents a 10:1 change in cross-sectional area—also, by doubling the cross-sectional area of the conductor, the resistance is cut in half. A decrease of three wire gauge numbers cuts the resistance of the conductor of a given length in half.

Rectangular Conductors (Bus Bars)

To compute the cross-sectional area of a conductor in square mils, the length in mils of one side is squared. In the case of a rectangular conductor, the length of one side is multiplied by the length of the other. For example, a common rectangular bus bar (large, special conductor) is 3/8 inch thick and 4 inches wide. The 3/8-inch thickness may be expressed as 0.375 inch. Since 1,000 mils equal 1 inch, the width in inches can be converted to 4,000 mils. The cross-sectional area of the rectangular conductor is found by converting 0.375 to mils (375 mils × 4,000 mils = 1,500,000 square mils).

AWG Number	Diameter in mils	Ohms per 1,000 ft.
0000	460.0	0.04901
000	409.6	0.06180
00	364.8	0.07793
0	324.9	0.09827
1	289.3	0.1239
2	257.6	0.1563
3	229.4	0.1970
4	204.3	0.2485
5	181.9	0.3133
6	162.0	0.3951
8	128.5	0.6282
10	101.9	0.9989
12	80.81	1.588
14	64.08	2.525
16	50.82	4.016
18	40.30	6.385
20	31.96	10.15
22	25.35	16.14
24	20.10	25.67
26	15.94	40.81
28	12.64	64.9
30	10.03	103.2

Figure 10-42. Conversion table when using copper conductors.