PART

B

U T A

Rail Maintenance Study Guide

Advanced Coach Electrical Theory and Maintenance Practices

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Introduction

The goal of this manual, and those who support it, is to give you the necessary information in preparation for the *Coach Technician Qualifying Exam.* This study guide may be used to reference items during the course of your maintenance career. However, it is NOT intended to be the final answer to maintenance practices. Never substitute information in this study guide for information provided in specific equipment maintenance manuals. Always follow maintenance guidelines, manuals, and the information provided by your supervisor.

The study guide is separated in to two parts, Part A and Part B, to cover basic areas of study to advanced wiring schematic diagnosis. Part A provides basic information regarding safety, tools, theory, and hardware. Part B will primarily cover advanced electronic theory and multiple circuit configurations. While this study guide attempts to cover most maintenance and informational topics, it is not all encompassing. Again, specific maintenance manuals should be used in all cases. However, if you find your self in a situation to where you find no written guidance, consult your supervision and the Utah Transit Authority training office.

This manual provides Chapter review questions. They are intended for you to gauge your understanding of the material. They are NOT intended to be solely studied in preparation for the exam. Failure to comprehend the information provided could result in poor exam results

Chapter 1
Theory of Current

Current

Electrons

The electron orbits around the nucleus at a fantastic speed. What keeps electron from flying into space? It's not gravity, it's called electrostatic force. It's the attraction of the negative charge of the electron to the positive charge of the proton. Every charged particle has an electrostatic field around itself. An electron has a negative charge (an inward pull towards itself). A proton has a positive charge (force around it pushes away from the nucleus).

PROTON
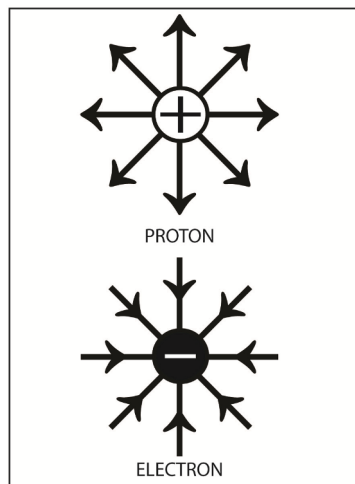
ELECTRON

Fig. 1.1

Coulomb's Law

There is a very basic law of nature that describes the action of electrical charges. It's called *Coulomb's Law* after Charles A. de Coulomb who discovered the relationship. Coulombs Law states that:

  ➢ Like charges repel
  ➢ Unlike charges attract

Like charges repel, two electrons repel each other, as do two protons. An electron and a proton attract each other. (One is positive and the other is negative.)
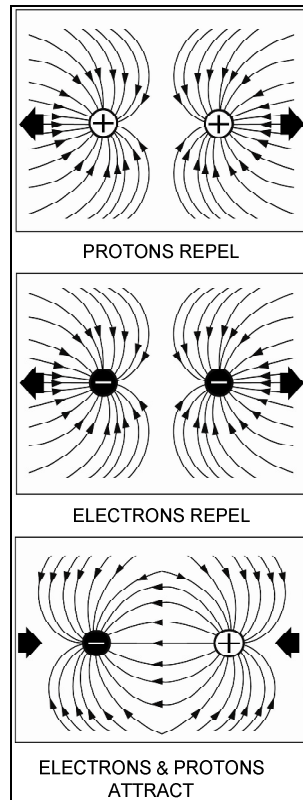
Fig. 1.2

Action of Electrostatic Charges

If you've seen lightning or removed clothes from a dryer, combed out your hair or rubbed a balloon on your head, you've experienced the effects of electrostatic charges. There are several ways an object can be charged. Three ways are:

> Charging by Friction

Example: Brushing your hair vigorously with a hard rubber comb, our hair gives up electrons to the comb. The comb becomes negatively charged while our hair becomes positively charged, because the comb collects a large number of free electrons from our hair.

> Charging by Contact

The charged comb can give up some of its charge to another object that is uncharged. When the comb comes into contact with an uncharged object, excess electrons leave the comb and collect onto the other object.

> Charging by Induction

As in Figure 1.2 below, take a charged comb and place it near, but not touching an aluminum rod. The excess electrons in the comb repel the free electrons in the rod. As a result, the free electrons gather at the end of the rod away from the charged comb. The opposite end acquires a positive charge because of the deficiency of electrons. If we now touch the negative end of the rod with a neutral body, some of the electrons will leave the rod and enter the neutral body. This leaves the rod with a net positive charge. Thus, a positive charge has been induced into the rod without touching it with a charged body.
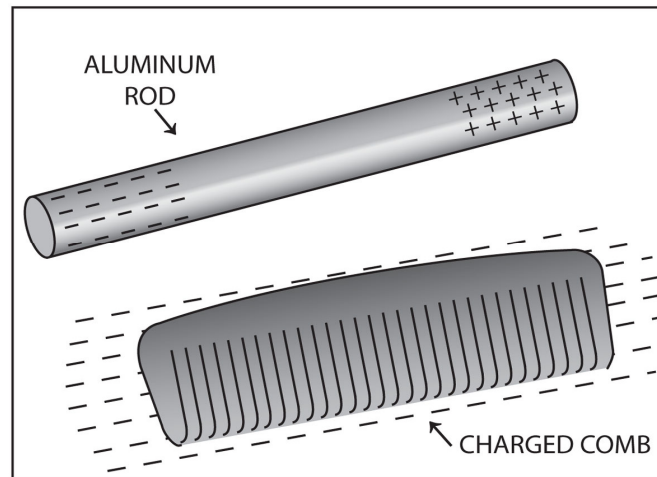
Fig. 1.3

Neutralizing Electrical Charges

Take a glass rod and rub it with a silk cloth, the glass gives up electrons onto the silk. Now, the glass has a positive charge and the silk is now negatively charged. If brought back together they would be attracted to one another. The force of attraction pulls the electrons back out of the silk, so now the charge is neutralized.

Current Flow

In electrons, current is defined as the flow of electrical charge form one point to another. We have seen then when a negatively charged body is touched to a positively charged body, electrons flow from the negative object to the positive object. Since electrons carry a negative charge, this is an example of electrical charges flowing, because electrons carry a negative charge. An electron must first be freed from the atom, before it can flow from one point to another.

Freeing Electrons

Electrons revolve around the nucleus at very high speeds. There are two forces holding the electron in a balance. The centrifugal force of the electron is exactly offset by the attraction of the nucleus. Sometimes, this balance condition can be easily upset so that the electron is dislodged. However, not all electrons can be dislodged form the atom with the same ease. Some are dislodged more easily than others. To understand this process, we must discuss the concept of orbital shells. Scientists think that the orbits electrons in an atom fall into a certain pattern. In all atoms, which have two or more electrons, two of the electrons orbit relatively close to the nucleus. This area in which these electrons rotate is called a *shell*. The shell closest to the nucleus contains two electrons. This area can only support two electrons and all the other electrons must orbit in shells further form the nucleus.

A second shell can contain up to eight electrons. There is also a third shell which can contain up to 18 electrons and a fourth shell which can hold up to 32 electrons. Some atoms are heavier and have additional shells. Figure 1.3 displays the different shells and their electrons.
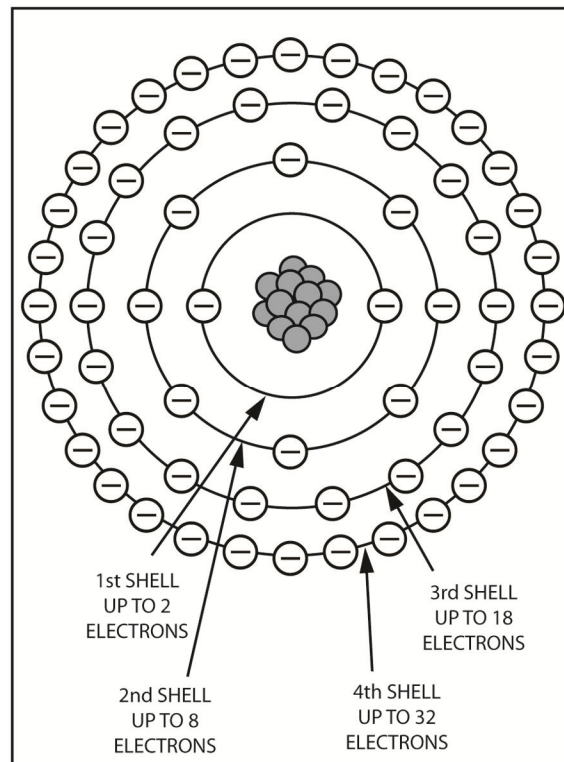
Fig. 1.4

Hydrogen and helium atoms have one and two electrons. Because of this, the outer shell is the first and only shell in these atoms. With atoms, which have three to ten electrons, the outer shell is the second shell. Regardless of which shell it happens to be, the outer shell is called the *valence shell*. Electrons in this shell are called *valence electrons*.

The valance shell of an atom will never have *more than* 8 electrons. This may seem confusing because the third and fourth shell can contain up to 18 electrons. An example shows how this can occur. An argon atom has 18 electrons, 2 in the first shell, 8 in the second shell, and 8 in the third shell. In a heavier element like a potassium atom that has 19 electrons, the extra electron is placed in the fourth shell. So, the 19 electrons are distributed with 2 electrons in the first shell, 8 in the second shell, 8 in the third shell, and 1 in the fourth shell. Notice that the outer, or valence shell becomes the fourth shell rather than the third, since the fourth shell is established as the valence shell, the third shell can fill up to its full capacity of 18 electrons.

Valence electrons are very important to electronics because they are more easily freed from their atoms to perform useful functions. Therefore, we want to focus on valence electrons and the freeing of electrons from an atom. As you know, the electrons that are closer to the nucleus have stronger attractions and the electrons in the outer valence shell have a weaker attraction to the nucleus. In Figure 1.4 below, two atoms of copper are displayed in the top part of the figure not very close together. However, in the bottom half of the figure, as the two atoms get closer together, the repulsion between the electrons in the outer valence of the two atoms may be stronger than the attraction of the nucleus to the electrons in the outer shell. Thus, one or both of the electrons may be forced out of orbit to wander as a free electron. When an electron leaves, an atom becomes a positive ion.
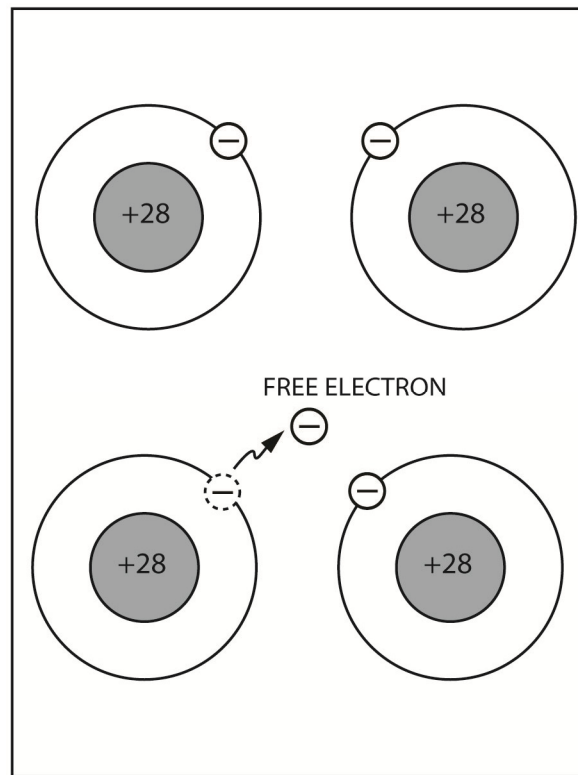
Fig. 1.5

As the free electrons roam through the atomic structure, they may eventually be captured by another positive ion, or come close enough to other valence electrons to force them from orbit. So, we see in a normal piece of copper wire containing billions of atoms, there are billions of electrons wandering around freely.

Conductors and Insulators

As already mentioned, valance electrons are very important, because many of the electrical and chemical characteristics of the elements depend upon the action of the valence electrons. Much of an element's electrical and chemical stability is determined largely by the number of electrons in its valence shell. We know that the valence shell can contain up to eight electrons. Those elements with valence shells that are filled or nearly filled tend to be more stable. For example, the elements neon, argon, krypton, xenon, and radon have 8 electrons in their valence shell. These elements are so stable that they resist any kind of chemical activity. They won't combine with other elements to form compounds. Atoms from these elements are very reluctant to give up electrons. These elements are all inert gases and very similar characteristics.

When an element's variance shell is almost filled, it tends to be stable. Although they are not as stable as those whose valences are completely filled. These elements will strive to fill their valence shell by capturing free electrons. Consequently, these elements have very few free electrons wandering around through the atomic structure and are called *insulators*. For this very reason, Insulators are important in electrical and electronics work. The plastic material on electrical wires is an insulator which protects us from electrical shock.

Then there are elements where the valence shell is almost empty. They have very opposite characteristics of those with filled and nearly filled valence shells. Those which have one or two electrons tend to give up these electrons very easily. For example, copper, silver, and gold each have

one valence electron. In these elements, the valence electrons are very effortlessly dislodged. Consequently, these elements will have a very large number of free electrons. Substances which have a large number of free electrons are called *conductors*. Some other conductors are iron, nickel and aluminum, and they are all metals. Conductors are essential because they are used to transport electrical current from one place to another.

Sometimes, the valence shell is only half filled. That is, there are four valence electrons. We call these elements *semiconductors*. They aren't good conductors or good insulators. Silicon and gerinanium are both semiconductors. Semiconductors are important in electronics because transistors and integrated circuits are comprised of these elements. However, we are going to focus on conductors and insulators.

Battery

The movement of free electrons from one place to another is referred to as *current flow*. Current flow can only exist where there are free electrons. We have already discussed how valence electrons can be freed from atoms to form free electrons and positive ions. This process becomes useful when very large numbers of electrons are able to be dislodged and concentrated in one area. One device that does this is a battery.

Two familiar types are the dry cell (flashlight battery) and the wet cell (automobile battery). These two types of batteries are very different in construction, but they do have several points in common. Both have two terminals or poles to which an electrical circuit can be connected. Also, both employ a chemical reaction which produces an excess of electrons at one terminal and a deficiency of electrons at the other. The terminal where the electrons congregate is called the negative terminal. It is indicated with a minus sign. The other terminal is indicated by a plus sign and has a deficiency of electrons. Let's see how the battery affects the free electrons in a conductor.
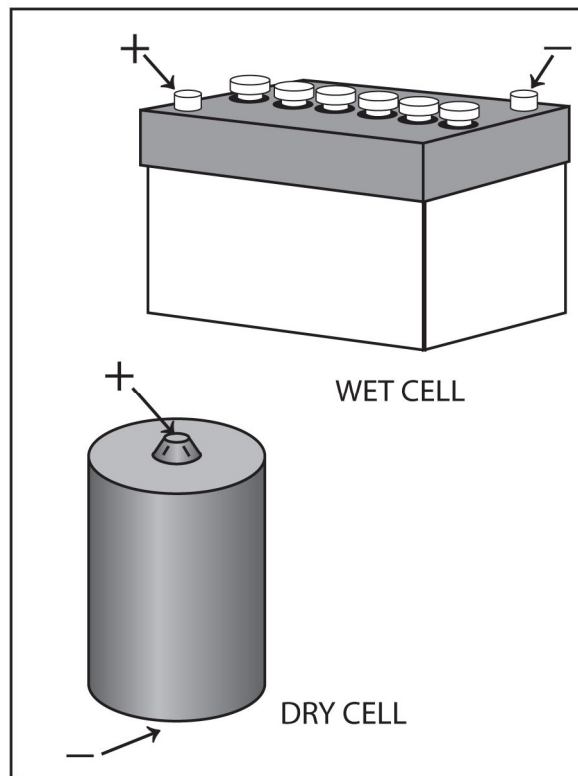
Fig. 1.6

Random Drift and Direct Drift

As already mentioned, a conductor is a substance that has a large number of free electrons. The electrons in a conductor don't stand still. They drift about randomly. At any instant, the free electrons are drifting at random in all directions. This is referred to as *random drift*. This type of drift occurs in all conductors, but it has little practical use. To do useful work, the free electrons must be forced to drift in the same direction.

By proper influence, drifting electrons can be made to move in the same direction through a conductor. This is done by placing electrical charges at the opposite ends of the conductor. By placing a negative charge at one end and a positive one at the other end, the negative charge repels the free electrons, while the positive charge attracts them. As a result, all of the free electrons move or drift from the negative charge to the positive charge, this process creates flow.
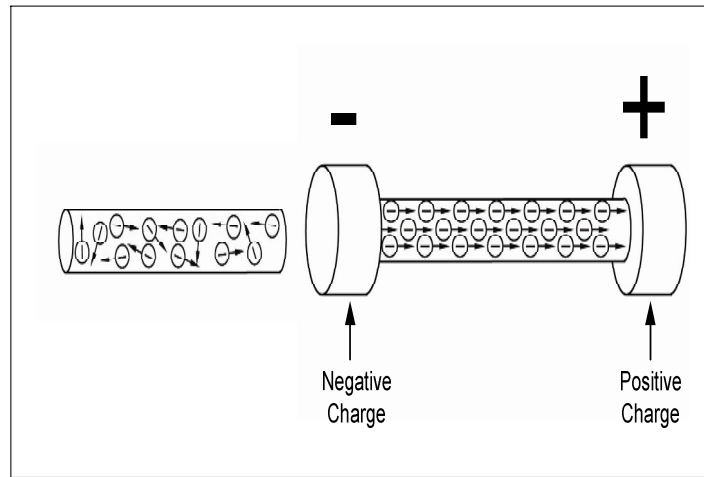
Fig. 1.7

Flow

Flow is the directed drift of free electrons. We say that an electric current is flowing through the conductor. If the electrical charges are isolated from one another, the flow of electrons will quickly cancel both charges and only a momentary current will flow. However, if the two electrical charges are caused by a battery, the chemical action of the battery can maintain the two charges for some time. Therefore, a battery can maintain a continuous current through a conductor for a long period. In Figure 1.8 below, a length of copper wire is connected from one terminal of a battery to the other. A heavy current will flow from the negative terminal to the positive one. The negative terminal is a source of free electrons. An electron at this point is repelled by the negative charge and attracted by the positive charge at the opposite terminal. Thus, the electrons flow through the wire from negative to positive pole.
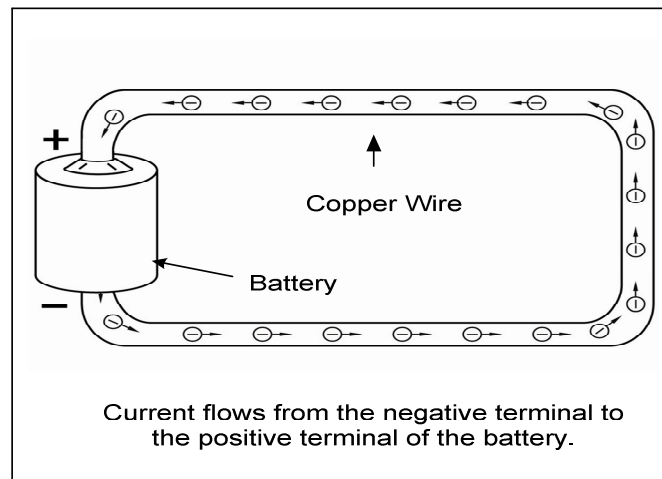
Fig. 1.8

It should be pointed out that we never connect a conductor directly across the terminals of the battery. The heavy current would quickly exhaust the battery. This is an example of a "short circuit" and should be avoided.

Current Measuring

Current is the flow of electrons from a negative to a positive charge. Current flow is measured by counting the number of electrons flowing past a point in a specific length of time.

The Coulomb

We have discussed that the charge on an object is determined by the number of electrons, which the object loses or gains. If the object loses electrons, the charge is positive. However, an object, which gains electrons, has a negative charge. The unit of electrical charge is called the *coulomb*. The coulomb is equal to the charge of 6.24×10^{18} electrons.

An object, which has gained 6.24×10^{18} electrons, has a negative charge of one coulomb. On the other hand, an object, which has given up 6.24×10^{18} electrons, has a positive charge of one coulomb.

Scientific Notation and Powers of Ten

A few reminders about powers of ten and scientific notation may be helpful at this point. The number 6,240,000,000,000,000,000 can be written as 6.24×10^{18}. This number is read, six point two four times ten to the eighteenth power. The expression, ten to the eighteenth power, means that the decimal place in 6.24 should be moved 18 places to the right in order to convert it to the proper number. The idea is that it is easier to write and remember 6,240,000,000,000,000,000.

This shorter method of expressing numbers is known as *powers of ten or scientific notation*. It's used in electronics to represent very large and very small numbers. Very small numbers are expressed by using negative powers of ten. The number, 2.2×10^{7} is scientific notation for the number 0.00000022. In this number, ten to the minus seventh power represents moving the decimal in 2.2 seven places to the left. There are some examples below.

Positive Powers of Ten

$8.2 \times 10^4 = 82{,}000$

$6.4 \times 10^6 = 6{,}400{,}000$

$2.0 \times 10^{12} = 2{,}000{,}000{,}000{,}000$

Negative Powers of Ten

$5.5 \times 10^{-4} = 0.00055$

$3.2 \times 10^{-8} = 0.000, 000{,}032$

$2.0 \times 10^{-12} = 0.000, 000, 000, 002$

Study these examples until you feel comfortable reading and writing numbers in this way.

The Ampere

The ampere, often shortened to amp, is a unit of electric current, or amount of electric charge per second. It can also be abbreviated as A. The ampere is the rate at which electrons move past a given point. As already mentioned, 1 coulomb is equal to 6.24×10^{18} electrons. An ampere is equal to 1 coulomb per second. That is, if 1 coulomb (6.24×10^{18} electrons) flows past a given point in 1 second, then the current is equal to 1 ampere. *Coulombs indicate numbers of electrons; amperes indicate the rate of electrons flow or coulombs per second.*

When 6.24×10^{18} electrons flow through a wire each second, the current flow is 1 ampere. If twice as many electrons flow each second, the current is 2 amperes. This relationship is expressed by the equation, amperes equals coulombs divided by seconds. It's expressed in the example below:

$$Amperes = Coulombs/Seconds$$

If 20 coulombs flow past a point in 4 seconds, then the current flow is 5 amperes.

Often the ampere is too large a unit. So, metric prefixes are used to break the large unit into smaller ones. The milliampere (mA) represents one thousandth (.001) of an ampere. The microampere (μA) is one millionth (.000 001) of an ampere. Basically, there are 1000 milliamperes or 1,000,000 microamperes in an ampere. Amperes can be changed to milliamperes by multiplying by 10^3. So, 2.8 amperes is equal to 2.8×10^3 mill amperes. Also, Amperes become microamperes by multiplying by 10^6. So, 2.8 amperes is equal to 2.8×10^6 microamperes.

The Ammeter

A device used to measure current flow is the ammeter. The name ammeter is a shortened form of the name ampere meter. It has a pointer, which moves in front of a calibrated scale. The movement of the pointer is proportional to the amount of current flowing through the meter. The amount of current flowing into the device is obtained by reading where the pointer indicates on the scale. The ammeter and its scale are shown in Figure 1.9 below.
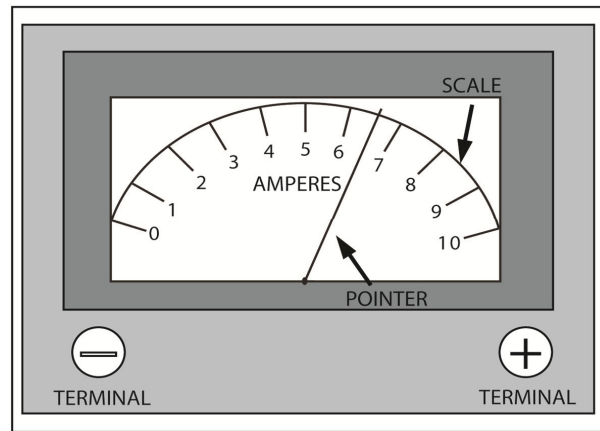
Fig. 1.9

Current can be measured by inserting an ammeter into the circuit. Note the schematic symbol for the ammeter is a circle with the letter A. Before the ammeter can measure current, it must be placed in the circuit in such a way that the current we wish to measure actually flows through the meter. This is often referred to as having the ammeter connected in series with the circuit elements. In a series circuit, the same current flows through all the elements in one continuous loop.

The maximum current that an ammeter can safely measure is indicated by the highest number on the scale. The highest current that the ammeter can safely measure is 10 amperes. This is called its full scale reading. Many current meters are much more sensitive. Some have a full scale reading of 1 milliampere. Others provide a full scale reading with only 50 microamperes flowing through them.

Certain safety precautions must be taken when using ammeters, because they are very delicate instruments and can easily be destroyed if the applied current exceeds the full scale reading of the meter. To protect yourself and the ammeter, the following steps should be taken when using the device.

1. The first step is to insure that the ammeter you are using is heavy enough for the job. As mentioned above, if the current rating is exceeded, the meter may be damaged.

2. Very Important! To protect you from electrical shock, power must be removed from the circuit being tested. In battery powered circuits this can be done by removing the battery or by disconnecting one of the battery leads.

3. The third step is to break the circuit at the point where the current is to be measured. The circuit must be broken, because the ammeter must be placed in series with the circuit.

4. Fourth, you must *observe polarity* while you connect the ammeter into the circuitry. The ammeter has two terminals labeled negative and positive. Current must flow through the ammeter from the negative to the positive terminals. Thus, the wire from the negative terminal of the battery must lead to the negative terminal of the ammeter. If the ammeter is connected backwards, the pointer will attempt to deflect backwards and may end up bent or broken. Observing polarity simply means that the negative terminal of the ammeter is connected to the wire that leads to the negative terminal of the battery. Naturally, the positive terminal of the ammeter is connected to the wire that leads to the positive side of the battery.

5. Finally, power is reapplied to the circuit and the current is read from the ammeter scale.

Figure 1.10 below reiterates the steps listed above for proper use of an ammeter.

Step 1

CIRCUIT IN WHICH CURRENT IS TO BE MEASURED

Step 2

REMOVE POWER BY DISCONNECTING
ONE SIDE OF THE BATTERY

Step 3

BREAK CIRCUIT AT POINT WHERE CURRENT IS
TO BE MEASURED

Step 4

CONNECT METER, OBSERVE POLARITY

Step 5

RESTORE POWER AND READ CURRENT

Steps to Properly Use an Ammeter
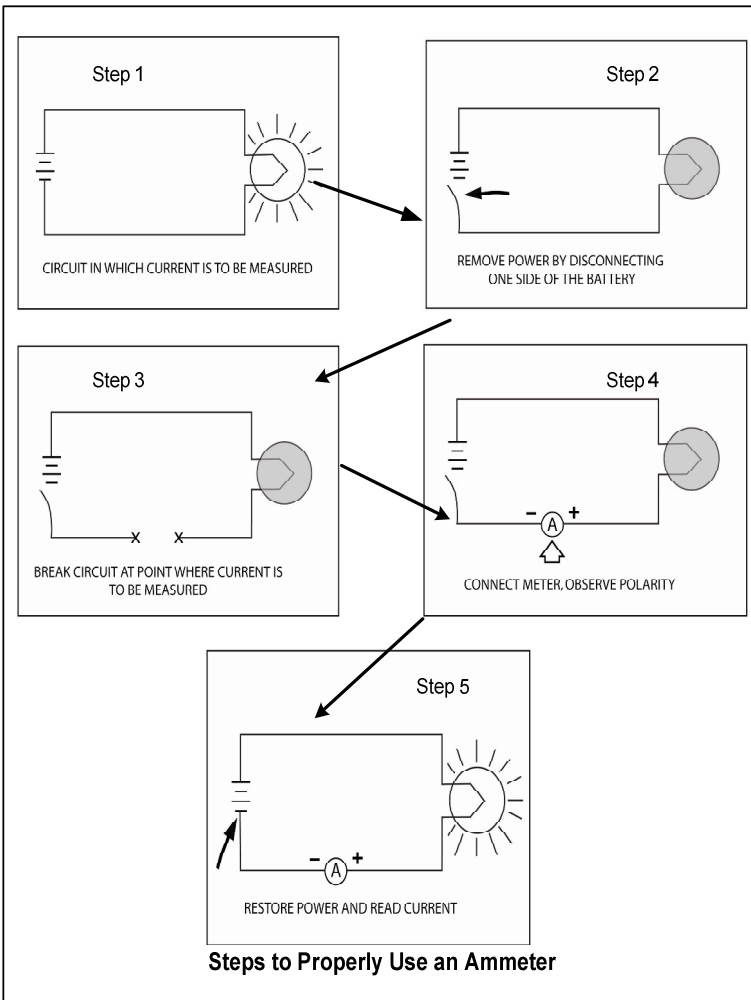
Fig. 1.10

Chapter 2
Voltage

In this chapter, we discuss electrical force and the terms it goes by electromotive force, potential difference, and voltage

Electrical Force

You now understand from the previous chapter, that it takes an external force to make currant flow in a circuit. Let's take the battery for an example. The battery changes chemical energy to electrical energy by separating negative charge (electrons) from positive charges (ions). These are the charges which, produce force, or pressure which causes electrons to flow and do useful work. This force has several names. Let's take a closer look at the three most popular names and see what each name implies.

Electromotive Force (EMF)

One popular name is electromotive force, which abbreviated is EMF. The name explains itself literally means a force that moves electrons. This force is a natural result of Coulomb's law. Let's

review Coulomb's law, it states that like charges repel while unlike charges attract. The battery, by chemical action, produces a negative charge at one terminal and a positive charge at the other end. The negative charge is simply an excess of electrons while the positive charge is an excess of ions. If a closed circuit is connected across the battery, a path for electron flow exists between the battery terminals. Free electrons are repelled by the charge on the negative terminal and are attracted by the charge on the positive terminal. The two opposite charges exert a pressure that, forces the electrons to flow. So, the force or pressure is the result of the attraction of the unlike charges. EMF is the force, which sets electrons in motion in a closed circuit. Figure 2.1 below graphically represents flow in a closed circuit.

EMF CAUSES ELECTRONS TO
FLOW IN CLOSED CIRCUIT

POTENTIAL FOR CURRENT
FLOW EXISTS EVEN THOUGH
THERE IS NO CURRENT
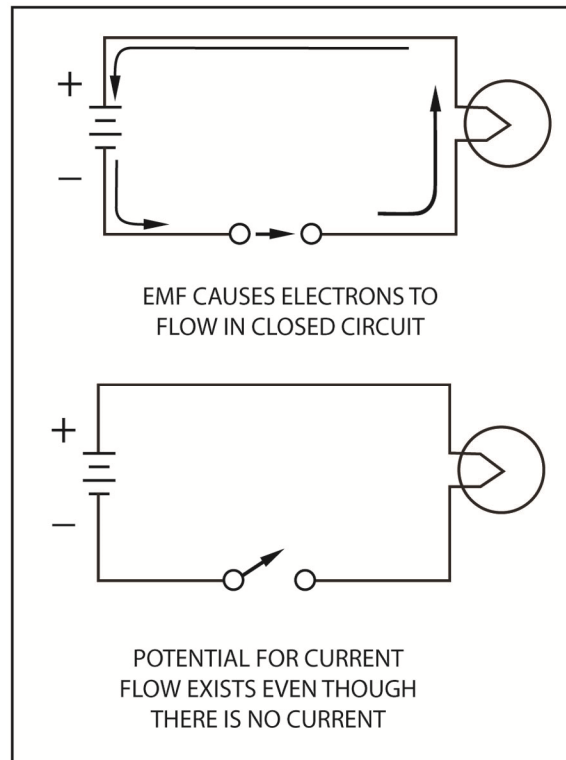
Fig. 2.1

Potential Difference

The second name for this force is called potential difference. This name is too very descriptive. It describes the characteristics of EMF in an open circuit, not a closed circuit. EMF is the force, which causes electrons to move. However, when the switch is open, electrons cannot flow. Remember, the battery still produces the same amount of pressure or force as before. So, the potential is there for producing current flow, even though no current is presently flowing. As used here, potential means the possibility of doing work. If the switch is closed, the flow continues in the circuit and useful work can be accomplished. Therefore whether a battery is connected into a circuit or not, it still has the potential for doing work. This potential for current flow and work to be accomplished is also shown in the bottom half of Figure 2.1.

Every charge has the potential for accomplishing work. For example, it can move another charge either by attraction or repulsion. Even a single electron can repel another electron. In the battery, we are concerned with two different types of charges rather than a single charge. The electrons at the negative terminal are straining to rush to the positive terminal and cancel out the positive charge there. In the same way, the positive ions at the other terminal are straining to draw electrons. We

call the force *potential difference*. <u>It is the potential for doing work that exists between two different charges</u>.

The characteristics of the charges will help determine how much work can be done. Static charges can help explain this process. With static charges, there is a small positive charge on one end and a small negative charge on the other end. Let's just say one side has an excess of one million electrons and the other side has a deficiency of one million electrons. If a conductor is connected between the two charges, electrons would flow from the negative charge to the positive one. The work here is moving of electrons. To cancel the two charges, one million electrons will flow from negative to positive charge. Now if you were to double the two charges, twice as much work would be done. However, the magnitude of the charges is not the important consideration. It is the difference between the two charges that is important. No work can be done if both charges have the same polarity and magnitude. If both charges on either end are the same (either negative or both positive), how much work can be done, if these two charges are connected by a conductor? The answer is none. The two objects have exactly the same charge; no electrons can flow from one to the other. So, there is no potential for doing any work.

1. They can be of opposite polarity. Simply means, that one is positive and one is negative.

2. They can have different magnitudes. Simply stated, one charge is more negative because it has more excess electrons than the than the other charge.

If a conductor is connected between the two charges, electrons flow from the greater negative charge to the less negative charge. <u>The number of electrons will be exactly the right amount to equalize the two charges</u>. In this case charge A originally has three million excess electrons while charge B has only one million excess electrons. To equalize the two charges, one million electrons flow from charge A to charge B. Electron flow ceases as soon as the two charges become equal. <u>The direction of current flow is from the more negative charge to the less negative charge</u>.

Take two positive charges of different magnitudes. There is potential for flow here because electrons will flow if given the chance. When connected with a conductor, the electrons flow from the less positive (more negative) to the more positive charge. Again, the number of electrons, which will flow, is the amount necessary to exactly balance the two charges. In Figure 2.1 both of the situations described above are shown.
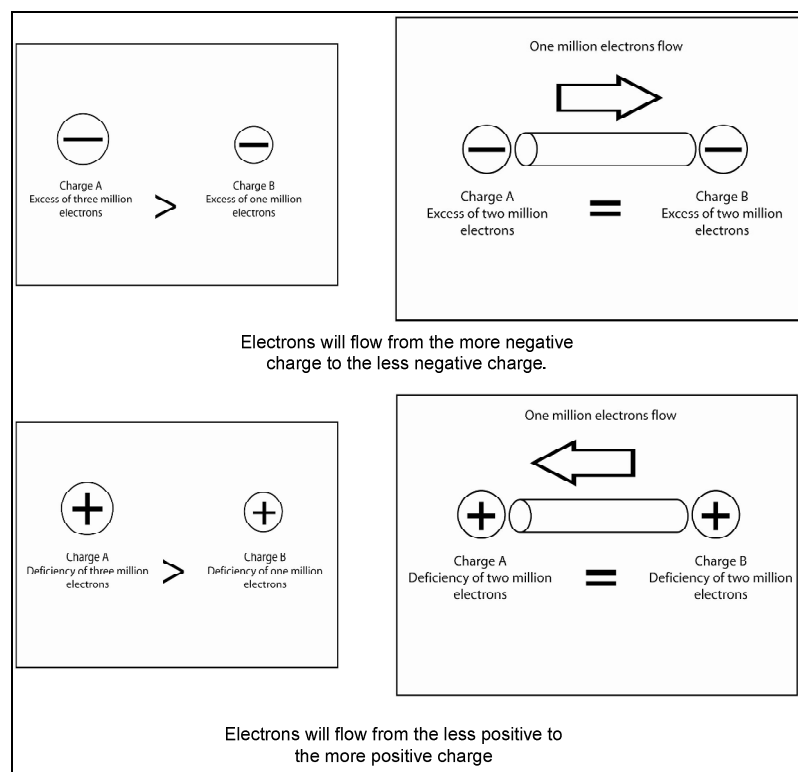
Fig. 2.2

Another example uses five terminals at various levels of charge. Since no two terminals are at the same charge level, a difference of potential exists between any two terminals. Thus, if a conductor is placed between any two terminals, electrons will flow until those two charges are balanced. Notice that if the third terminal has no charge. It contains the same number of electrons as positive ions. All the same, if the third terminal is connected to any other terminal, electrons will still flow. If it is connected to one of the negative terminals, electrons will flow into the third terminal. If it is connected to a positive terminal, electrons will flow from the third terminal. Remember that electrons always flow from the more negative to the more positive terminal.

Voltage

Voltage is another used to represent electrical force. However, there is a difference between EMF and voltage. Voltage is the measure of EMF or potential difference. So, the battery in your car has an EMF of 12 volts. The EMF supplied by wall outlets is 115 volts while that is required by most stoves is 220 volts. A large screen TV receiver produces an EMF that can go as high as 25,000 volts.

The unit of EMF or potential difference is the *volt.* One volt is the degree of EMF, which causes one unit of energy or work to move one coulomb of charge from one point to another. The metric unit of energy or work is the *joule.* This unit can also be difficult to understand. It was often referred to as newtons. Yet, joules can be expressed in more recognizable English units like one joule is equal to 0.738 foot-pounds. A foot-pound is the amount of work required to lift one pound, one foot. Consequently, a joule is approximately the amount of work required to lift ¾ of a pound one foot, off the ground.

One volt is the EMF required to cause one joule (or 0.738 foot-pounds) of work to move one coulomb of charge ($6.24\text{x}10^{18}$ electrons) form one point to another. To look at it another way, when movement of one coulomb of charge between two points produces on joule (or 0.738 foot-pounds) of work, the EMF between the two points is 1 volt.

The abbreviation used to represent the volt is V. So, 2.3 volts is abbreviated 2.3V. As with amperes, metric prefixes are attached to indicate smaller and larger units of voltage. Thus, one millivolt equals 1/1000 volt, while one microvolt equals 1/1,000,000 volt. Also, one kilovolt equals 1000 volts while one megavolt equals 1,000,000 volts.

Chapter 3
Electrical Power Production

This chapter covers methods of producing electrical power including magnetism, chemical (electrochemistry), friction, light, pressure, and heat. More information regarding batteries is also presented

Magnetism

Magnetism is the central method of producing electrical power in the world today. With our current technology, it is the only technique that can produce enough electrical power to run an entire city. Over 99% of all electrical power is produced by this process.

As a conductor is moves through a magnetic field, an EMF is produced. This is called *magnetoelectricity*. The force of the magnetic field and the movement of the conductor supply the energy necessary to free electrons in the conductor.

The essential requirements are a magnetic field, a conductor, and relative motion between the two. This is shown in a simple example, Figure 3.1, using a magnetic field produced by a permanent magnet. The field is represented by the lines drawn from the north to south poles of the magnet. If a conductor is moved up so that it cuts the field, electrons will flow in the direction indicated. The same effect will be obtained if the conductor is held still and the magnet is moved down. All that is required is relative motion between the magnetic field and the conductor.
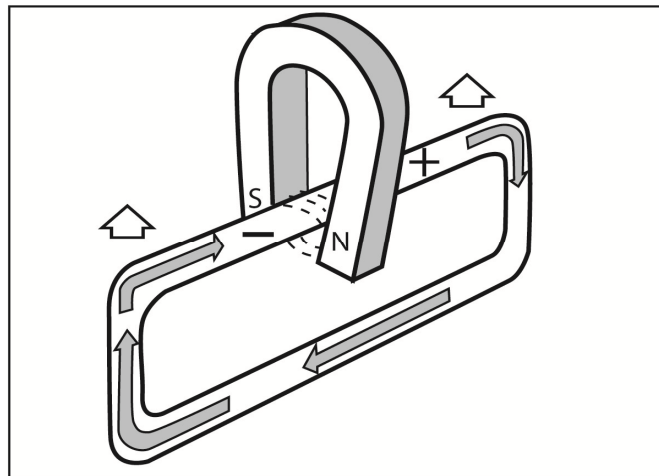
Fig. 3.1
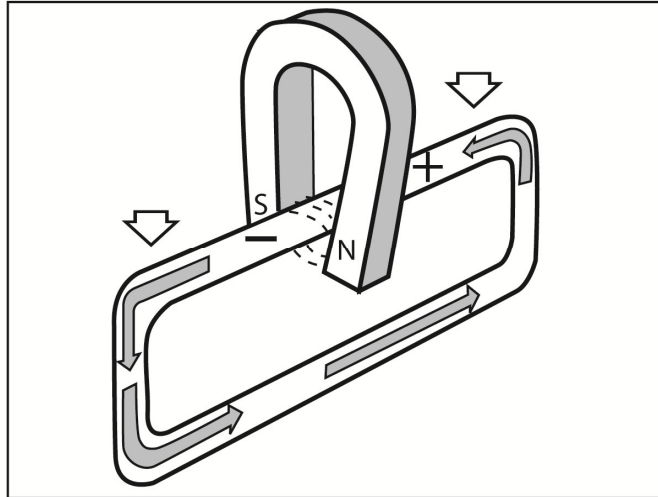
Fig. 3.2

Above in Figure 3.2, we see that electrons will flow in the opposite direction if the relative motion is reversed. When the conductor is moved up and down in the magnetic field, the electron flow reverses each time the motion reverses. In generators, a reciprocal motion like this is required. Thus, the current produced first flows in one direction then the other. This is known as alternating current or simply AC. In power generating stations the reciprocal motion occurs 60 times each second. This is why the electricity that runs through our homes if often to as 60-cycle AC. In this course, we are not concerned with alternating current although we will discuss magnetism in some detail later.

Chemical

The next most popular method of generating electricity is by chemical means sometimes called electrochemistry. Automobile and flashlight batteries are both use electrochemistry to produce their power. There are many chemical reactions that transfer electrons so that an EMF is produced.

A good example is produced by taking a glass beaker filled with a solution of sulfuric acid and water, often called electrolyte. In the electrolyte, the sulfuric acid breaks down into hydrogen and sulfate. Due to the chemical action involved, the hydrogen atoms give electrons to the molecules of sulfate. Thus, the hydrogen atoms exist as positive ions while the sulfate molecules act as negative ions. Even so, the solution has no net charge since there is the same number of negative and positive charges. Figure 3.3 shows the electrolyte solution breaking down into positive hydrogen ions and negative sulfate ions.
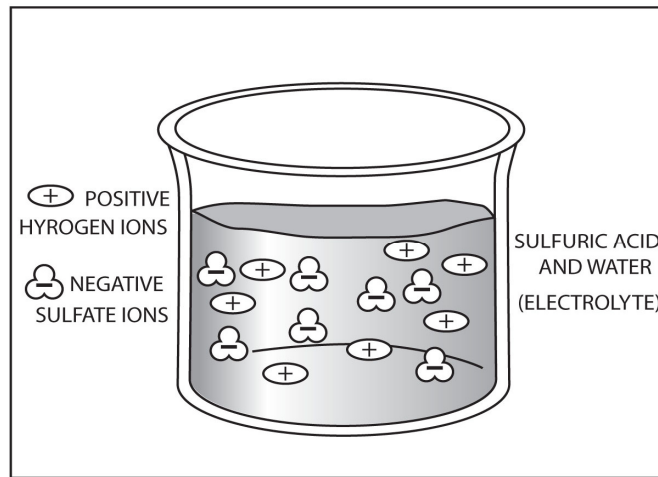
Fig. 3.3

Next, two bars, one copper bar and one zinc bar, called electrodes are put into the electrolyte solution. The positive ions of hydrogen attract the free electrons in the copper. Thus, the copper bar gives up electrons to the electrolyte. This leaves the copper bar with a net positive charge. The zinc reacts with the sulfate in a very similar way. The sulfate molecules have a negative charge. Thus, positive zinc ions are pulled from the bar. This leaves the zinc bar with a surplus of electrons and a net negative charge.

If a conductor is connected between the zinc and copper bars, electrons will flow from negative to the positive terminal. Figure 3.4 below shows this process. Because current flow is always in the same direction, we call this direct current or DC.
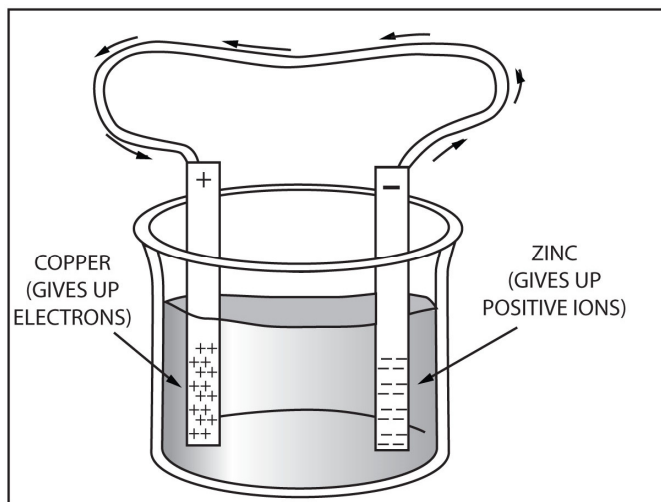
Fig. 3.4

Friction

Friction is the oldest known method for producing electricity. You have probably experienced this occurrence yourself many times. When you scuff your feet across a nylon or wool rug, your shoes develop a charge, which is transferred to the body. When you touch a neutral object such as a metal knob or another person, a discharge occurs. Frequently, there is a tiny arc between your finger and the neutral body.

In many cases, static electricity produced by friction is troublesome or annoying. However, the Van de Gaaff generator used in physics laboratories uses this principle to develop high voltages. Some Van de Gaaff generators can 10 million volts or more. Producing electricity from friction is called the *triboelectric effect*.

Light

Light energy can be converted to electrical energy in large enough quantities to provide limited amounts of power. A familiar example is the solar cells. Recent scientific advances have greatly reduced the cost. In fact, in the not-too-distant future, solar cells will probably be used for commercial purposes on a much larger scale.
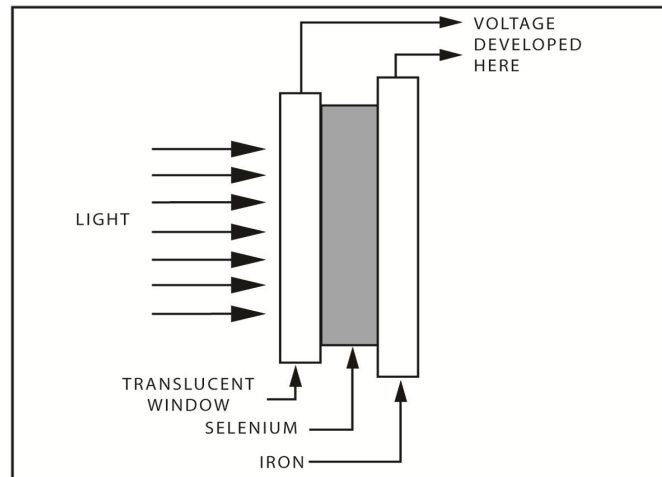
Fig. 3.5

Figure 3.5 above shows the different parts a solar or photo cell. A solar or photo cell consists of some type of photosensitive material sandwiched between two plates which act as electrodes. A photosensitive material is one, which develops a charge when it is bombarded by light. Substances like cesium, selenium, germanium, cadmium and sodium are photosensitive. When these materials are struck by light, some of the atoms release electrons. This is known as photoelectric effect. Take for instance a light passing through a translucent window and striking the selenium alloy underneath it. Some of the selenium atoms give up electrons and a charge is developed between the two plates. When a single cell is exposed to sunlight, it can provide a fraction of a volt charge and deliver a few mill amperes of current. When they are used as a power source, hundreds of the cells are tied together so that they produce usable voltage and current levels.

Pressure

When some materials are subjected to pressure or bending, a small electrical charge is produced. This is referred to as the piezoelectric effect. Although present to a small degree in many different materials, it is especially noticeable in substances such as quartz, tourmaline and Rochelle salts, all of which have highly crystalline structures. For instance in a normal structure, negative and positive charges are distributed so that no overall charge can be measured. However, when these materials are subjected to pressure or bending, electrons leave one side of the material and accumulate on the other side. Thus, a charge is developed. When the pressure is relieved, the charges are again distributed so that the net charge disappears. In Figure 3.6 blow, the piezoelectric effect is shown.
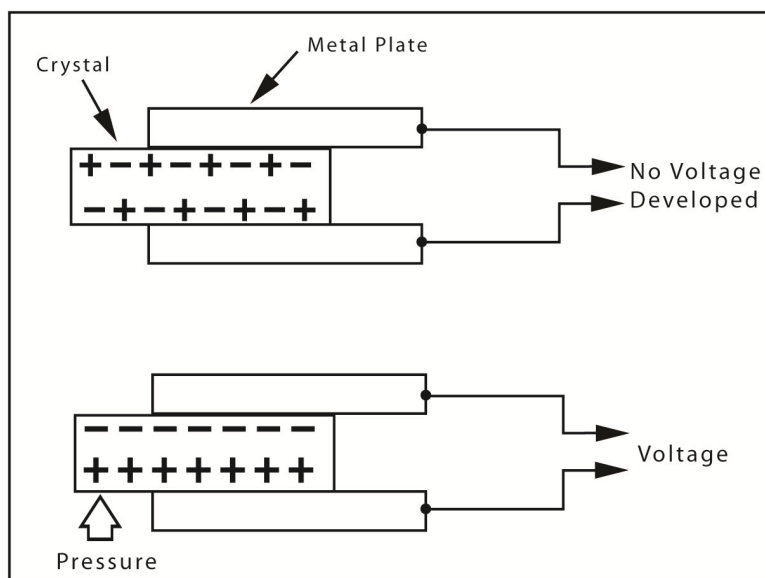
Fig. 3.6

This effect is used in devices like crystal microphones and phonograph pickups, which actually convert mechanical vibration into a small, but amplifiable, electrical vibration (signal) based upon the piezoelectric effect.

Heat

Heat can, of course, be converted directly into electricity. The device for doing this is called a thermocouple. A thermocouple consists of two different or dissimilar metals joined together like copper and zinc. You have seen that copper readily gives up electrons. This is especially true when the copper is heated. If copper is placed on top of a piece of zinc and heated, free electrons from the copper are transferred to the zinc. Thus, the copper develops a positive charge while the zinc develops a negative charge. Since more heat causes more electrons to transfer, the charge developed is directly proportional to the heat applied. This process is shown in Figure 3.7 below.
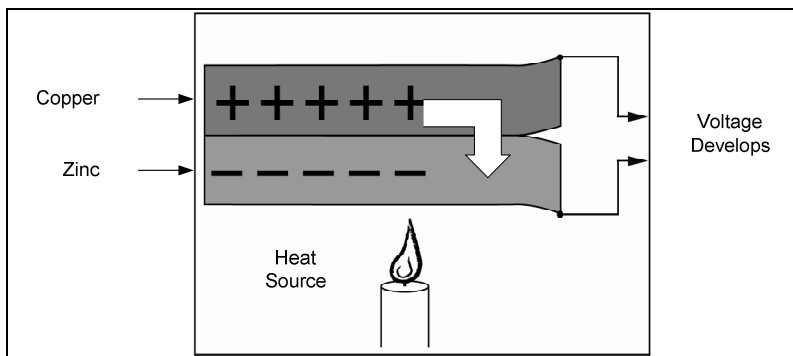
Fig. 3.7

This characteristic allows the thermocouple to be used as a thermometer in areas, which are too hot for conventional thermometers. A specific voltage across the thermocouple corresponds to a specific temperature. Therefore, the voltage can be measured and compared to a chart to find the corresponding temperature. The process by which heat is converted directly to electricity is called thermoelectric effect.

Effects of EMF

As shown, EMF can be produced by light, heat, magnetism, pressure and chemical activity. The reverse is also true. EMF can also produce light, heat, magnetism, pressure and chemical activity. Some examples are a light bulb where light is produced through electricity and the toaster and electric stoves where electricity is used to produce heat.

Batteries

In the previous section, we discussed one type of battery or cell; it consisted of zinc and copper electrodes inserted into an electrolyte of sulfuric acid and water. In this section, the construction and operation of several more common types of batteries will be discussed. First, we need to distinguish between a battery and a cell. <u>A cell is a single unit, which contains negative and positive electrodes, which are separated by an electrolyte. A battery is a combination of two or more electrochemical cells.</u> So, a flashlight battery is really a cell since it only contains one unit for producing EMF. In the non-technical world, people often use the word battery is loosely represent a single cell.

There are two basic types of cells. One type can be recharged and is called a secondary cell. The other type can not be recharged and is called a primary cell. All cells and batteries store energy in a chemical form, which can be released as electricity.

Dry Cell

There are five common types of dry cell batteries: D, C, AA, AAA, and 9 Volt batteries. We use theses on a daily basis with our common household electronics. Now take for instance the dry cell battery of a flashlight. The positive terminal is the steel top at the end of the carbon electrode. The negative terminal is the zinc can or container, which holds the rest of the cell. A plastic jacket protects the zinc container and insulates the negative terminal from the positive terminal.

This type of cell is referred to as a dry cell, but isn't dry on the inside but contains a moist paste. A wax seals off the open end of the zinc container. This prevents the paste from oozing out when the battery is turned upside down or on its side. Due to this, this type of cell can be used in any position without the electrolyte escaping. The electrolyte used in this cell is a solution of ammonium chloride and zinc chloride. The electrolyte gradually dissolves the zinc by pulling away positive ions. This process leaves behind an excess of electrons. Thus, the remaining zinc acts as the negative electrode. If it were not for the carbon rod, the electrolyte would develop a positive charge by virtue of the positive ions pulled from the zinc. However, the positive charge is neutralized by electrons pulled from the carbon rod. Thus, the carbon rod has a deficiency of electrons, which causes a positive charge. Figure 3.8 below also graphically shows the construction of a dry cell battery.
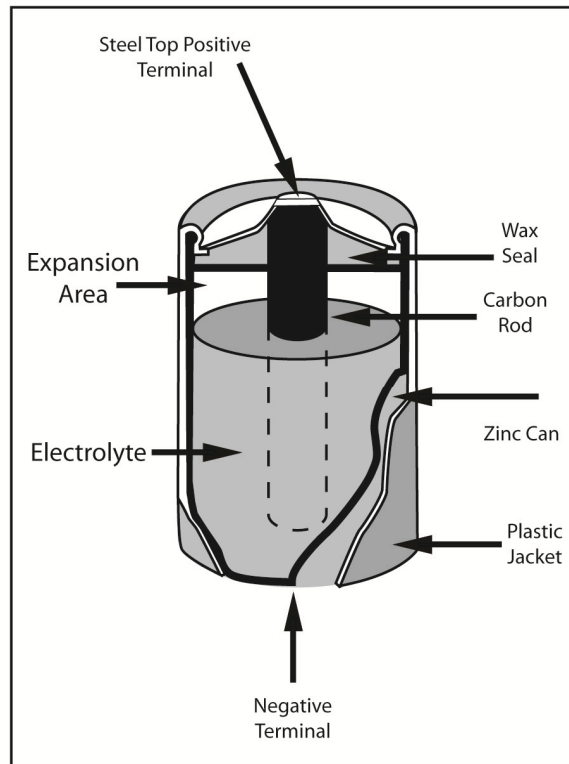
Fig. 3.8

This type of cell is referred to as the Leclanch'e cell and it produces just over 1.5 volts when new. As it is used, the chemical action slows and the voltage gradually decreases. This type of cell cannot be recharged so it is considered a primary cell. Also, because the paste gradually dries out, the dry cell slowly loses its ability to produce EMF. This occurs even if the battery is not in use. For this reason, the dry cell must be used within about two years, and it has a shelf life of two years.

The voltage delivered by this type of cell is determined strictly by the types of material used as the electrodes and the electrolyte. So, the voltage is determined by the chemical reaction and not the size of the cell. Thus, a small pen light cell produces the same voltage as the much larger D cell. But the larger battery has a higher current rating.

Lead-Acid Battery

The primary disadvantage of the dry cell is that it can't be recharged. Other cells, called secondary cells, can be recharged. The most popular of the secondary cells is the lead-acid battery. In this type of cell, a reversible chemical reaction takes place. It is this reaction that produces EMF between the battery terminals.

Figure 3.9 below shows an average lead-acid battery. The positive electrode is made of a plate of lead dioxide (PbO_2) and the negative electrode is a plate of spongy lead (Pb). These are submerged in a solution of sulfuric acid (H_2SO_4) and water (H_2O).

The sulfuric acid in the solution separates into positive hydrogen ions ($H+$) and negative sulfate (SO_4--) ions. While this is occurring, the lead plate begins to release electrons and form $Pb++$ ions. Some of the negative sulfate ions in the solution combine with the positive lead ions on the surface of the negative electrode and form a coating of lead sulfate. The electrons released by the lead plate will travel through the conductor to the positive electrode.

In the meantime, the atoms on the surface of the lead dioxide plate give negatively charged oxygen ions (O--) into the solution. The loss of the electrons from oxygen into the solution, gives the lead dioxide plate an overall positive charge. So, Pb++++ ions are formed on the surface of the plate. Again, as with the negative electrode, some of the negative sulfate ions combine with the positive lead ions to form a coating of lead sulfate on the positive electrode. Yet, this does not completely neutralize the charge of the lead ions. In fact, each of the lead ions on the plate is still Pb++. It is the positive charge that attracts the electrons from the negative electrode through the conductor.

The negatively charged oxygen ions in the solution now combine with the positively charged hydrogen ions, which resulted from the separation of the sulfuric acid, and form water (H2O). As the cell discharges, the amount of water increases, while the amount of acid decreases. This entire process is shown in Figure 3.9 below.

The entire process can be reversed as represented in Figure 3.10, by reversing the ion flow through the battery. You can do this by connecting a source of dc voltage greater than that produced by the lead-acid cell. However, during the recharging process, some of the hydrogen in the solution will escape into the air.

The amount of EMF produced by a cell is determined by the chemical reaction that occurs within the cell. The lead-acid cell just described produces an EMF of about 2.1 volts. Cells made of other materials will produce different voltages. The amount of current that a cell can deliver is determined by the size of the cell or, to state it more correctly, by the physical size of the electrodes and the amount of sulfuric acid in the solution.
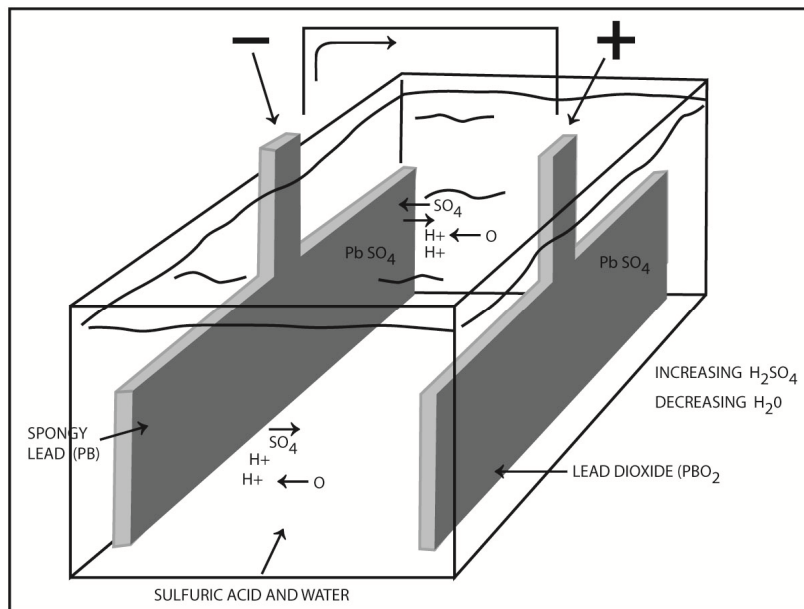
Fig. 3.9
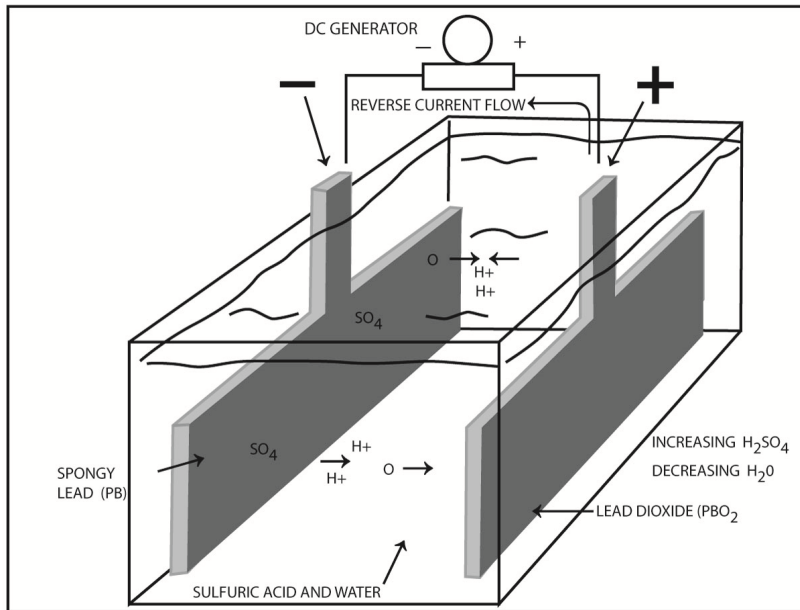
Fig. 3.10

Connecting Batteries

Current ratings and voltage can increase when cells are connected together. There are four different ways that cells or batteries can be connected: series-aiding, series-opposing, parallel and series-parallel.

Series-Aiding Connection

A 12-volt automobile battery contains six cells that are connected together so their individual cell voltages add together. In the 6-volt battery, three cells are connected in the same way. This arrangement is called a series-aiding connection and is shown in Figure 3.11 below as it occurs in a three-cell flashlight. The cells are connected so that the positive terminal of the second connects to the negative terminal of the third and so on and so forth. This is a series connection because the same current flows through all three cells. It is an aiding connection because the voltages add together. Since the individual EMF of each cell is 1.5 volts, the overall EMF is 4.5 volts.
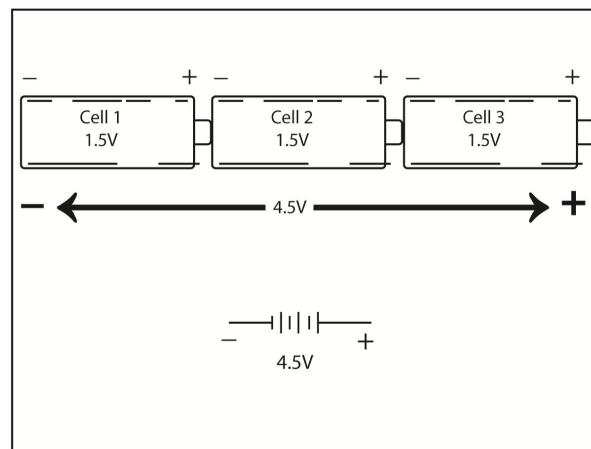
Fig. 3.11
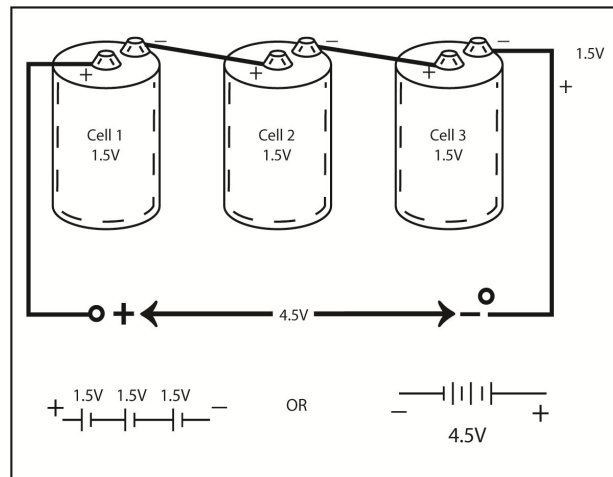
Fig. 3.12

A different type of cell is shown in Figure 3.12 above. In this example, the three cells are wired together in series. Notice, the voltages of each cell add together because the opposite polarity terminals of the cells are connected. This means the negative terminal of the first cell connects to the positive terminal of the next and so on. Therefore, the three 1.5 volt cells provide a total EMF of 4.5 volts.

With the series-aiding connection, the total voltage across the battery is equal to the sum of the individual values of each cell. However, the current capacity of the battery does not increase, because the total circuit current flows through each cell. So, the current capacity is the same as for one cell.

Series-Opposing Connection

We just discussed the series-aiding connection. This is a very important and widely used method for connecting batteries. However, the series-opposing connection of cells is just the opposite. It has little practical use and is generally avoided. We cover it here to complete your understanding of battery connections. The two cells in this type of connection are linked in a series, but like terminals of the cells are connected together. Here the two voltages cancel each other so that the overall EMF is 0 volts. Because the two voltages cancel, this arrangement cannot produce current flow.

In a series-opposing connection, the three cells are connected in series but cell number 2 is connected backwards. Consequently, its voltage is subtracted from the voltage of the two cells that are connected in series-aiding. The total voltage for cells 1 and 2 is 0 volts. This leaves the output voltage of cell 3. Therefore, the total output of the three cells is only 1.5 volts. Series-opposing batteries with identical voltages act like a short in a circuit.

Parallel Connection

In the series-aiding connection, the output of voltage for cells increases but not the current capabilities of the cells. But, in a parallel connection, there's a way to connect cells so that their current capabilities add together. This is shown below in Figure 3.13. Here, like terminals are connected so that all the positive terminals are connected together as are all the negative terminals.

Figure 3.14 shows why the current capacities of the cells are added together. The total current through the cells is the sum of the individual cell currents. Each cell provides only one third of the total current. Thus, the total current capacity is three times that of any one cell. However,

connecting the cells in this way does not increase their voltage. The total voltage is still the same as for any one cell. If three 1.5-volt cells are used, then the total voltage is 1.5 volts.
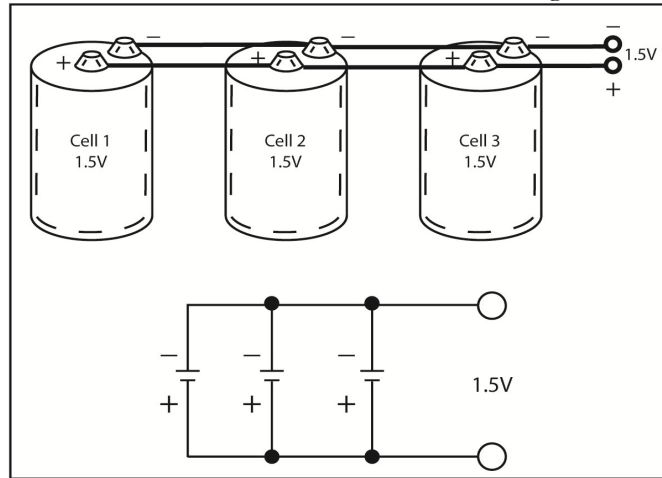
Fig. 3.13
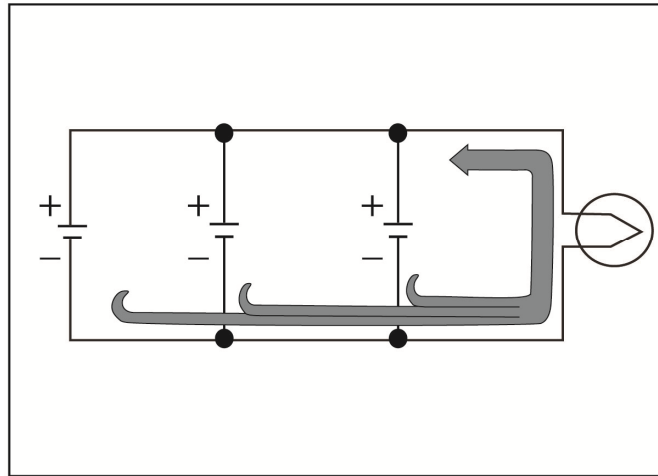
Fig. 3.14

Series Parallel Connection

Cells are connected using this process when both a higher voltage and an increased current capacity are needed. For example, four 1.5 volt cells need to be connected so that the EMF is 3 volts, and the current capacity is twice that of any one cell. To accomplish this, cell 1 and 2 are connected in series, but this does not increase the current capacity. To double the current capacity, cells 3 and 4 must be connected in a second series string parallel with the first string. The result is a series-parallel connection as shown in Figure 3.15.
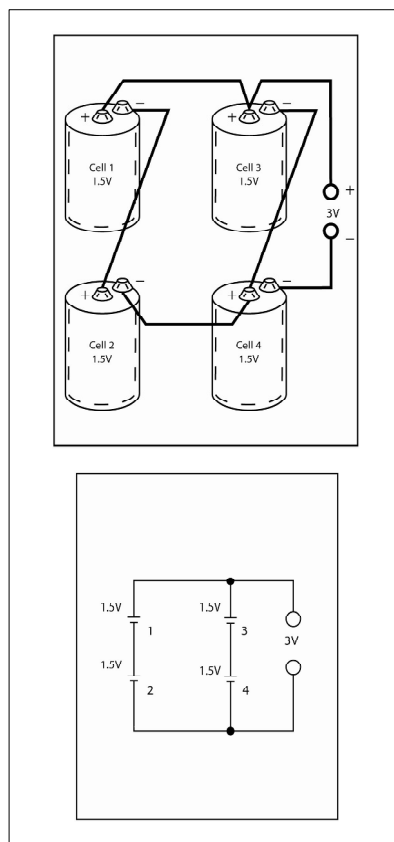
Fig. 3.15

Another example involves a number of identical 1.5 volt cells which will be used to construct a battery with an EMF of 4.5 volts and current capacity three times that of the individual cells. Figure 3.16 shows that nine cells are required for this process. Cells 1, 2, and 3 are connected in a series string to provide 4.5 volts. However, as shown in Figure 3.16 below, to achieve a higher current, three of these strings must be connected in parallel.
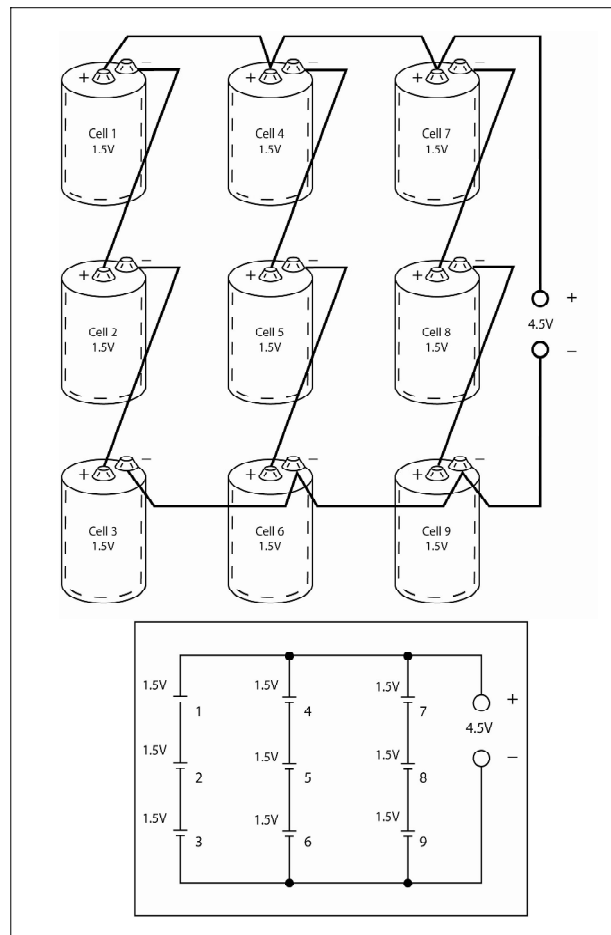
Fig. 3.16

Voltage Rises and Voltage Drops

There are two kinds of EMF or potential difference in electronics and electrical work. Both are expressed in volts but both have different characteristics. One type of EMF is called a *voltage rise*. The other is called a *voltage drop*.

Voltage Rise

Batteries provide an EMF or voltage by chemically producing an excess of electrons at the negative terminal and an excess of positive ions at the positive terminal. When a load is connected across the battery, electrons flow through the load. Each electron, which leaves the negative terminal, is replaced by an electron from the battery. At the positive terminal each electron arriving from the load cancels one positive ion. However, for each ion that is cancelled, the battery produces a replacement ion. Thus, the voltage between the two terminals remains constant even though electrons are constantly flowing from the negative terminal and into the positive terminal.

Energy is required to move the electrons through the load. The battery gives each electron the energy required to make the trip. We have seen that energy in joules is related to the EMF of the battery in volts and the number of electrons moved in coulombs. This energy comes from the chemical reaction within the battery and has a capacity to do work. The amount of work is determined by the voltage of the battery. It's the EMF or voltage of the battery, which causes the electrons to flow in the first place. The battery is the source of the EMF. This type of EMF is referred to as a voltage rise. So, a voltage rise, in an electrical circuit, is just an EMF provided by a voltage source.

The two most common voltage sources are the generator and the battery. Solar cells and thermocouples also produce an EMF so they are considered voltage sources as well. Any EMF introduced into a circuit by a voltage source is called a voltage rise. So, a 12-volt battery has a voltage rise of 12 volts.

Voltage Drop

When electrons leave the negative terminal, they are given energy by the battery. As the electrons flow through the load, they give up their energy to the load, most commonly as heat. However, if the load is a light bulb, both heat and light are given off. The important point is that electrons release to the circuit, the energy given to them by the battery.

Since, this energy introduced into the circuit is called a voltage rise; the energy removed from the circuit by the load is called a voltage drop. Voltage drop is expressed in volts just as with the voltage rise. In fact, the same equation expresses the relationship between volts, joules and coulombs in both cases. The equation is:

$$Volts = Joules/Coulombs$$

With this equation, the voltage drop of a load can be determined if the energy consumed by the load in joules and the number the number of electrons flowing through the load in coulombs is known.

Let's assume that a light bulb releases 15 joules of energy in one second when a current of 3 amperes flows through it. With a current of 3 amperes, 3 coulombs flow through the bulb each second. Using the above equation, we can determine the voltage drop:

$$Equation: Volts = Joules/Coulombs$$

$$Example: Volts = 15 \ Joules / \ 3 \ Coulombs$$

$$Answer: Volts = 5$$

Thus, the voltage drop of the light bulb is 5 volts. It is important to realize that this voltage exists between the two terminals of the bulb, and it can be measured by a meter. In fact, the meter cannot tell the difference between voltage rise produced by a battery and a voltage drop produced by a load. This is the reason that a battery and a light bulb may both have a rating of 12 volts. In the battery's case, it means that the battery supplies 12 volts. This is a voltage rise. However, for the light bulb, it means that 12 volts is required to make it work. This is voltage drop.

One difference between the voltage rise and the voltage drop is that the voltage drop occurs only when current flows through the load. Thus, a battery has a voltage rise whether or not it is connected to a circuit. However, a load produces a voltage drop only when current flows through it.

Voltage Drops Equal Voltage Rises

Let's say a battery provides a voltage rise of 10 volts for a light bulb. As electrons flow through the lamp, a voltage drop is developed across it. Since the lamp consumes the same amount of energy that the battery provides, the voltage drop across the lamp is equal to the voltage rise across the battery. The voltage drop is 10 volts.

Another example uses two light bulbs connected in series across a 10-volt battery. Each bulb drops part of the 10 volts supplied. If the two lamps are identical, each will drop half of the supplied voltage. If the two lamps are not identical, one bulb will drop more voltage than the other. However, the sum of the voltage drops will always equal the sum of the voltage rises.

Concept of Ground

A very important concept in electronics is the concept of a ground. Originally ground was just what the name implies—the earth. In some countries, the name earth is used, instead of ground. Earth is considered to have zero potential. Thus, the earth or ground is the reference point to which voltages are most often compared. Many electrical appliances in your home are grounded. This is especially true of air conditioning units, electric clothes dryers, and washing machines. Often this accomplished by connecting a heavy wire directly to a cold water pipe, which is, buried deep beneath the earth. Other times, a third prong on the power plug connects the metal frame to the ground. The purpose of this is to protect the user in case of a short circuit that may develop in the appliance. It also places the metal parts of different appliances at the same potential so that you are not shocked by a difference in potential between two appliances. This type of ground is sometimes called an *earth ground.*

However, there electronics use a slightly different ground. For example, a certain point in a small transistor radio is called ground although the radio does not connect to the earth in any way. This is the concept of ground with which we will be primarily concerned with in this course. In this case, *ground is simply a zero volt reference point within an electric circuit.* The metal frame or chassis on which the various circuits are constructed is the zero reference point or ground point on large pieces of electronics. All voltages are measured with respect to the chassis.

On a car, the chassis or metal body of the automobile is considered ground. If you look closely at the straps leavening your battery, you will notice that one wire connects directly to the metal frame of the car.

In electronics, ground is important because it allows us to have both negative and positive voltage. Until now, we have been concerned only with relative voltages between two points. For example, a 6- volt battery has an EMF between its two terminals of 6 volts. We haven't worried if this is +6 volts or –6 volts.

Now, the concept of ground permits us to express negative and positive voltages. If we assume that the positive terminal of a 12-volt battery is ground, then the negative terminal is 12 volts more negative. Thus, the voltage at this terminal with respect to ground is –12, negative 12 volts.

Let's assume that the negative terminal of the battery is ground, then the positive terminal with respect to ground is +12, positive 12 volts. Notice that the battery can produce –12 volts or +12 volts depending upon which terminal we call ground.

Many small electronic devices like calculators don't have metal frames. Instead, their components are mounted on a printed circuit board. Here, ground is nothing more than an area of copper on the board. However, as before, all voltages are measured with respect to this point. In this case, ground is simply a common reference, which is the specified starting point for measuring voltages. The most widely used schematic symbol for ground is shown in Figure 3.17. This figure also shows how the ground symbol is used in the circuit.

Ground   Chassis   Common
                                  Circuit

Common Schematic Symbols for Basic
Electrical Items
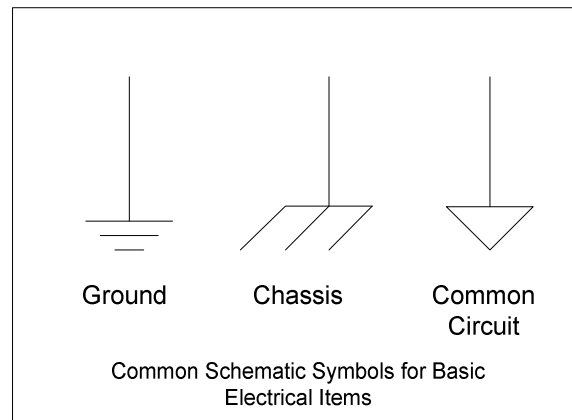
Fig. 3.17

Ground is very important. There's an example in Figure 3.18 below. A 10 volt battery is connected with the positive terminal connected to ground. That is, the positive terminal is the zero point in the circuit. Because the negative terminal is ten volts more negative, the voltage at point A with respect to ground is –10 volts. Thus, we can use the battery as a +10-volt source depending upon where we connect ground.
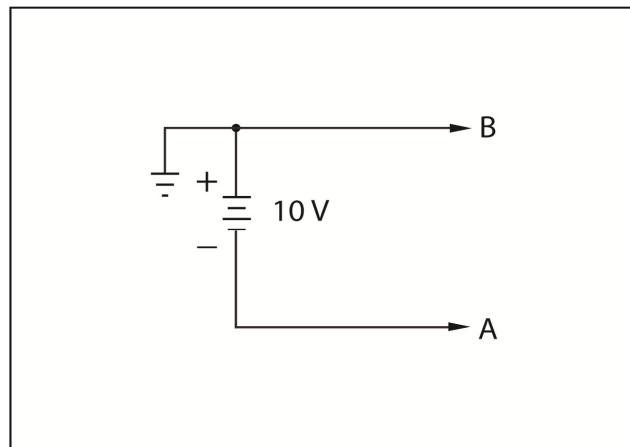
Fig. 3.18

In Figure 3.19, two batteries are connected in series, with the ground connection between them. Thus, the zero reference is at point B. Since the top battery has an EMF of 10 volts, the voltage at point C, with respect to ground, is +10 volts. The lower battery has an EMF of 6 volts. Because the positive terminal is connected to the ground, the EMF at point A, with respect to ground, is –6 volts.
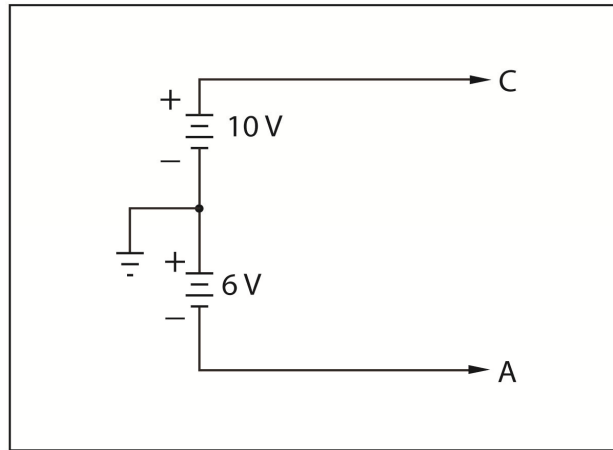
Fig. 3.19

Voltage is always the measure of the potential difference between two points. So, when we speak of the voltage at point A., what we really mean is the voltage between point A and ground.

Measuring Voltage

A voltmeter is used for measuring voltage. There are many different types of voltmeters in use today. Many use a mechanical (analog) meter movement like the one shown here in Figure 3.20 below. Here, you read the voltage on a scale behind the moving pointer.

Analog Voltmeter

Digital Voltmeter

Two Types of Voltmeters
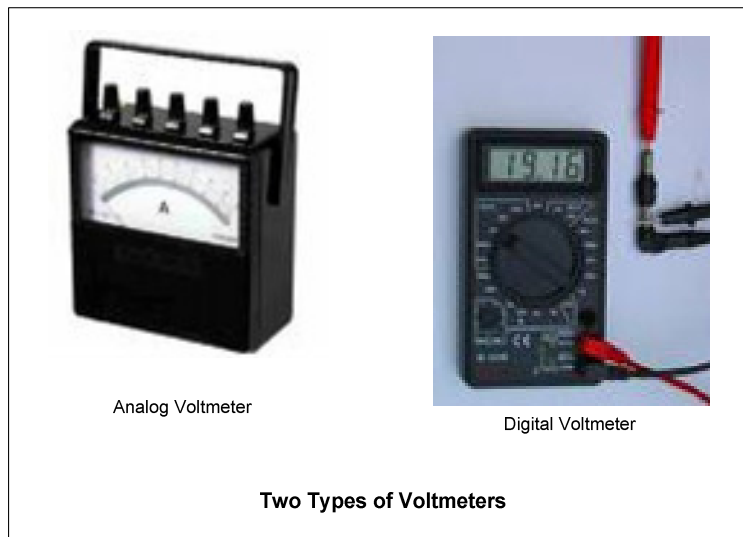
Fig. 3.20

Another type, called the digital voltmeter, is much more popular today. It is shown on the right side of Figure 3.18. Here, the voltage is displayed as numerals. This type of meter is more accurate and easier to read. It's also more expensive.

You must be very careful to take accurate readings. To begin with, voltage is always measured between two points. The schematic symbol for the voltmeter is shown in Figure 3.19 below.
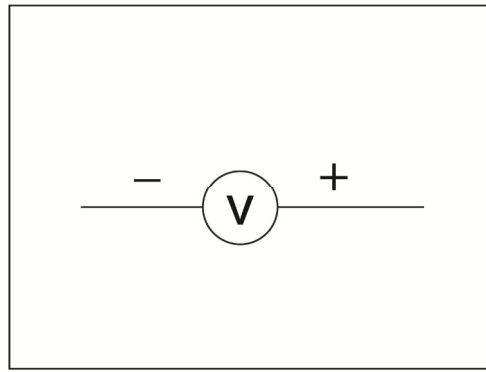
Fig. 3.21

Notice that one of the leads is marked negative while the other is marked positive. As with the ammeter discussed earlier, you should observe polarity when you use a voltmeter. This means that the negative lead must go to the more negative of the two points across which the voltage is measured. Modern digital voltmeters have automatic polarity sensing and can be connected either way in a circuit, but it is a good idea to get into the practice of observing the correct polarity anyway.

Fortunately, the voltmeter is much easier to use then the ammeter. With the voltmeter, the circuit under test does not need to be broken or disturbed in any way. To measure the voltage between two points, you merely touch the two leads of the voltmeter to the two points. However, you need to remember to observe polarity. Figure 3.22 shows how the voltmeter is connected to measure the voltage drop across the lower lamp. Notice that the negative lead is connected to the more negative point. Notice also that the meter is connected directly across the lower bulb.
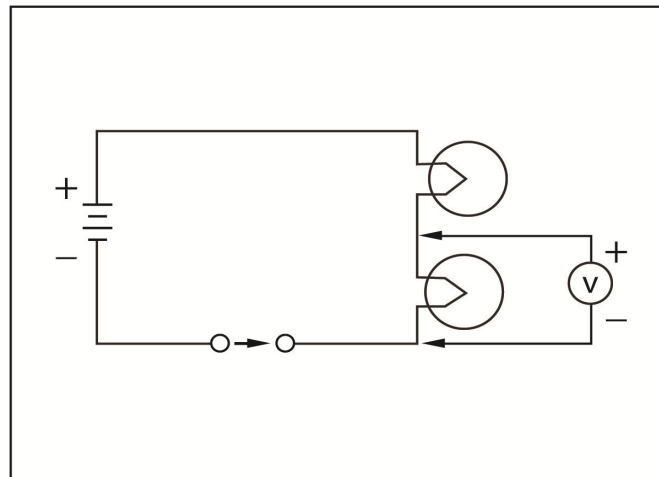
Fig. 3.22

In this case, the meter is measuring a voltage drop. If the switch is opened so that the current flow stops, the voltage drop disappears and the meter reading falls to zero.

Figure 3.23 shows a different circuit with the meter connected to measure the voltage rise of the lower battery. Once again polarity is observed and the meter is connected directly across the component. Here, the meter is measuring a voltage rise, rather than a voltage drop. Therefore, the voltage remains constant when the switch is opened. Notice that the voltage rise does not depend upon current flow.
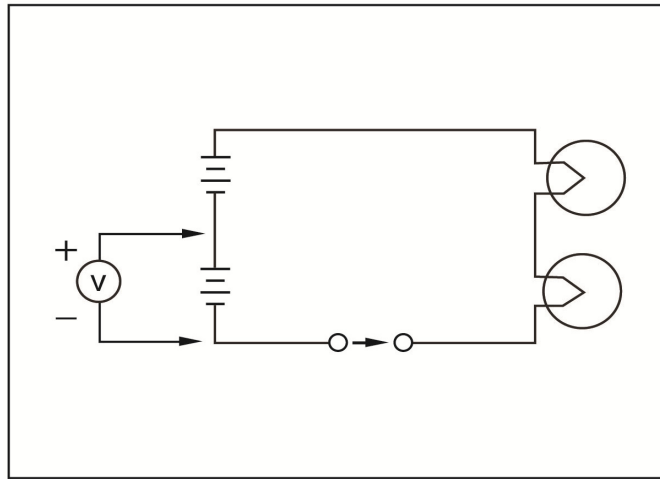
Fig. 3.23

There are some specific precautions that should be taken when using a voltmeter. First, you should always make sure that the voltage you are going to measure is not higher that the meter can measure. If it is, the high voltage may damage the meter. Also, you should be certain the meter is on the proper range. For example, you should not attempt to measure 200 volts with the meter set to the 1 volt range. This could damage the meter. When you are unsure of the value of voltage being measured, make your first measurement with the meter on a high range. This will help prevent the unknown voltage from pegging or damaging the meter.

For your own safety, there are some other precautions that you should observe. You should hold the meter lead only by the insulated portions. When you work on electronic equipment, it is a good idea to connect one lead to ground and leave it there. This way only one hand is required to make voltage measurements. You can hold the other hand away from the equipment. This greatly reduces your chances of receiving an electrical shock, since there is no complete path for the current to flow through your body.

Chapter 4
Resistance

In this chapter we will look at Resistance.

Basic Concepts

If a short length of copper is connected across a battery, so much current will flow that soon the battery will discharge. If the same length of rubber is connected across the same battery, no measurable current will flow. From this example, copper and rubber have very different characteristics when it comes to passing current flow.

The difference stems from the atomic structure of the two materials. In copper, there are a great number of free electrons drifting around aimlessly through the spaces between the atoms. When an EMF is applied, a great number of electrons are free to move. This results in a high current flow. However, with rubber, very few electrons drift around free between molecules. Therefore, an EMF can cause very few electrons to move. This result is little or no current flow.

Copper gives current flow little resistance while rubber offers a great deal of opposition. This opposition to current flow is called *resistance*. Copper has very low resistance while rubber has very high resistance. <u>The resistance of a material is determined largely by the number of free electrons in the material.</u>

The Ohm

The unit for measurement of resistance is the ohm. This unit is named for George Simon Ohm, a German physicist who discovered the relationship between voltage, current, and resistance.

An ohm may be defined in several different ways. Originally, the ohm was defined as the resistance of a column of mercury, which is 106.3 centimeters long, and 1 square millimeter in a cross sectional area. Figure 4.1 graphically represents this. Once the ohm was defined in this way, it allowed anyone with the proper equipment to construct a 1 ohm standard.
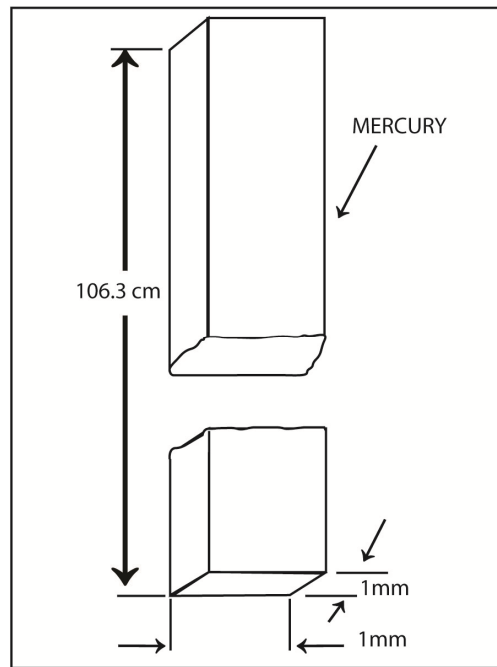
Fig. 4.1

This amount of resistance can be hard to visualize. It can be helpful to think in terms of something that's more familiar. For example, in Figure 4.2 below, 60 feet of insulated, number 22, copper wire has a resistance of about 1 ohm.
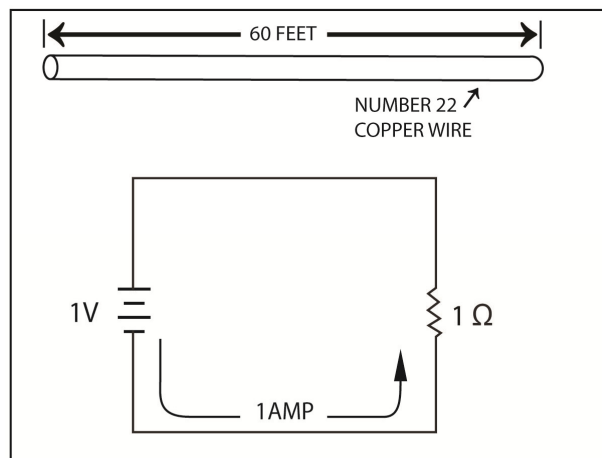
Fig. 4.2

The most common way to define the ohm is in terms of voltage and current. One ohm is the amount of resistance, which allows on ampere of current to flow in a circuit when one volt of EMF is applied, or if one volt causes one ampere of current in a circuit, the resistance of the circuit is one ohm.

The Greek letter omega, Ω, is commonly used to represent ohms. 1 ohm may be written 1Ω, and one thousand ohms may be written as 1000Ω, 1 kilohms, or as $1k\Omega$ (sometimes you may see an upper case K for kilo). Finally, one million ohms may be written as $1,000,000\Omega$, 1 megohm, or as $1M\Omega$. In electronics, the letter R is used to represent resistance. Thus, in shorthand of electronics the statement, <u>the resistance is ten ohms,</u> could be written as an equation:

$$R = 10\Omega$$

Resistivity

The shape, size, and temperature of different substances determine their resistance and make it difficult to directly compare the resistance of two different materials. However, every substance has a property called *specific resistance* or resistivity, which can be compared directly. <u>The resistivity of a substance is defined as the resistance of a one-foot length of wire of the substance</u>. Also, the wire must be exactly 0.001 inch (1 mil) in diameter and the temperature must be exactly 20^0 centigrade. These requirements standardize the shape, size, and temperature of the substance so that only the atomic structure determines the resistance.

The resistivity of several substances is shown in Table 1 below. Silver and copper are the best conductors at the top of the list and have very low resistance. While glass and rubber are the two best insulators, have very high resistivity, and are at the bottom of the list.

Substances	Resistivity in Ohm per Mil. Foot at 20^0 C
Silver	9.9
Copper	10.4
Gold	15.3
Aluminum	17.0
Nichrome	680.0
Glass	10^{16}
Rubber	10^{20}

Table 4.1

Both conductors and insulators are important in electronics. Conductors have many free electrons and can conduct current very easily. Thus, they are used to carry electricity from one place to another. Most metals are good conductors. Thus, metals such as silver, copper, gold, aluminum, tungsten, zinc, brass, platinum, iron, nickel, tin, steel and lead are good conductors.

Insulators or nonconductors are substances, which have few free electrons. They have very high values of resistivity. These substances are used to prevent an electrical connection. Most wires are coated with an insulator so that they do not accidentally short out when they are used to carry electricity. Some example of insulators is glass, rubber, plastic, mica, and dry air.

Conductance

It's important to consider how well a material conducts current. Because of this, a property called conductance is often used. Conductance is just the opposite of resistance. It is defined as the ease with which a substance passes current flow. Mathematically, conductance is the reciprocal of resistance. This simply means that conductance is equal to the number 1 divided by the resistance. :

Conductance =1/Resistance

The letter G is used to represent conductance. Therefore, the equation is:

Equation: G (Conductance) = 1/R (Resistance)

The unit of conductance is the mho, pronounced "moe". Notice that this is ohm spelled backwards. The mho is reciprocal of the ohm. Therefore,

$$Mhos = 1/Ohms$$

A resistance of 1 ohm equals a conductance of 1 mho. However, a resistance of 2 ohms equals a conductance of ½ or 0.5 mhos. Also, if the resistance is 1000 ohms, or 1 kilohm, the conductance is 0.001 mhos or 1 milliohm. The term, *siemens*, is also used as unit of conductance. It has the same meaning as the mho. That is 1 mho equals 1 siemens.

In most cases it is more convenient to think in terms of ohms (resistance) rather than in terms of mhos (conductance). Therefore, in this course, we will be primarily concerned with resistance. However, it is important to remember the mho, because a key characteristic of the vacuum tube and the field-effect transistor is given in mhos.

Factors That Determine Resistance

The single most significant factor in determining resistance is the resistivity of the material. However, three other factors are also important. These are the length, the cross-sectional area, and the temperature of the material.

The insulated wire with this course is number 22 copper wire. A 60-foot length of this wire has a resistance of about 1 ohm. A 129-foot length of the same wire has a resistance of about 2 ohms. If you double the length of the wire, you also double the resistance. In fact, with any material, the greater the length, the higher the resistance will be. The reason for this is that the electrons must travel further through the resistance material. Thus, if the length doubles, the resistance doubles; if the length triples, the resistance triples.

The cross-sectional area of a conductor is determined by its thickness or its diameter. You have seen that good conductors have a lot of free electrons. In fact, the more free electrons per unit of length, the better the conductor. Obviously then, a large diameter conductor has more electrons per unit of length than a small diameter conductor of the same material. Therefore, large diameter conductors have less resistance than small diameter conductors. The resistance of a substance is inversely proportional to its cross-section area. If the cross-section area doubles, the resistance drops to one half its former level. Also, if the area triples, the resistance drops to one third.

When resistivity is defined, the length and the cross-sectional area are carefully defined because they affect resistance. The temperature is also carefully defined for the same reason. That is, with most materials, the resistance changes if the temperature changes. With changes in length and cross-sectional area, you know exactly how the resistance will change. Not only that, but all materials change resistance in the same way. However, with changes in temperature, this is not the case. Not all materials change resistance in the same direction or by the same amount when temperature changes.

In most materials, an increase in temperature causes an increase in resistance. Materials, which respond in this way, are referred to as having a *positive temperature coefficient*. If a material has a positive temperature coefficient, its resistance increases as temperature increases, and decreases as temperature decreases.

A few substances such as carbon have a *negative temperature coefficient*. This means that their resistance decreases as temperature increases. There are also materials whose resistances do not change at all with temperature. These materials have a zero or *constant temperature coefficient*.

In most simple circuits, the temperature coefficients of the components are not critical and are simply ignored. However, in some circuits temperature coefficients are important and you must consider them in a design.

However, temperature characteristics are not always troublesome. A device called a *thermistor* uses these characteristics to great advantage. <u>A thermistor is a special type of resistor, which can achieve a large change in resistance for a small change in temperature.</u> Such devices normally have a negative temperature coefficient. In many thermistors, the resistance value can drop to one half its former value for a temperature rise of 20 degrees centigrade. Thermistors are often used in temperature sensing circuits and as protective devices in other types of circuits.

Resistance of Wire

Below in Table 4.2, you can see the resistance of a length of copper wire. The first column of this table shows the gauge of the wire. The diameter of each wire in this chart is 1.123 as large as the diameter of the succeeding wire. The second column 2 lists the actual diameter of each gauge wire in mils. A mil is equal .001 inches. If you look at #000, pronounced "three aught" wire, you see that it has a diameter of 410 mils. Now if you multiply 410 mils times 1.123 you get the diameter of the next largest size wire; 46 mils for #0000 wire.

Column three contains the cross sectional area of each wire in circular mils. A circular mil is the area of a circle with the diameter of 1 mil.

Columns four and five are the resistance of 1000ft of a given gauge of wire. Column four contains the resistance of the wire at 68^0F. Column five; the resistance values are given at 167^0F. For example, 1000ft of #9 wire has a resistance of .792 ohms at 68^0F and .963 ohms at 167^0F.

If you want to determine the resistance of a specific length of copper wire, you use the formula;

Equation: Length of wire/1000 X Resistance-1000 ft of wire

For example, the resistance of 500 feet of 24 gauge copper wire at 68° F is:

Example: 500ft/1000 X 25.7 ohms/1000 ft = 12.85Ω

You won't always be using copper wire, and each type of material has its own resistivity. So, you must adjust your resistance calculations according to the type of wire that you are using. You can do this by using the conversion factors given in Table 4.3

If you look at this table, you see that the conversion factor for aluminum is 1.59. Therefore, the resistance of aluminum wire is 1.59 times as great as the resistance of the same amount of copper wire. So, if you use the calculations from the previous problem, you see that the resistance of 500 ft of 24 gauge aluminum wire is;

Example: 12.85 ohms x 1.59 = 20.43 ohms.

Using Table 4.3, you can determine the resistance of any of the types of wire shown.

Wire Gauge Number	Diameter in Mils=001 in.	Cross Sectional Area in Circular Mills	Resistance Ohms/1000 Ft Copper 68⁰ F	Resistance Ohms/1000 Ft Copper 167⁰ F
0000	460	211,600	.049	.0596
000	410	167,800	.0618	.0752
00	365	133,100	.078	.0948
0	325	105,500	.0983	.1195
1	289	83,690	.1239	.151
2	258	66,370	.1563	.190
3	229	52,640	.1970	.240
4	204	41,740	.2485	.302
5	182	33,100	.3133	.381
6	162	26,250	.395	.481
7	144	20,820	.498	.606
8	128	16,510	.628	.764
9	114	13,090	.792	.963
10	102	10,380	.999	1.215
11	91	8,234	1.260	1.532
12	81	6,530	1.588	1.931
13	72	5,178	2.003	2.44
14	64	4,107	2.525	3.07
15	57	3,257	3.184	3.87
16	51	2,583	4.016	4.88
17	45.3	2,048	5.06	6.16
18	40.3	1,624	6.39	7.77
19	35.9	1,288	8.05	9.79
20	32.0	1,022	10.15	12.35
21	28.5	810	12.8	15.6
22	25.4	642	16.1	19.6
23	22.6	510	20.4	24.8
24	20.1	404	25.7	31.2
25	17.9	320	32.4	39.4
26	15.9	254	40.8	49.6
27	14.2	202	51.5	62.6
28	12.6	160	64.9	78.9
29	11.3	126.7	81.8	99.5
30	10.0	100.5	103.2	125.5
31	8.93	79.7	130.1	158.2

32	7.95	63.2	164.1	**199.5**
33	7.08	50.1	207	**252**
34	6.31	39.8	261	**317**
35	5.62	31.5	329	**400**
36	5.00	25.0	415	**505**
37	4.45	19.8	523	**636**
38	3.96	15.7	660	**802**
39	**3.53**	**12.5**	**832**	**1012**

Table 4.2

Metal	Resistance Level
Aluminum	1.59
Brass	4.409
Gold	1.38
Iron	6.67
Lead	12.76
Nichrome	60
Nickel	7.73
Platinum	5.80
Silver	0.92
Steel	8.62
Tin	8.2
Tungsten	3.2
Zinc	3.62

Table 4.3

Resistors

<u>A resistor is an electronic component, which has a certain specified resistance.</u>   Other types of components also have some resistance; however the resistor is designed exclusively to introduce a desired amount of resistance into a circuit.

Wire-Wound Resistors

Copper has resistivity of about 10 ohms per mil-foot. You could wrap a one-foot length of 1 mil diameter copper wire on an insulated form and attach contact leads. This would form a 10 oh wire-wound resistor. The actual process for making a practical wire-wound resistor is a little more complicated but the concept is the same. The resistance wire used is generally a nickel-chromium alloy called nichrome, which has a much higher resistivity than copper. The form is often a ceramic tube. After the leads are attached, the entire resistor is covered with a hard protective coating.

Used in high current circuits where relatively high amounts of power must be dissipated, this resistors resistance range can vary from less than an ohm to sever thousand ohms. The wire-wound technique is also used to produce a precise value resistor. Such precision values are required in meter circuits. The top portion of Figure 4.3 shows an example of a wire-would resistor, its different parts, and schematic symbol.
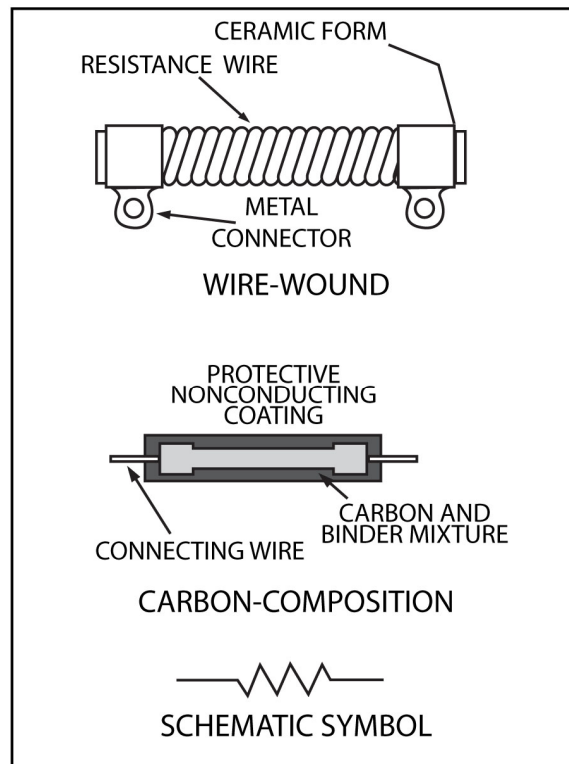
Fig. 4.3

Carbon-Composition Resistors

Carbon isn't a good conductor or a good insulator. Instead, it falls between and is called a *semiconductor*. This makes carbon ideal as a material for resistors. By combining carbon granules and a powdered insulating material in various proportions, a wide range of resistor vales are possible.

To construct this type of resistor, granules of carbon and a binder material are mixed together and shaped into a rod. Wire leads are inserted, and the package is sealed with a non-conduction coating. The carbon-composition conductor is shown in the bottom half of Figure 4.3.

Generally, carbon-composition resistors are used in low current circuits where they do not have to dissipate large amounts of power. Values can vary from 10 ohms or less to 20 megohms or more.

The resistance value is indicated by color bands around the resistor. A chart that shows the color codes for over 160 standard value fixed resistors has been supplied in appendix of this manual. This chart can be used to determine the value of most any carbon-composition resistor you are likely to find.

Deposited-Film Resistors

The film-type resistor is quite popular. In these types of devices, a resistance film is deposited on a nonconductive rod. Then the value of resistance is set by cutting a spiral groove through the film. This changes the appearance of the film to that of a long, flat ribbon spiraled around the rod. The groove adjusts the length and width of the ribbon so that the desired vale is achieved. The most common type is the carbon-film resistor. Here a carbon film is deposited on a ceramic rod. Several metal-film types are also available. One uses a nickel-chromium (nichrome) film on an aluminum oxide rod. Another uses a tin oxide film on a glass rod.

Resistor Ratings

Resistors have three important ratings: resistance (in ohms), tolerance (in percent), and wattage (in watts). If you know what to look for, you can usually determine these ratings by simply examining the resistor. The following paragraphs describe each of these in more detail.

Resistance. We have already discussed this topic in great detail. Resistance is determined by the length, the cross-sectional area, and the resistivity of the material used. With wire-wound resistors, the value is normally written somewhere on the resistor. However, with carbon-composition and film resistors, the value is usually indicated by color bands.

Tolerance. The resistance is rarely the exact value indicated on the resistor. It is extremely difficult and expensive to make the resistor the exact value indicated. For this reason, resistors have a tolerance of +5 percent. Five percent of 1000 is 50. Therefore, the actual value of the resistor can be anywhere from 950 ohms (1000 – 50) to 1050 ohms (1000 + 50). Tolerances of +5 percent, +10 percent, and +20 percent are common for carbon-composition resistors. Precision resistors often have a tolerance of +1 percent or better. Generally, the lower the tolerance, the more the resistor costs.

Wattage. Wattage rating refers to the greatest amount of power or heat that the resistor can dissipate without burning up or changing value. The larger the physical size of the resistor, the more power it can dissipate and the higher the wattage. Carbon-composition resistors generally have fairly low wattage ratings. Ratings of 2 watts, 1 watt, ½ watt, and ¼ watt are the most common. Wire-wound resistors can have much higher wattage ratings. A rating as high as 250 watts is not too uncommon for wire-wound resistors. Figure 4.4 below shows the different dimensions for some of the carbon-composition resisters mentioned in this section.
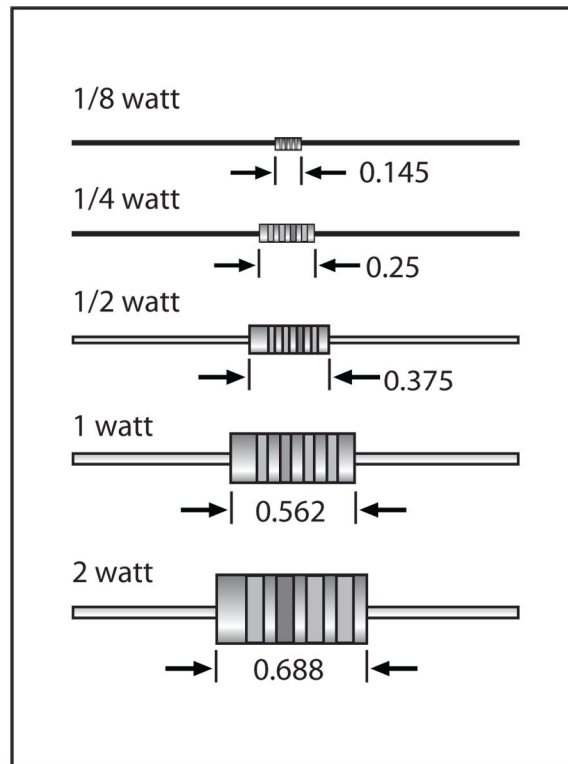
Fig. 4.4

Chip Resistors

Thus far, all of the resistors presented have lead (wires) so you can attach them to other circuitry. These leads take up a lot of room that is not available in many of today's miniature electronic pieces, such as hand calculators, pocket games, and laptop computers, etc., and manufacturers continue to cram more circuitry into a smaller space with every new model.

In Figure 4.5, an internal view of a chip resistor that does not use leads is shown. Instead of leads, it has metal contacts on its ends that allow you to solder it directly to circuit board foils.
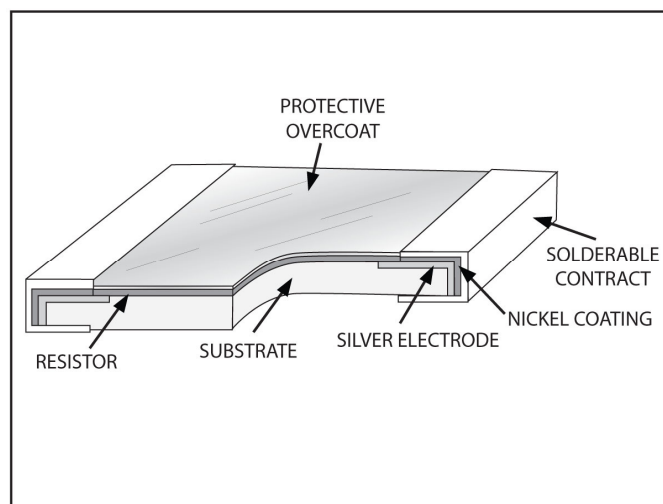
Fig. 4.5

The foundation of the chip resistor is made from an aluminum (ceramic) substrate. First, the substrate is cut to the proper length, width, and thickness, depending upon the required value and

power rating. Next, silver electrodes are attached to opposite end of the substrate. A resistive paste or ink is then applied to the upper surface of the substrate and overlaps the electrodes. After this resistive material dries, it is baked to bond it to the substrate. A thin protective layer of glass protects the resistive material from becoming scratched, contaminated or short-circuited.

Next, the exposed portions of the silver electrodes are coated with a thin film of nickel followed by a thin layer of solder. The nickel layer helps prevent the silver from slowly leaching away from the substrate.

Lastly, solderable contacts are attached to the assembly so that the resistor can be easily connected to other circuitry. Chip resistors are used extensively in a manufacturing technique called surface mount technology (SMT). Chip resistor sizes vary from 0.039" to 0.250" long x 0.019" to 0.125" wide x 0.014" to 0.025" thick.

Variable Resistors

The volume controls on television sets and radios are examples of variable resistors.   The values on these resistors can change by simply rotating a shaft.

In Figure 4.6, the construction of a variable carbon resistor is shown. The bottom portion of this figure also shows a rearview of the inside of the device and how resistance is changed in the resistor. A flat, circular strip of carbon is mounted between the two end terminals. A contact, which moves along the resistant element, connects to the center terminal. This arm is attached to the moveable shaft. If you move the arm in the direction, shown by the arrow, the resistance between terminals 1 and 2 increases. Simultaneously, the resistance between terminals 2 and 3 will decrease. This type of variable resistor is called a *potentiometer* or simply a pot. A potentiometer has three terminals.
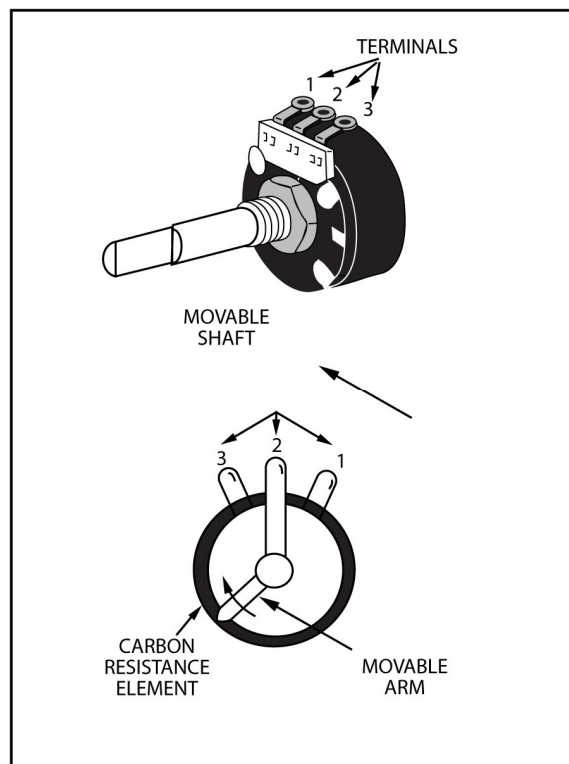
Fig. 4.6

The *rheostat* has only two terminals. So, you can change a potentiometer into a rheostat by removing or not using terminal 3. The resistance between terminals 1 and 2 can still be varied without terminal 3. However, without the third terminal, the flexibility of the device is greatly reduced.

Another time of potentiometers is the wire bound. They are also common. As seen in the top portion of Figure 4.7, many have the same outward appearance as the potentiometer, but the internal construction is slightly different. On the inside of the wire bound resistor, a wire is wound around an insulating core. A contact arm moves along the bare wire and changes the resistance between the center and outside terminals.
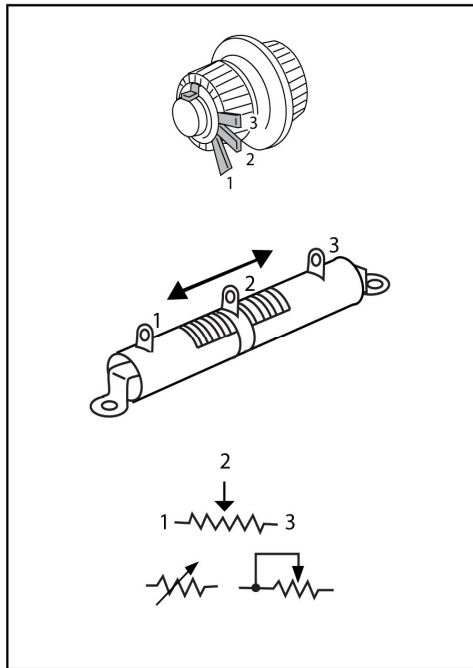
       Fig. 4.7

The sliding-contact resistor is shown in the middle of Figure 4.7. It is used in high-power applications where the resistance value must be initially set or occasionally reset. You can change the resistance value by moving the sliding contact along the bare resistance wire. The bottom portion of Figure 4.7 shows common schematic diagrams representing variable resistors.

Connecting Resistors

Resistors are often connected in series, in parallel, and in series-parallel combinations. To understand and analyze electronic circuits, you must be able to compute the total resistance of resistor networks.

Resistors in Series

In a series circuit the components are linked end to end as shown in Figure 4.8. The current in the circuit must flow through all three resistors one after the other. Therefore, the total opposition to current flow is the total of the three resistances.
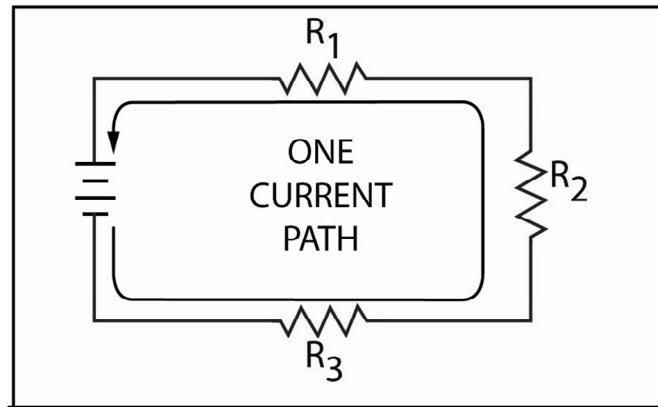
Fig. 4.8

Figure 4.9 below shows an example. Here three resistors are connected in series. The total resistance is called RT and represents the resistance across the entire circuit. To determine R_T add the individual resistor values together.

$$\text{Equation: } R_T = R_1 + R_2 + R_3$$

$$R_T \text{ (Total Resistance)} = 20\Omega + 40\Omega + 60\Omega$$

$$R_T = 120\Omega$$
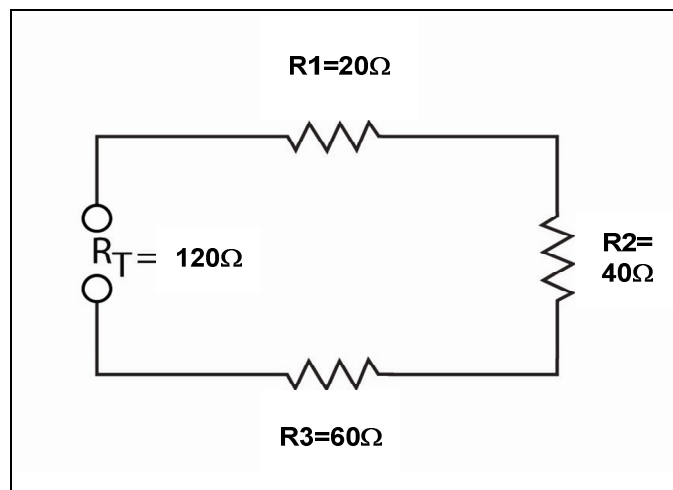
Fig. 4.9

The three resistors in series have the same opposition to current flow as a single 120- ohm resistor.

In the example above, three resisters were used, but the same principle holds true for any number of series resistors. So in a situation like Figure 4.10, 2 k ohm resistor in series with a 4 k ohm resistor has a total resistance of 8 k ohms or 6000 ohms. The circuit shown in Figure 4.11 uses six resistors. Some of the values are given in kilohms while others are given ohms. To avoid confusion, convert all values to ohms. R_1, R_3, and R_5 are already expressed in ohms. R_2 is equal to 2 k ohms or 2000 ohms. R_4 is 1 k ohms or 1,000 ohms, and R6 is 3 k ohms or 3000 ohms. The total resistance is 7.8 k or 7800 ohms.
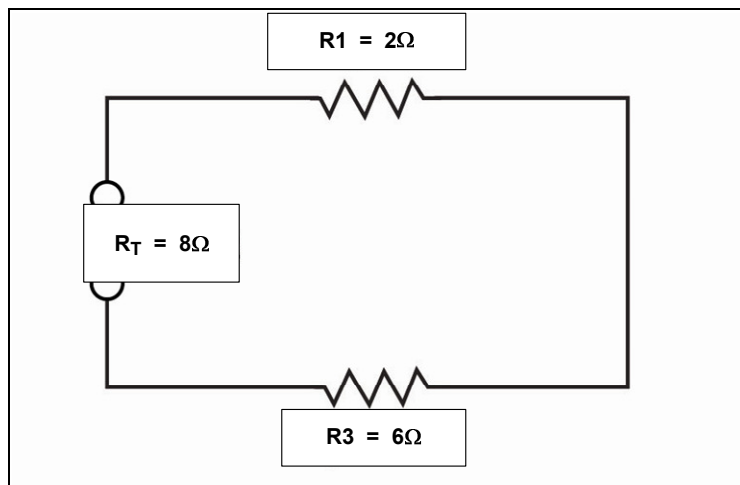
Fig. 4.10

Equation: $R_T = R_1 + R_2 + R_3 + R_4 + R_5 + R_6$

$R_T = 200\Omega + 2000\Omega + 800\Omega + 1000\Omega + 800\Omega + 3000\Omega$

$R_T = 7800\Omega$ or $7.8\ k\Omega$
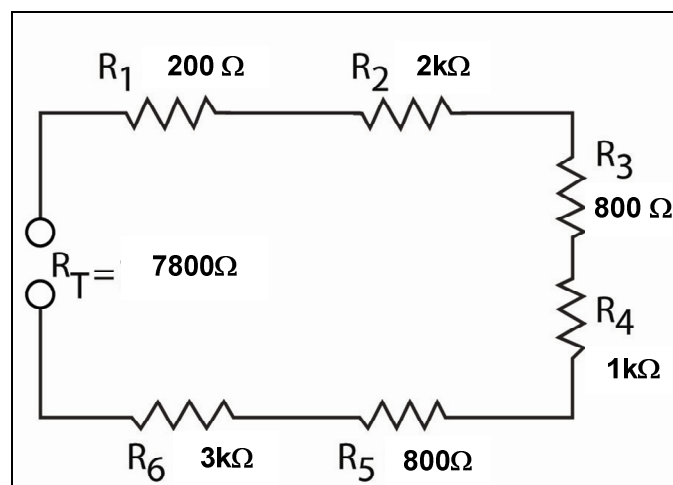
Fig. 4.11

Resistors in Parallel

In parallel circuits, components are connected across each other so that there are two or more paths for current to flow. Figure 4.12 is an example.
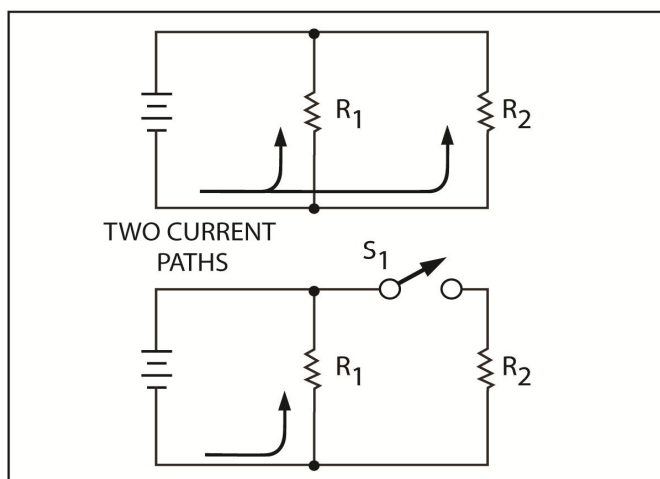
Fig. 4.12

When resistors are in parallel and a switch S_1 is added into the series with R_2 so that it can be switched in and out of the circuit, the only path left for current flow is R_1 when S_1 is left open. The amount of current is determined by the resistance of R_1 and the applied voltage. The current through R_1 is the total circuit current. There's an example of this on the bottom half of figure 4.12 above. Now close the switch and see what happens. The current through R_1 remains unchanged since neither the resistance of R_1 nor the applied voltage has changed. However, an additional current now flows through R_2. Thus, the total current provided by the battery increases. If R_2 has the same resistance as R_1, both resistors will offer the same amount opposition to current flow. Thus, the current through R_1 equals the current through R_2. In this situation, the current provided by the battery doubles when R_2 is switched in parallel with R_1.

The total current provided by the battery always increases when R_2 is placed in parallel with R_1 because a second current path is created. Obviously then, the total opposition to current flow decreases since more current now flows. <u>Thus, when one resistor is placed in parallel with another, the total resistance decreases</u>. Let's assume that R_1 and R_2 are equal, when the switch is closed, the total current doubles. So, the total resistance drops to one half of its former value.

There is a simple formula for finding the total resistance of two resistors in parallel. The formula is:

Equation: $R_T = R_1 \times R_2 / R_1 + R_2$

In Figure 4.13, a 10 ohm resistor, R_1, is in parallel with a 16 ohm resistor, R_2. Find the total resistance R_T:
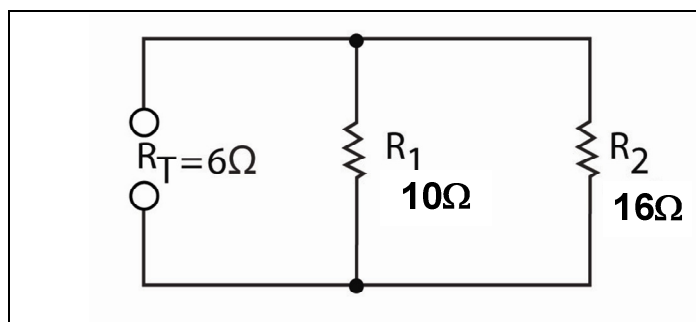
Fig. 4.13

$$R_T = 10\Omega \times 16\Omega / 10\Omega + 16\Omega$$

$$R_T = 160/26$$

$$R_T = 6.15\Omega$$

The total resistance of the circuit is the same as that of 6.15 ohm resistor.

Another example, in Figure 4.14, shows a 2 k ohm resistor is parallel with an 8 k ohm resistor. The formula is shown below.
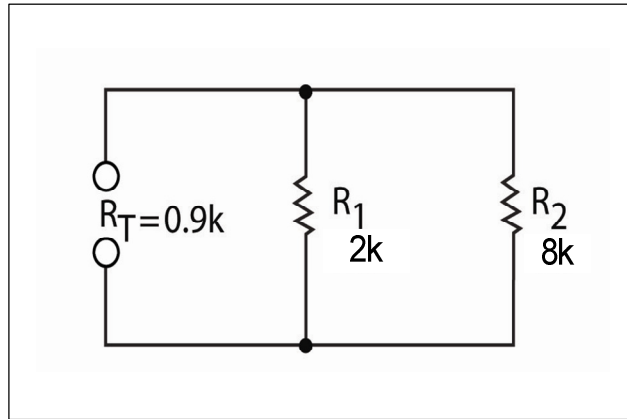
Fig. 4.14

$$R_T = 2000 \text{ x } 8000/ \ 2000 + 8000$$

$$R_T = 16{,}000{,}000/10{,}000$$

$$R_T = 1600 \text{ ohms or } 1.6 \text{ k ohms}$$

Usually, the formula above is used when two resistors are parallel. However, it can be also used with three or more resistors. For example, Figure_____ shows four resistors in parallel. You can use the above formula again to find an equivalent resistance for R_1 and R_2. Then, you can use the formula again to find an equivalent resistance for R_3 and R_4. Finally, you can apply the formula to the two equivalent resistances to find the total resistance. However, this method requires you to use the formula three different times.

There is a better formula to use when more than two resistors are connected in parallel. The formula is:

$R_T=$ 1
_____

$$1/R_1+1/R_2+1/R_3+1/R_4+\ldots1/R_n$$

Use this formula for the circuit shown in the top half of Figure 4.15 to find the total resistance (R_T):

Fig. 4.15

$R_T=$ 1
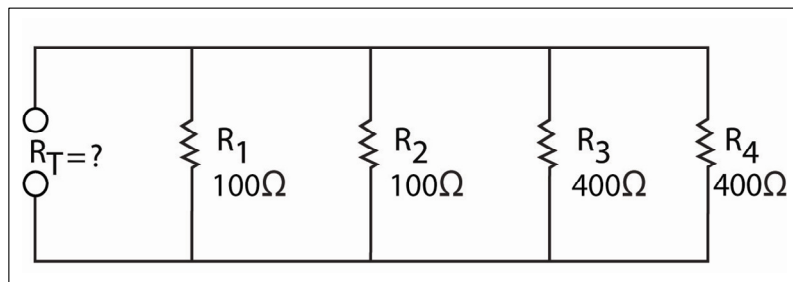
$$\frac{1/100 + 1/100 + 1/400 + 1/400}{1}$$

$$R_T = \frac{1}{.01 + .01 + .0025 + .0025}$$

$$R_T = \frac{1}{.025}$$

$$R_T = 40 \text{ ohms}$$

Equal Resistors in Parallel

Occasionally two or more resistors, which have the same value, are connected in parallel. There is a simple rule, which covers this situation. When all the resistors in parallel have the same value, you can find the total resistance by dividing that value by the number of resistors in parallel. Figure 4.16 shows 40-ohm resistors connected in parallel.

$$R_T = \text{Value of one resistor/ Number of resistors in parallel}$$

$$R_T = 40 \ \Omega/2$$

$$R_T = 20 \ \Omega$$
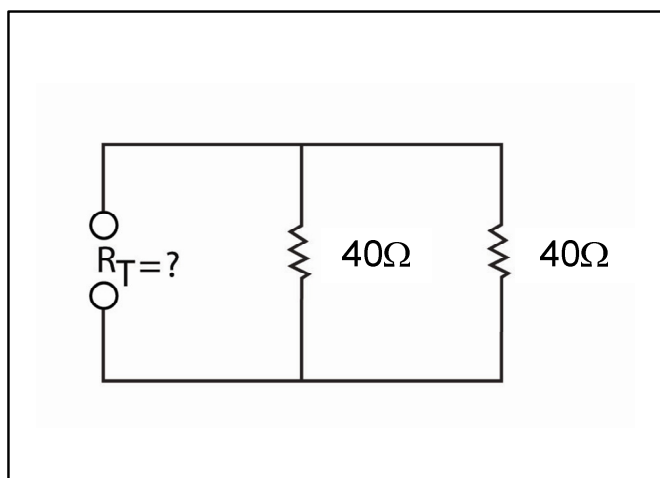
Fig. 4.16

Similarly, when three resistors of the same size are connected in parallel, the total resistance is one-third the value of one resistor. There's an example of this in the Figure 4.17 below.

$$R_T = 200 \ \Omega/3$$

$$R_T = 66.67 \ \Omega$$
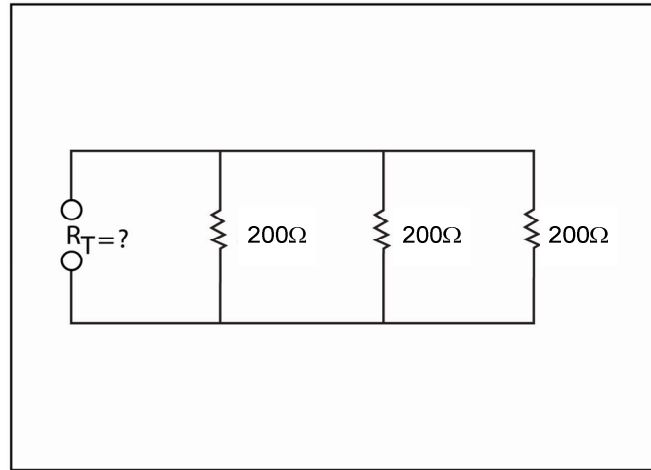
4.17

Series-Parallel Connections

In many circuits things get more complicated, a parallel circuit is connected in series with one or more resistors. Even in this situation, you can use the formulas shown earlier to easily calculate the total resistance. First, calculate an equivalent resistance for the parallel circuit. Then, add this equivalent resistance to the series resistance values.

For example, first find the equivalent resistance for the parallel network made up of $R_2 = 100\Omega$ and $R_3 = 300\Omega$. Call this equivalent resistance R_A. Use the formula for a two-resistor parallel network, we find:

$$R_A = R_2 \text{ x } R_3 / \ R_2 + R_3$$

$$R_A = 100 \text{ x } 300/ 200 + 200$$

$$R_A = 30,000/400$$

$$R_A = 75 \text{ ohms}$$

Now substitute R_A for the parallel network. Once you have the circuit in this simplified form, use the formula for finding the total resistance in a series circuit. The following amounts will help you with this formula, $R1=100\Omega$, and $R4=100\Omega$.

$$R_T = R_1 + R_A + R_4$$

$$R_T = 100 \ \Omega + 75 \ \Omega + 100 \ \Omega$$

$$R_T = 275 \ \Omega$$

The top section of Figure 4.18 is an example of a more complex series-parallel circuit. To figure out the resistance of this circuit, you must first simplify the circuit. The first step is to use the two-resistor parallel network formula to determine the equivalent resistance R_A

$$R_A = R_2 \text{ X } R_3/R_2 + R_3$$

$$R_A = 400 \text{ x } 100/400 + 100$$

$$R_A = 40,000/500$$

$$R_A = 80 \text{ ohms}$$
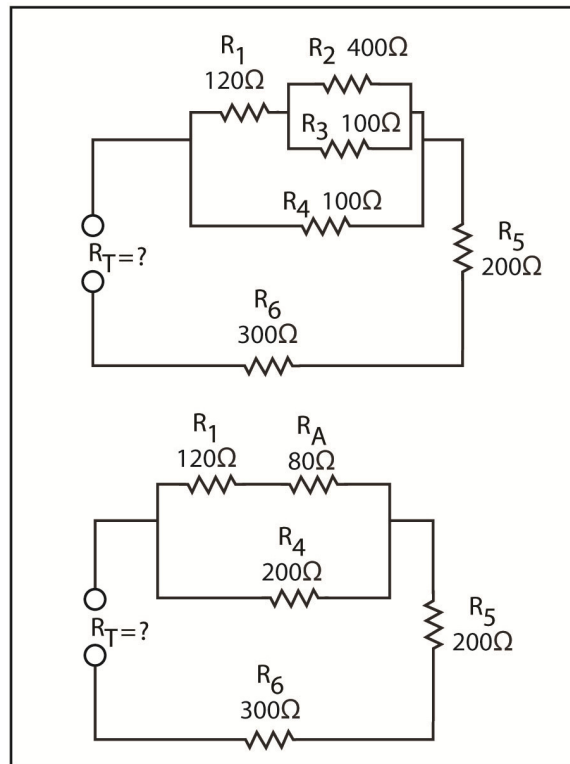
Fig. 4.18

From the bottom section of Figure 4.18 add this value of R_A to R_1 to find the resistance of the one leg of the branch formed by resistors R_1, R_2, and R_3. Call the resistance of the leg, R_B:

$$R_B = R_A + R_1$$

$$R_B = 80 + 120$$

$$R_B = 200 \text{ ohms}$$

We will determine the equivalent resistance of the parallel network made up by R_B and R_4 as shown in Figure 4.19. For this section, employ the equation for resistors having the same value in parallel. Call this resistance R_C.

$$R_C = \text{Value of one resistor/Number of resistors in parallel}$$

$$R_C = 200/2$$

$$R_C = 100 \text{ ohms}$$
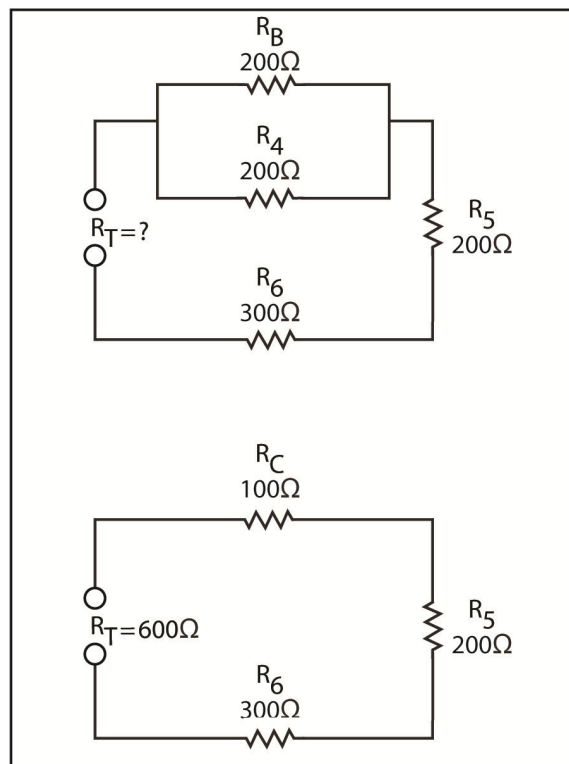
Fig. 4.19

At last, the circuit shown in the bottom of Figure 4.19 has a resistor called R_C in series with resistors R_5 and R_6. In this simplified form, use the formula for total resistance in a series circuit to determine total resistance.

$$R_T = R_C + R_5 + R_6$$

$$R_T = 100 + 200 + 300$$

$$R_T = 600 \text{ ohms}$$

Chapter 5
Ohm's Law

Ohm's Law defines the way in which current, voltage, and resistance are related.

Determining Current

Ohm's Law states current is directly proportional to voltage and inversely proportional to resistance. The source of voltage is the battery. Voltage is the force, which causes current to flow, therefore, the higher the voltage, the higher the current. On the other hand, the lower the voltage is, the lower the current will be. This assumes that current stays constant. Resistance is the opposition to current flow. Assuming that the voltage is constant, the higher the resistance is, the lower the current. Also, the lower the resistance is, the higher the current will be.
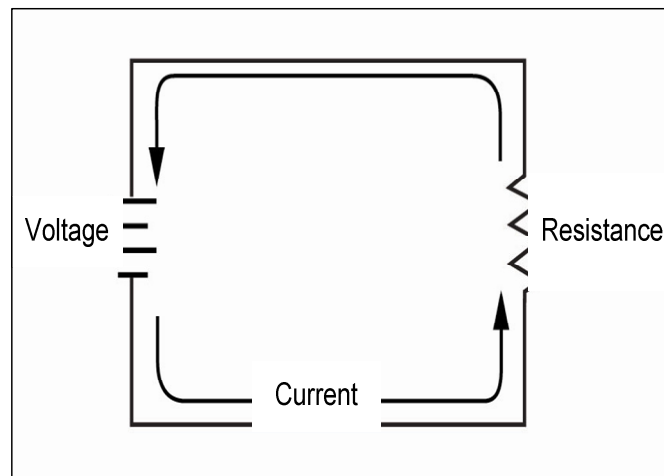
Fig. 5.1

This equation below summarizes these facts:

$$\text{Current} = \text{Voltage} / \text{Resistance}$$

Or, stated in terms of the units of current, voltage, and resistance:

$$\text{Amperes} = \text{Volts}/\text{Ohms}$$

In these formulas, single letters from the alphabet are used represent current, voltage, and resistance. Figure 5.1 graphically represents the different sides of equation. Resistance is represented by the letter R. Voltage by the letter V (for voltage), or the letter E (for EMF). This course uses the letter E to represent EMF or voltage. Current is recognized by the letter I. While this may seem a bit illogical, this convention is used throughout electronics. If you substitute the letters I, E, and R for the quantities current, voltage, and resistance respectively; the formula for current becomes:

$$I = E/R$$

This formula may be used to find current in any circuit in which the voltage and resistance are known. To calculate the current for Figure 5.2, you -plug the known values into the formula:

$$I = E/R$$

$$I = 20 \text{ volts}/ 10 \text{ ohms}$$

$$I = 2 \text{ amperes}$$

All we had to do was divide the 20 into the 10, and we got our answer of 2 amperes. Anytime you divide ohms into volts, the answer is expressed in amperes.
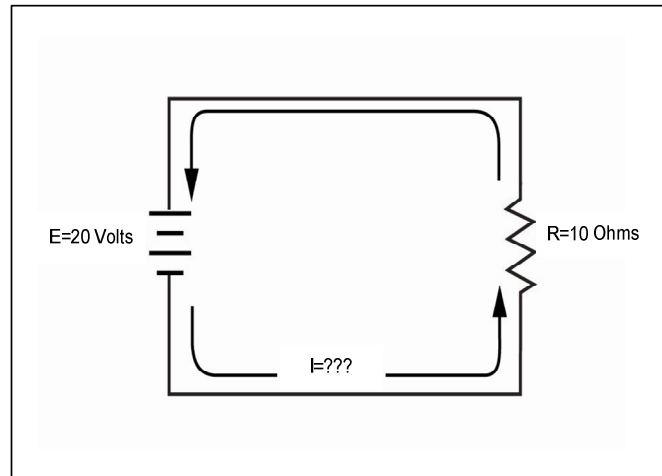
Figure 5.2

Another example is a circuit in which the value of E=200 volts and R=50 ohms are given. When you solve for I, you find that the current is:

$$I = 200 \text{ volts}/ 50 \text{ ohms}$$

$$I = 4 \text{ amperes}$$

The example below shows what happens to current if you double the applied voltage.

$$I = 400 \text{ volts}/ 50 \text{ ohms}$$

$$I = 8 \text{ amperes}$$

When the voltage is doubled, the current also doubles. This is expected, because current is directly proportional to voltage.

What happens if you double the resistance and hold the voltage constant? The current becomes one-half of its former value. This is also expected, because current in inversely proportional to resistance.

$$I = 200 \text{ volts}/ 100 \text{ ohms}$$

$$I = 2 \text{ amperes}$$

Let's calculate how much current flow goes through a 3 k ohm resistor when it's connected to a 9 volt battery. An easy way to solve this problem is to convert the 3 k ohms to 3000 ohms.

$$I = 9 \text{ volts} / 3000 \text{ ohms}$$

$$I = 0.003 \text{ amperes}$$

Recall that 0.003 amperes is another way of saying 3 mill amperes. Because resistance values are often given in kilohms, it is convenient to be able to work problems without converting kilohms to ohms. In current problems, when volts are divided by kilohms, the result is expressed in mill amperes.

For example, how much current flows when a lamp with a resistance of 2.4 kilohms is connected across a 120-volt line? The current in mill amperes is:

$$I = 120 \text{ volts}/ 2.4 \text{ k ohms}$$

$$I = 50 \text{ mill amperes}$$

To check this, convert 2.4 kilohm to 2400 ohms and solve as you did earlier:

$$I = 120 \text{ volts}/ 2400 \text{ ohms}$$

$$I = 0.05 \text{ amperes}$$

Remember that 0.05 amperes is the same as 50 milliamperes.

Resistance is often specified megohms. What would the current be when a 5 megohm resistor is connected across a 25 volt battery? You can convert 5 megohms to 5,000,000 ohms and solve for current in amperes:

$$I = 25 \text{ volts}/ 5,000,000 \text{ ohms}$$

$$I = 0.000.005 \text{ amperes}$$

This is 5 microamperes. Hence, when you divide volts by megohms, the answer is in microamperes. That is:

$$I = 25 \text{ volts}/ 5 \text{ megohms}$$

$$I = 5 \,\mu \text{ amps.}$$

To review what we've covered in this section, the basic formula for current is:

$$I = E / R$$

If R is specified in ohms, you can think of the equation as:
$$\text{amperes} = \text{volts}/ \text{ohms}$$
However, if R is given in kilohms, you can think of the equation as:
$$\text{milliamperes} = \text{volts}/ \text{kilohms}$$
Finally, if R is given in megohms, you think of the equation as:
$$\text{microamperes} = \text{volts}/ \text{megohms}$$

Finding Voltage

In the previous section, we discussed the formula for current.

$$I = E / R$$

If you transpose the above formula, a formula for calculating voltage can be created. The formula must be changed E is on one side of the equation by itself. This is easy to do if you remember a basic algebra rule for transposing equations. The rule states that you can multiply or divide both side of the equation by any quantity without changing the equality. The current equation is: To apply this rule, multiply both sides of the equation by R, as shown below:

$$I \times R = E \times R / R$$

Observe that R appears in both the numerator and the denominator of the fraction on the right side of the equation. Recall from basic mathematics that the two R's in the fraction can cancel each other out. The strikethroughs on the two R's on the right side of the equation represent this canceling out.

$$I \times R = E \times \cancel{R}/ \cancel{R}$$

When the canceled out R's on the right side of the equation are removed, you are left with:

$$I \times R = E$$

   You can switch the two sides of the equation without changing the equality. Interchanging the two sides, you find the basic equation for voltage:

$$E = I \times R$$

In other words, voltage is equivalent to current multiplied by resistance.   Generally, the multiplication sign (x) is omitted so that the formula simply reads:

E=?

R= 100 OHMS

I = 2 AMPS
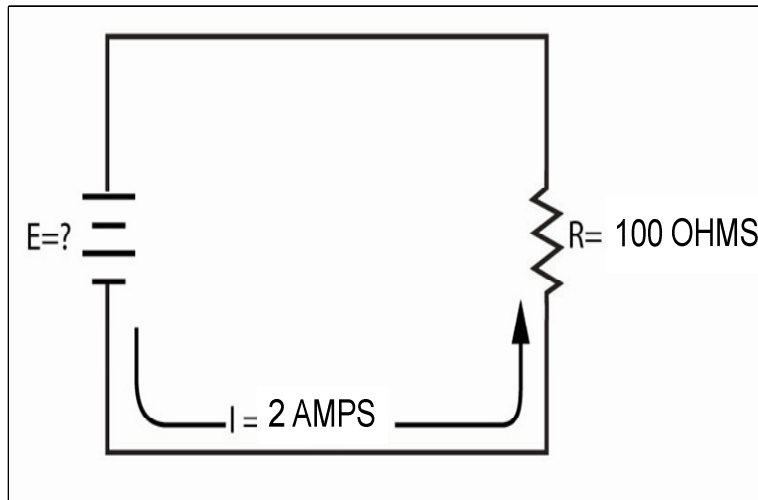
Fig. 5.3

$$E = IR$$

$$E = 2 \text{ amperes} \times 100 \text{ ohms}$$

$$E = 200 \text{ volts}$$

So, when amperes are multiplied by ohms, you end up with volts. Figure 5.3 is an example of the above problem.

E_{R1}=? R_1 = 40 OHMS

R_2

R_3

I = 4 AMPS
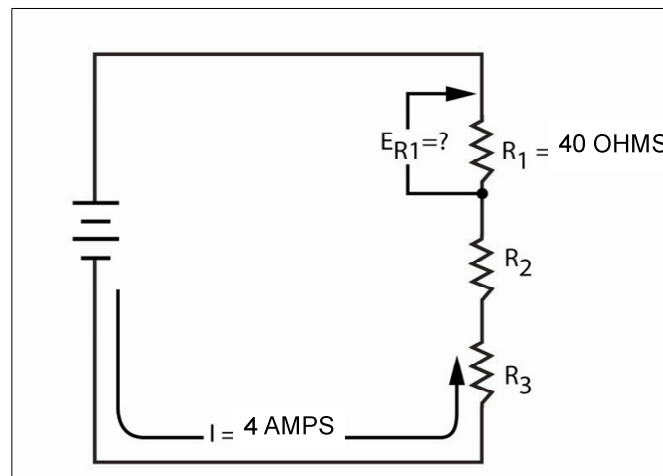
   Fig. 5.4

Figure 5.4 shows a slightly different problem. Here, you wish to find the voltage drop across R_1. Call this voltage ER_1. You know that R_1 is 4 amperes. Consequently, you can find the voltage drop across R_1:

$$ER_1 = I \times R_1$$

$$ER_1 = 4 \text{ amperes} \times 40 \text{ ohms}$$

$$ER_1 = 160 \text{ volts}$$

Figure 5.5 shows two know resistance values connected in a series. The current is provided, but the battery voltage is not. To find the battery voltage you must multiply the total resistance (R_T) times the current. Next, you add the two series resistances to calculate the total resistance.

$$R_T = R_1 + R_2$$

$$R_T = 1.5 \text{ k ohms} + 3.5 \text{ k ohms}$$

$$R_T = 5 \text{ k ohms}$$
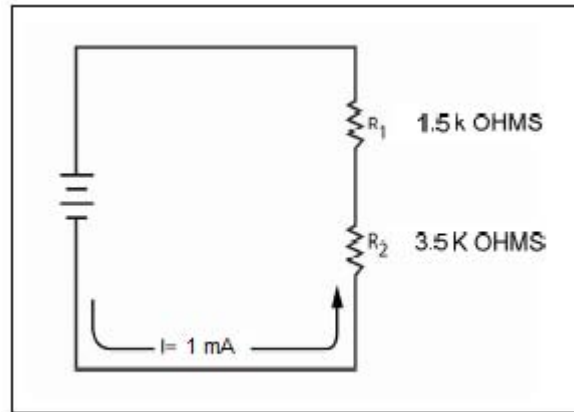
Fig. 5.5

Now, you know the total resistance, you can figure out the voltage, however the resistance is given in kilohms while the current is given in milliamperes. You could change kilohms to ohms and milliamperes to amperes and then solve for volts as you did above. But this is unnecessary, because milliamperes multiplied by kilohms equals volts.

$$E = 1 \times R_T$$

$$E = 1 \text{ milliampere} \times 5 \text{ kilohms}$$

$$E = 5 \text{ volts}$$

In Figure 5.6, a partial schematic presents resistance in megohms.   The current is given in microamperes (μA), and the voltage drop in unknown. Once again, you don't need to convert to ohms and amperes because megohms multiplied by microamperes gives volts. Thus, to find the voltage drop across R, you simply multiply:

$$E = I \times R$$

$$E = 2\mu A \times 7.8 \text{ M}\Omega$$

$$E = 15.6 \text{ volts}$$
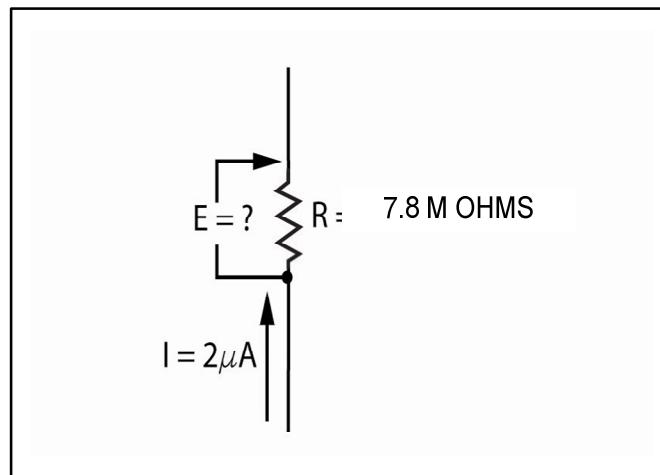
Fig. 5.6

Finding Resistance

The voltage formula can also be changed to produce a used for calculating resistance. To do this, you transpose the voltage formula as follows:

Voltage Formula: $E = IR$

Dividing both sides by I you get:

$E/I = IR/I$

The I's in the fraction on the right cancel each other out. This canceling each other out is represented with the strikethrough in the example of the formula below.

$E/I = \cancel{I}R/\cancel{I}$

So the formula becomes:

$E/I = R$

By switching the equation, you have the formula for resistance:

$R = E/I$

This formula means that resistance is equal to voltage divided by current, or

ohms = volts / amperes
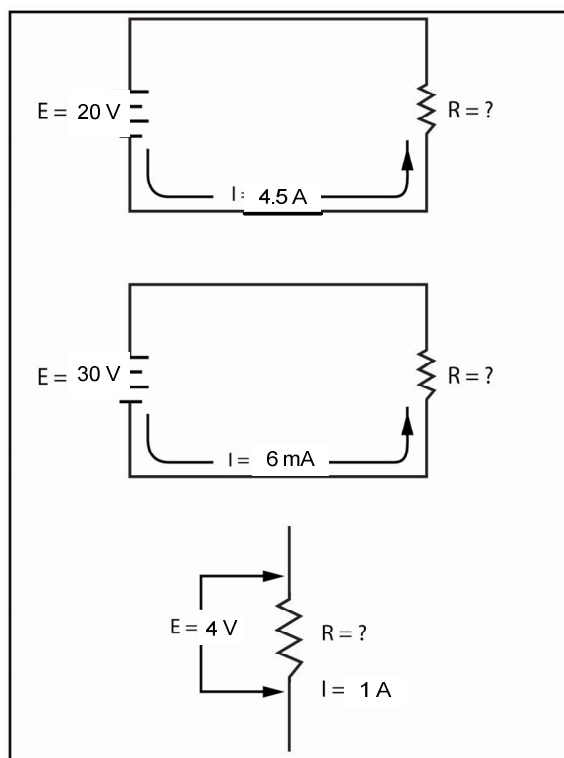
Fig. 5.7

Any circuit's resistance can be found using this formula when voltage and current are known. The top schematic in Figure 5.7 shows such a circuit. Solving for R, you find that:

$$R = E/ I$$

$$R= 20 \text{ V}/ 4.5 \text{ A}$$

$$R= 4.44 \text{ ohms}$$

The middle schematic in Figure 5.7 shows another example. Here, the current is given in milliamperes while the EMF is expressed in volts. When milliamperes are divided into volts the result is kilohms. Thus:

$$R = 30 \text{ v}/ 6 \text{ mA}$$

$$R = 5 \text{ kilohms}$$

You can easily verify this by converting 6 mA to 0.006 A and solving for R:

$$R = 30 \text{ V}/ 0.006 \text{ A}$$

$$R = 5000 \text{ ohms}$$

In the bottom schematic of Figure 5.7, a circuit with a resistance that drops 4 volts when the current is 1 microamp is shown. When micro amps are divided into volts the results is megohms.

$$R = 4 \text{ V}/ 1 \text{ }\mu\text{A}$$

$$R = 4 \text{ megohms}$$

This   can   be   checked   and   proven   by   converting   1   μA   to 0.000 001 amps and dividing.

$$R = 4 \text{ V}/ 0.000001 \text{ A}$$

$$R = 4,000,000 \text{ ohms}$$

Summary

To help remember the three equations involved with Ohm's Law, see Figure 5.8.
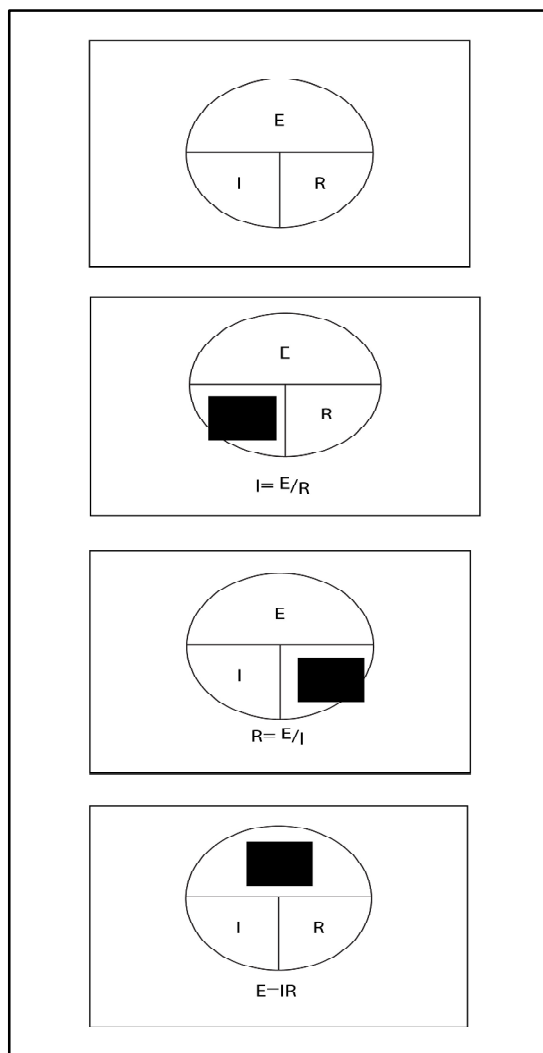
Fig. 5.8

To use the diagram, cover the quantity for which you wish to find the equation. If you wish to find the current, cover the quantity I, as shown in the second down diagram of Figure 5.8. The quantity you covered is the left hand side of the equation. The remaining two symbols represent the right hand side of the equation. Notice that the remaining quantities are:

$$E / R$$

So, the formula would read:

$$I = E / R$$
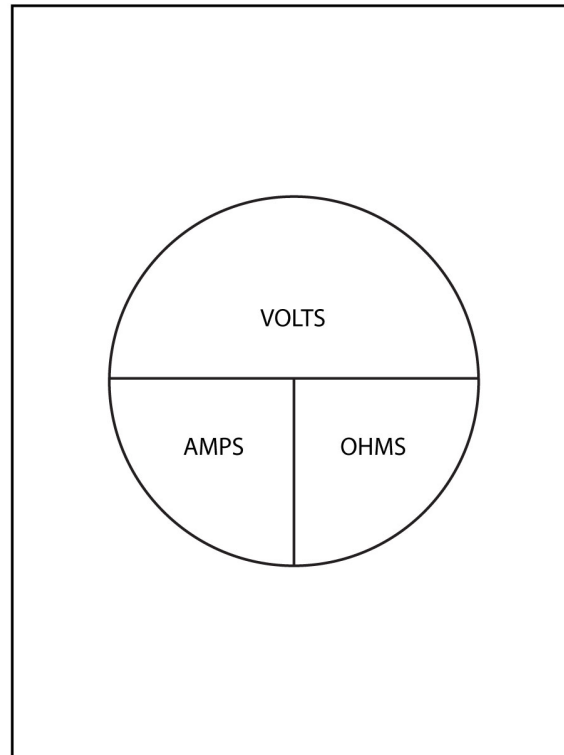
Fig. 5.9

Figures 5.9, 5.10, and 5.11 show some other handy diagrams that indicate how the quantities are grouped with and without metric prefixes. In Figure 5.9, no metric prefixes are used with any of the quantities. In any Ohm's Law problem, if two of the quantities are given in the units shown in Figure 5.9, then the third quantity is given in the third unit. For example, if resistance is given in ohms while voltage is given in volts, then current is in amperes.
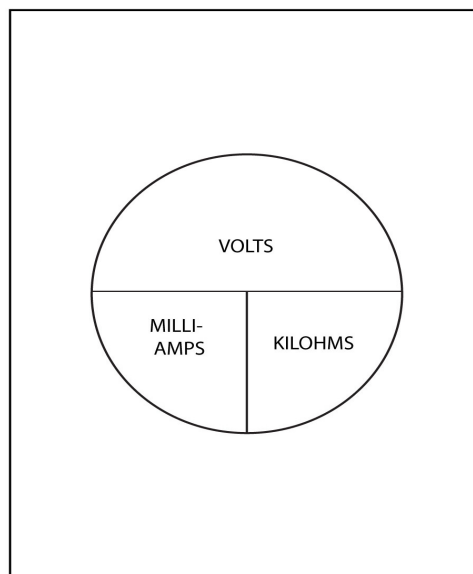
Fig. 5.10

In Figure 5.10, EMF is still presented in volts. However, current is given in milliamperes while resistance is given in kilohms. It is important to remember that these three quantities go together.

Thus, if resistance is given in kilohms while EMF is given in volts, the current is in milliamperes. Or, if current is in milliamperes while resistance is in kilohms, the EMF is in volts.

In Figure 5.11, the similar relationship exists between volts, micro amps, and megohms is demonstrated. For example, if EMF is given in volts and current is given in microamperes, resistance is in megohms.
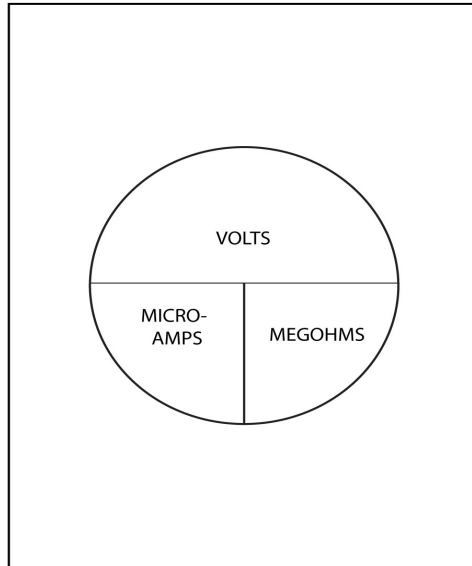
Fig. 5.11

Power

We have already discussed the three basic electrical quantities of current, voltage, and resistance. A fourth quantity called power is also very important. <u>Power is defined as the rate at which work is done, or the amount of work done in a specific length of time</u>. Power use or loss in a circuit is called *dissipation*.

Work and Power

Earlier, we learned that a joule is equal to the amount of work done by one volt of EMF when moving one coulomb of charge. Notice there is no time quotient mentioned in this definition. Thus, the same amount of work is done whether the charge is moved in one second or in one hour.

The English unit of work (the foot-pound) is easier to visualize than the joule. If one pound is lifted vertically, then one foot-pound of work is completed. The joule is equal to 0.738 foot-pounds. Therefore, the watt is equal to 0.738 foot-pounds per second. The unit of mechanical power in the English system is the horsepower. The horsepower is equal to 550 foot-pounds per second. In other words, if 550 pounds are raised one foot in one second, one horsepower is expended. In terms of watts, the horsepower is equal to 746 watts. Or, stated another way, the watt is equal to 1/746 or 0.00134 horsepower.

Power, Current, and Voltage

It's already been mentioned that a watt is equal to one joule per second. This means that a watt is the work done in one second by one volt of EMF when moving one coulomb of charge. If one coulomb of charge flows in one second, the current is one ampere. So, one watt is the amount of power used in a circuit when one ampere of current flows because one volt of EMF is applied.

Power is directly proportional to both current and voltage. Thus, the formula for power is:

$$power = Current \ x \ \ Voltage$$

Or, stated in terms of the units of the three quantities:

$$watts = amperes \ x \ volts$$

The symbol P is used to represent power in equations. Hence, the formula for power is:

$$P = I \ X \ E$$

$$P = I \ E$$

Following Ohm's Law, there are two other useful forms of this equation. The first expresses voltage in terms of current and power. You can create it by rearranging the first equation.

Dividing both sides by I:

$$P/I = I E / I$$

Canceling the two I's on the right side.

$$P/I= E$$

Interchanging the two sides of the equation:

$$E = P/ \ I$$

This equation states that voltage (in volts) is equal to power (in watts) divided by current (in amperes).

Another useful form of the equation is:

$$I = P \ / \ E$$

To summarize, power, voltage, and current are related by the following formulas:

$$P = I \ E,$$

$$E=P/I$$

$$I =P/E$$

 Following are some examples using these formulas. What is the power dissipated in a circuit in which an EMF of 40 volts is applied and a current of 2.2 amperes flows?

$$Let's \ Try \ this \ formula: P = I \ E$$

$$P = 2.2 \ amperes \ x \ 40 \ volts$$

$$P = 88 \ watts$$

How much current flows through a 50 watt light bulb, which is connected across a 60 volt power line?

$$Let' \ use \ the \ formula: I = P/E$$

$$I = 50 \ watts/ \ 60 \ volts$$

$$I =0.833 \ amperes$$

What is the voltage drop across a light bulb that dissipates 50 watts when the current through the bulb is .75 amperes?

$$E = P/I$$

$$E = 50 \text{ watts}/0.75 \text{ amperes}$$

$$E = 67 \text{ volts}$$

Power Dissipation in Resistors

Power is dissipated as heat in resistors and most other electronic components. Sometimes, the heat produced is a desired result. For example, the purpose of the resistance element in a toaster, heating pad, and electric stove is to produce heat. However, in most electronic devices, the heat produced by resistors is wasted power. The power lost when resistors heat up must be supplied by the power source. Since electrical power costs money, the power lost through resistors should be to a minimum.

Since resistors dissipate power, there are formulas for power that also involve resistance. There are actually two formulas that do this. One expresses power in terms of voltage and resistance. The other expresses power in terms of current and resistance. Here's how you derive these equations:

First, consider how P can be expressed in terms of E and R. The basic formula for power is:

$$P = I \times E \text{ or } P = E \times I$$

However, from Ohm's Law you know that:

$$I = E/R$$

So, you can substitute the I part of the equation with E/R, because they are actually equal to each other a shown in the equation above. When you do this, the equation becomes:

$$P = E \times E/R \quad \text{or} \quad P = E^2/R$$

Use this formula when you want to find the power but only the voltage and resistance are known. For example, how much power is dissipated by a 50 ohm resistor if the voltage drop across the resistor is 6 volts?

$$P = E^{2/}R$$

$$P = 6^2/50$$

$$P = 36/50$$

$$P = .72 \text{ watts}$$

How much power is delivered to a 20 ohm circuit by a 12 volt battery? Use the formula expressed above.

$$P = 12^2/20$$

$$P = 144/20$$

$$P = 7.2 \text{ watts}$$

Sometimes, only the current and resistance are known. By, combining the basic power formula with one of the Ohm's Law formulas, you can develop an equation in which P is expressed in terms of I and R. Remember that the basic power formula is:

$$P = I \times E$$

From Ohm's Law, we can recall that:

$$E = I \times R.$$

So, you can substitute IR for E in the power formula. The equation becomes:

$$P = I \times I R$$

$$P = I^2 R$$

This formula can be used when you wish to find power but only current and resistance are known. For example, how much power is dissipated by the circuit shown at the top of Figure 5.12?

80Ω

0.5 AMPS

$R_1 = 20\Omega$

$R_2 = 10\Omega$

2 AMPS

$R_3 = 30\Omega$
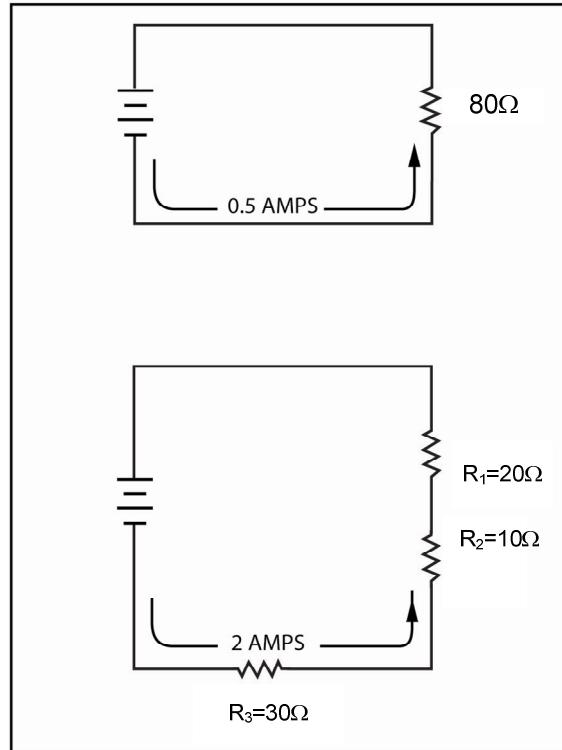
Fig. 5.12

$$P = I^2 R$$

$$P = 0.5 \times 80$$

$$P = 0.25 \times 80$$

$$P = 20 \text{ watts}$$

In the next example, we are trying to figure out how much power will be dissipated by R_1 in the circuit at the bottom of Figure 5.12.

$$P = I^2 \times R_1$$

$$P = 2^2 \times 20$$

$$P = 4 \times 20$$

$$P = 80 \text{ watts}$$
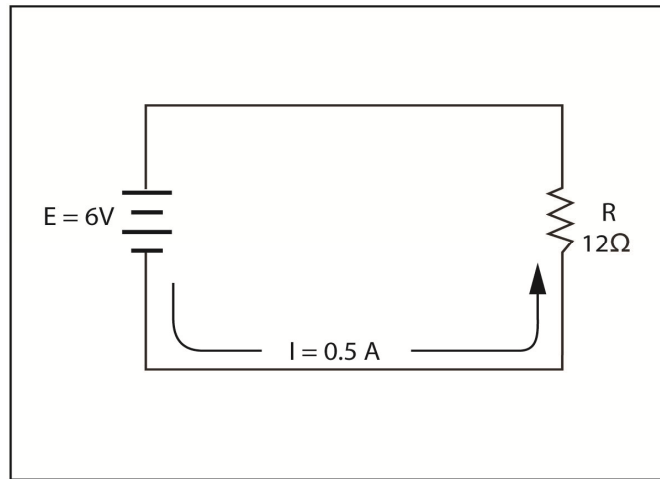
Fig. 5.13

The above equations can be checked for accuracy by working a sample problem three different ways. Look at Figure 5.13 for the values. In this circuit where the current and voltage are given, so you can use the formula P = I E:

$$P = 0.5 \times 6$$

$$P = 3 \text{ watts}$$

Or, if voltage and resistance are given, you can use the formula:

$$P = E^2 / R$$

$$P = 6^2 / 12$$

$$P = 36/12$$

$$P = 3 \text{ watts}$$

When current and resistance are given, you can use the formula:

$$P = I^2 R$$

$$P = 0.5^2 \times 12$$

$$P = 0.25 \times 12$$

$$P = 3 \text{ watts}$$

Notice that the same result is achieved regardless of the power equation used.

Deriving More Equations

We have seen that the basic equation for power, P = IE can be rearranged to form current and voltage equations like:

$$E = P/I \text{ and } I = P/E$$

The equation can also be reworked as shown previously with other equations, to read:

$$P = E^2 / R$$

This equation can be rearranged to form an equation for voltage by multiplying both sides by R:

$$P \times R = E^2 / R \times R$$

The two R's on the right cancel:

$$P \times R = E^2 / \cancel{R} \times \cancel{R}$$

So, you're left with:

$$P \times R = E^2$$

Now you can take the square root of both sides of the equation to get rid of the exponent:

$$\sqrt{PxR} = \sqrt{E}^2 \text{ or } \sqrt{PxR} = E$$

This equation expresses voltage in terms of power and resistance. In this problem, the resistance is 900Ω and the power is 4 watts, but the voltage is unknown.

$$E = \sqrt{PR}$$

$$E = \sqrt{4x900}$$

$$E = \sqrt{3600}$$

$$E = 60 \text{ volts}$$

In the same way, the equation $P = I^2 R$ can be converted to a current equation with a little re-working. Divide both sides by R and let the R's on the right side cancel:

$$P/R = I^2 \cancel{R}/\cancel{R}$$

All that's left is:

$$P/R = I^2$$

Take the square root of both sides:

$$\sqrt{P/R} = I$$

Thus, current can be expressed in terms of power and resistance by rearranging the equations:

$$P = I^2 \ R \text{ and } P = E^2 /R$$

You can also create equations for R in this instance; however. The process is not shown, but the final equations are:

$$R = P/I^2 \text{ and } R = E^2/P$$
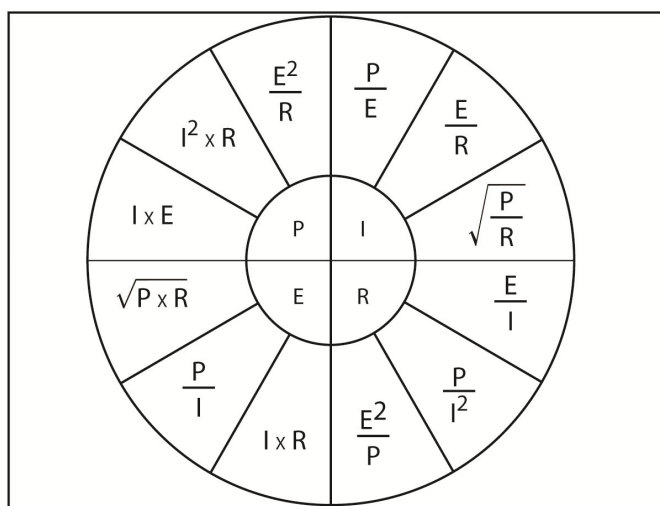
Fig. 5.14

In this section, we discussed twelve important formulas. The wheel diagram above, in Figure 5.14, may help you remember these equations. The inner circle contains the four basic units: power, current, voltage and resistance. The outer circle contains three formulas for each quantity. For example, the three formulas for resistance are:

$$R = E/I$$

$$R = E^2/P$$

$$R = P/I^2$$

The circle can be used find the proper formula for any problem in which two of the quantities are known. While it is not necessary to memorize these 12 equations, you should memorize the basic Ohm's Law and power formulas as soon as possible. You should know these two equations:

$$E = I\ R$$

$$P = I\ E$$

If you know these two formulas, you can create any of the other formulas. Until, you are more familiar with these equations, use the diagram of the wheel.

Summary

The following is a point-by-point summary of this unit.

Ohm's Law defines the relationship between the three fundamental electrical quantities. It describes how current, voltage, and resistance are related.

Formulas are used to define the relationship. In these formulas, the letter I is used to represent current; E is used to represent voltage; and R is used to represent resistance. The current formula states that current is equal to voltage divided by resistance. Or, stated as an equation:

$$I = E/R$$

The unit of current in the equation depends upon the units of voltage and resistance. If you assume that EMF is expressed in volts, current is in amperes if the resistance is in ohms. However, the current is in milliamperes if the resistance is in kilohms. Finally, the current is in microamperes if the resistance is in megohms.

The voltage formula states that voltage is equal to the current multiplied by the resistance.

$$E = I \times R.$$

E is expressed in volts when I is in amperes and R is in ohms. E is also in volts when I is in milliamperes and R is in kilohms. Finally, E is in volts when I is in microamperes and R is in megohms.

The resistance formula states that resistance is equal to voltage divided by current.

$$R = E/I$$

If you assume that E is given in volts, and R is in ohms when I is in amperes. However, R is in kilohms   when   I   is   in milliamperes. Finally, R is in megohms when I is in microamperes.

It can be difficult to remember which of the metric prefixes go together when you solve Ohm's Law problems, but it's very important. A trick to work around this is to convert all quantities to volts, ohms, and amperes; you can solve any Ohm's Law problem without worrying about metric prefixes.

Power is the rate at which work is done. The unit of work is the joule while the unit of power is the watt. The watt is equal to one joule per second. Expressed in English units, the watt is approximately equal to three-fourths of a foot-pound of work per second. The horsepower is equal to 746 watts or about three-fourths of a kilowatt. The watt can also be expressed in terms of current and voltage. The watt is the amount of power that is expended when one volt of EMF causes one ampere of current.

The letter P is used to represent power in equations. Power is equal to voltage multiplied by current.

$$P = I \times E$$

Power can also be expressed in terms of current and resistance or in terms of voltage and resistance.

Chapter 6
The Magnetic Field

This chapter talks about magnetic fields, electromagnets, induction, AC and DC generators, and magnetic and electromagnetic application.

Fields

Many happenings that are too grand or microscopic for us to see in science are often explained in terms of fields. Take for instance, how a charged particle can attract or repel another charged particle simply by coming close to it. A region of electrical influence extends outside each particle. This region of influence is called a field. Many scientists agree that an electrical field made up of lines of force that exist around every charged particle.

The idea of fields also helps explain why certain metals attract and repel each other. Its common knowledge that a magnet attracts small pieces of iron or steel. A region of influence extends outside the magnet into the surrounding space. This region is called magnetic lines of force. Thus, a magnet is a piece material which has a magnetic field surrounding it.

Magnets

Magnets have many classifications. First, they can be classified according to the method by which they obtain their magnetic field. The first recognized magnets were natural magnets called magnetite or lodestone. These materials have a magnetic field in their natural state. Artificial magnets are created from natural magnets. This occurs when you rub soft iron repeatedly over a piece of lodestone, a magnetic field transfers to the iron. Another type of magnet is the electromagnet which produces its magnetic field from an electrical. We'll learn about the electromagnet in detail later.

Magnets are also classified by their shapes. Thus, there are horseshoe magnets, bar magnets, ring magnets, etc.

Some materials maintain their magnetic fields for longer periods of time. These are called permanent magnets. Other materials lose their magnetism more quickly and are called temporary magnets. Both of these types are widely used in electronics.

Finally, magnets are classified by the type of material, such as metallic magnets and ceramic magnets. This is often carried even further and they are named according to the alloy used I the magnets. Two popular classifications are Alnico (an alloy of aluminum, nickel, and cobalt) and Cunife (an alloy of copper, nickel, and iron).
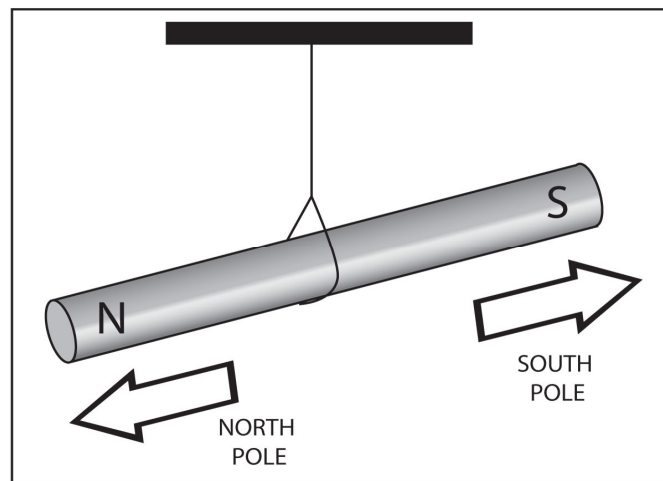
Fig. 6.1

The two ends of a magnet have opposite characteristics. One end is call a south (S) pole while the other end is called a north (N) pole. One reason for choosing these names is that a bar magnet will align itself in a north-south direction if you allow it to hang freely. There's an example of this in Figure 6.1. The north (N) pole of the magnet is defined as the end which points towards the north pole of the Earth. This is shown in Figure 6.2
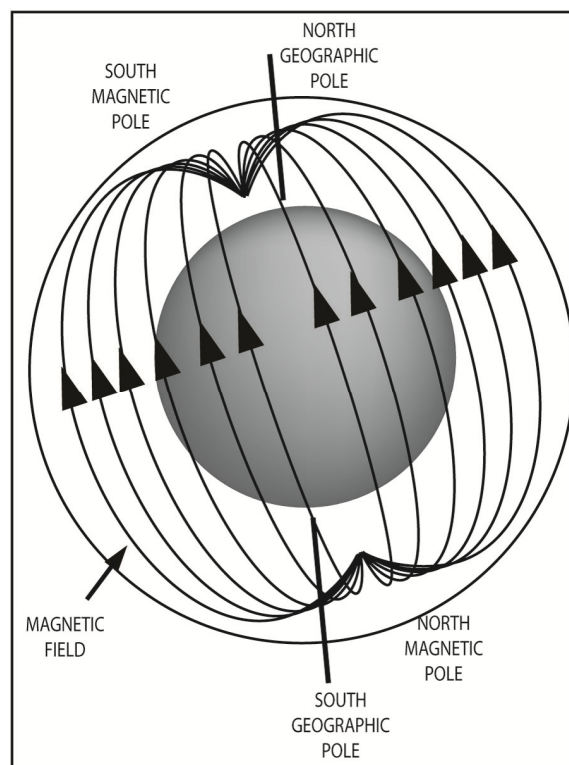
Fig. 6.2

Magnets align this way, because the Earth is a huge magnet. The magnetic compass was used by explorers for centuries as a guide for direction. The compass is nothing more than a tiny magnet balanced on a pin so that it rotates freely.

Magnets tend to align in a north-south direction to a *fundamental law of magnetism*. This law states that like poles repel while unlike poles attract. This is illustrated in Figures 6.3 and 6.4. To see why magnets behave in this way, you must consider the nature of the magnetic lines of force.
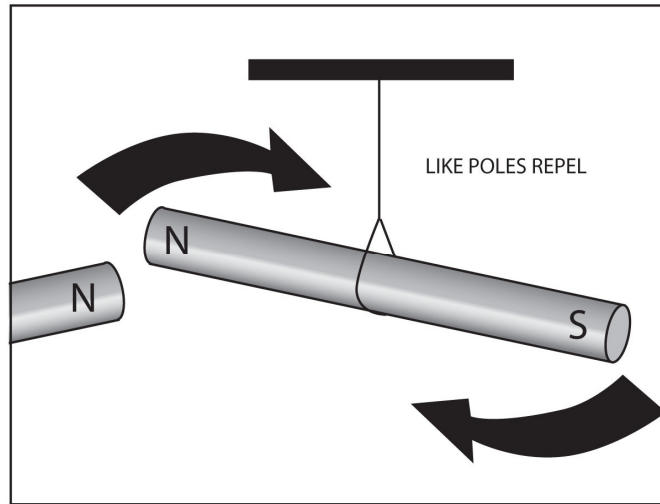
Fig. 6.3
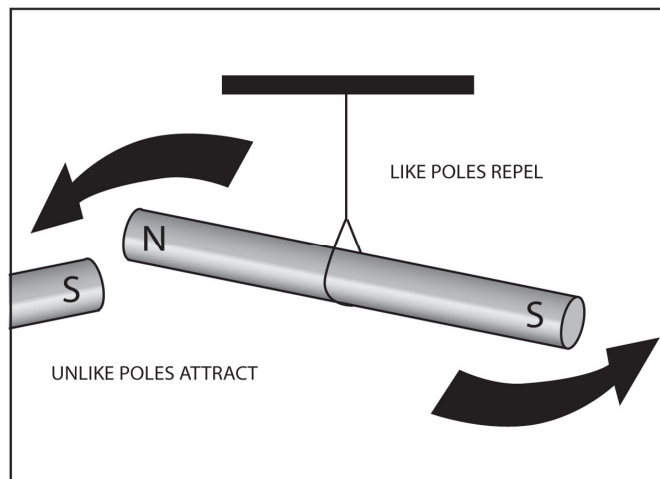
Fig. 6.4

Lines of Force

Magnetic fields are explained by assuming that lines of magnetic force called flux lines surround a magnet. While these lines are invisible, you can demonstrate their effects in many different ways. For example, if you sprinkle iron filings evenly over a piece of paper and place the paper over a magnet, the fillings align so that the effects of the lines of force, flux lines, are clearly visible. Figure 6.5 shows these flux lines as they might appear in the iron filings.
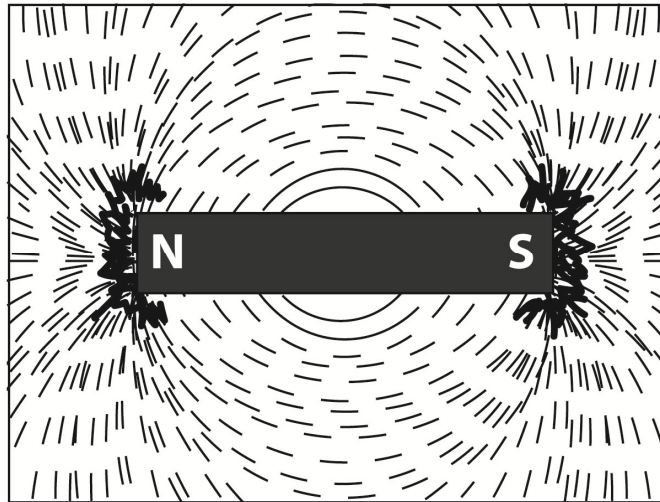
Fig. 6.5

There are several basic rules and characteristics of flux lines that are important. However, the four most critical ones are listed below:

➢ Flux lines have direction or polarity. The direction of the flux lines outside the magnet are arbitrarily assumed to be from the North Pole to the South Pole. Arrowheads often indicate this direction.

➢ The lines of force always form complete loops. These lines always curve back through the body of the magnet to form a complete loop.

➢ Flux lines can't cross each other. This is the reason that like poles repel. Lines, which have the same polarity, can neither connect nor cross. When one field intrudes into another, the lines repel and magnets push apart or away from each other. There's an example of this in Figure 6.6.

➢ Flux lines tend to form the smallest possible loops. This explains why unlike poles attract. Lines, which have opposite polarity, can link up. Then the loops attempt to shorten by pulling the two magnets together. This is shown in Figure 6.7.
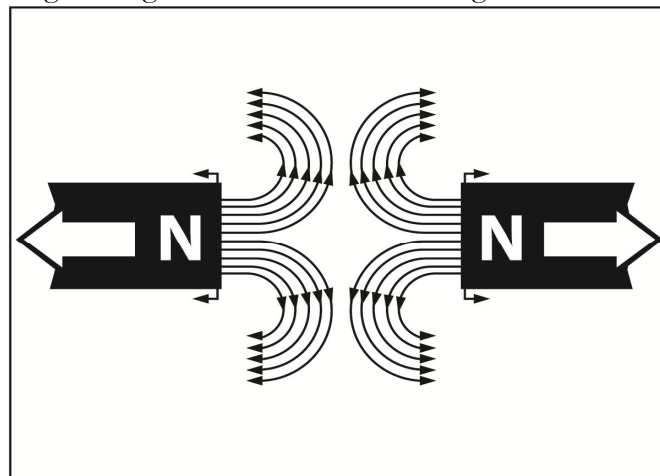
Fig. 6.6
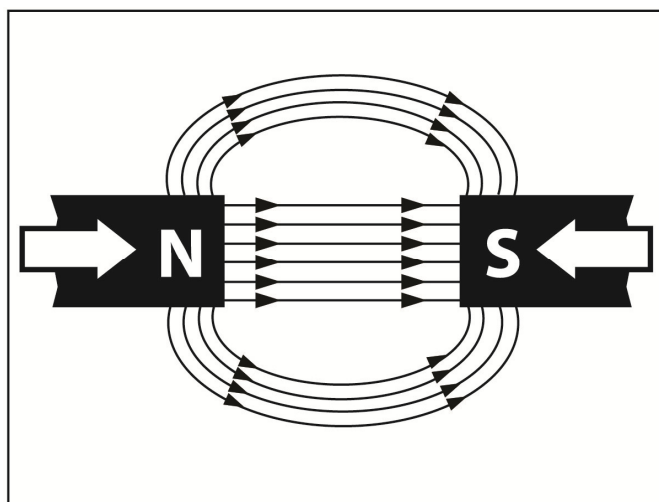
Fig. 6.7

Magnetic Materials

Out of the 90 naturally occurring elements that we are aware of, only three respond readily to magnetic fields. These are iron, cobalt, and nickel. All three are metals and have atomic numbers of 26, 27, and 28 respectively. Each has two valence electrons so their chemical and electrical characteristics are very similar. In addition to these elements, there are dozens of alloys, which have magnetic characteristics. Substances, which readily respond to magnetic fields, are called ferromagnetic substances. *Ferromagnetic* materials are strongly attracted by a magnetic field.

Most substances are classified as *paramagnetic*. They are only slightly attracted by a strong magnetic field. Generally, the force of attraction is so small, that these materials are considered to be non-magnetic. Substances such as air, aluminum, and wood are all paramagnetic in nature.

There is one other classification, to the technically minded, called *diamagnetic*. Diamagnetic materials are slightly repelled by magnetic fields. However, here again, the force of repulsion is so tiny that these materials are generally considered non-magnetic. Examples of diamagnetic materials are bismuth, quartz, water, and copper.

The characteristic which determines if a substance is ferromagnetic, paramagnetic, or diamagnetic is called *permeance* or *permeability*. Permeability is the ability of various materials to accept or allow magnetic lines of force to exist in them. Air is considered to be the standard with a permeability of 1. Other substances are given a permeability rating lower or higher than 1, depending upon their magnetic characteristics. Table 6.1 shows some of these different permeability scales of materials. Iron is about 7000 times more effective in accepting flux lines that air. Consequently, iron has a permeability of about 7000. Substances whose permeability is less than 1 are diamagnetic and are slightly repelled by flux lines. Those having permeability slightly greater than 1 are paramagnetic and are slightly attracted by flux lines. Finally, those having permeability's much higher that 1 are ferromagnetic and are strongly attracted by flux lines.

Material	Permeability	Characteristic	Action
Bismuth	0.999833	Diametric	**Slightly Repelled**
Water	0.999991	Diametric	**Slightly Repelled**
Copper	0.999995	Diametric	**Slightly Repelled**

Air	1.000000	Paramagnetic	**Non-Magnetic**
Oxygen	1.000002	Paramagnetic	**Slightly Attracted**
Aluminum	1.000021	Paramagnetic	**Slightly Attracted**
Cobalt	170	Feromagnetic	**Strongly Attracted**
Nickel	1000	Feromagnetic	**Strongly Attracted**
Iron	7000	Feromagnetic	**Strongly Attracted**
Permalloy*	100,000	Feromagnetic	**Strongly Attracted**
Supermalloy**	1,000,000	Feromagnetic	**Strongly Attracted**
*Permalloy, an alloy of 17% Iron, 4% Molybdenum, 79% Nickel			
**Supermalloy, an alloy of 15% Iron, 5% Molybdenum, 79% Nickel			

Table 6.1

The permeability of materials can be compared the conductance in a circuit. Remember that conductance indicates the ease with which a material or circuit allows current to flow through it. In much the same way, permeability is the ease with which materials accepts lines of flux.

Next, we'll learn why permeability is so important. Figure 6.8 shows the flux lines around a permanent magnet. Now if you take iron that has a high permeability, it can support lines of flux much more easily than the surrounding air. As a result, a large number of flux lines pass through an iron bar. At the same time, the lines attempt to contract to the smallest possible loops. This contraction causes the iron bar to be attracted or pulled toward the magnet. Figure 6.9 shows an example of the flux lines as they are distorted by iron.
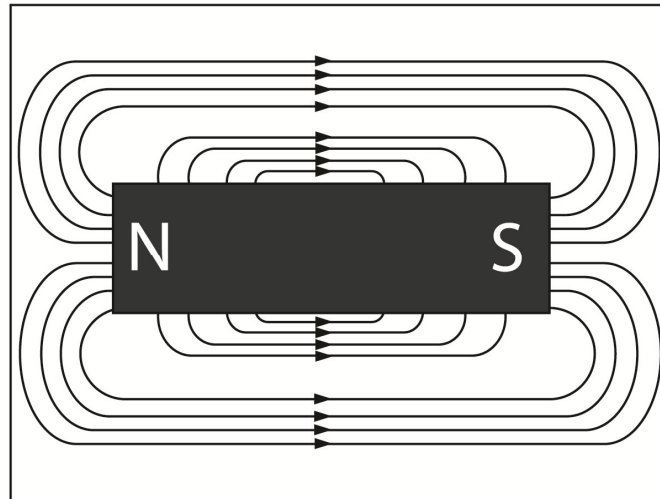
Fig. 6.8
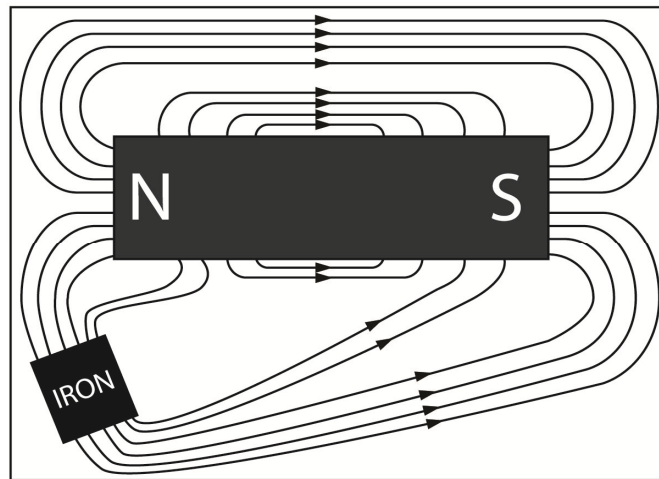
Fig. 6.9

Electricity and Magnetism

Electricity and magnetism are closely related. The electron has both an electrostatic field and a magnetic field. This might lead you to conclude that a charged object should have a magnetic field, but this isn't so, since the magnetic field of about half of the electrons are opposite to the other half. The electron plays an important part in magnetism. Electrons can be forced to produce magnetic fields in substances, which are normally considered non-magnetic, such as copper and aluminum. The key is motion. Motion is the catalyst, which links electricity and magnetism. Whenever a charged particle moves, a magnetic field is produced.

If large numbers of charged particles can be moved in a systematic way, a usable magnetic field is formed. You have seen that current flow is the systematic movement of large numbers of electrons. So, current flow causes a magnetic field.

Current Flow and Magnetism

As current flows through a wire; a magnetic field is developed around the wire. The fields are concentric circles. While these concentric circle fields have no North or South Pole, they do direction. The direction of the field depends upon the direction of current flow. Figure 6.10 below shows these concentric circles. The arrows on the flux lines represent their direction, it doesn't mean they are moving in this direction.
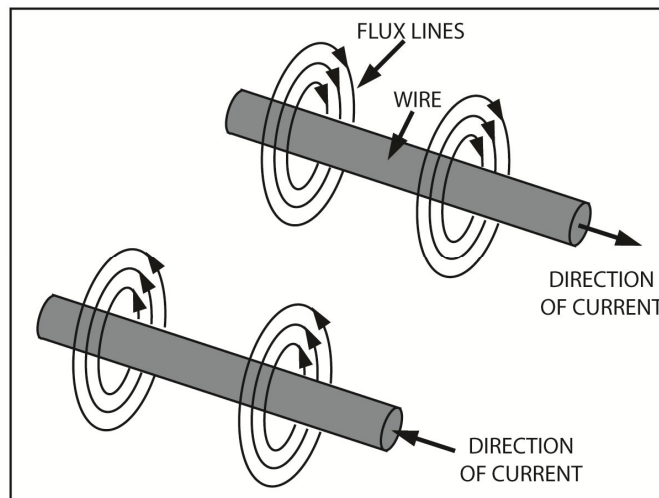
Fig. 6.10

You can determine the direction of flux lines if you know the direction of current flow. The rule for determining this is called the *left-hand magnetic-field rule* or the *left-hand rule for conductors*. If you grab the conductor in your left hand with your thumb pointing in the direction of current electron flow through the conductor, your fingers now point in the direction of the flux lines. Figure 6.11 shows an example of the left hand rule for conductors. You can see how the thumb points the direction of current flow.
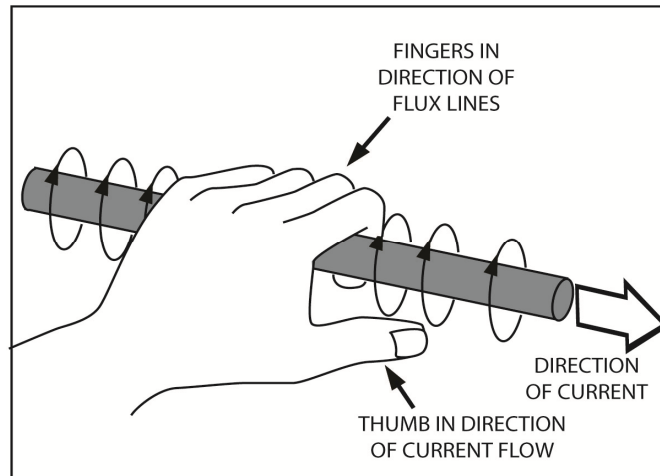
Fig. 6.11

Some aspects of electromagnetism are best explained by showing current flow in a third dimension. To do this, two new symbols are introduced in Figure 6.12 and Figure 6.13. Figure 6.12 shows current flowing into the page. When viewed from the end, the tail of the arrow appears as a cross. This cross represents current flowing into the page. If you view this wire from the end, the head of arrow appears as a round dot. The dot represents current flowing out of the page, Figure 6.13.
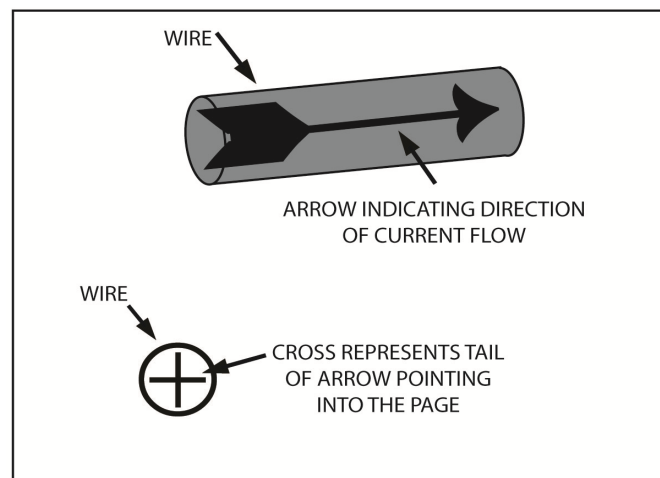
Fig. 6.12
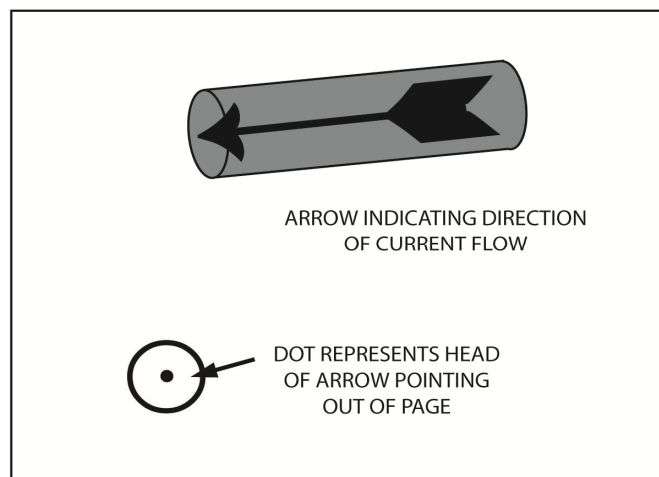
Fig. 6.13

In Figure 6.14, these two new symbols are used to show how opposite and similar currents establish magnetic fields. In Figure 6.14, opposite currents are shown. Use the left hand rule to verify the direction of the two magnetic fields. Since the fields point in opposite directions, they tend to repel each other. In Figure 6.15 the opposite in shown. When two currents flow in the same direction, the fields point in the same direction. So, they are free to connect. This tends to draw the two fields together.
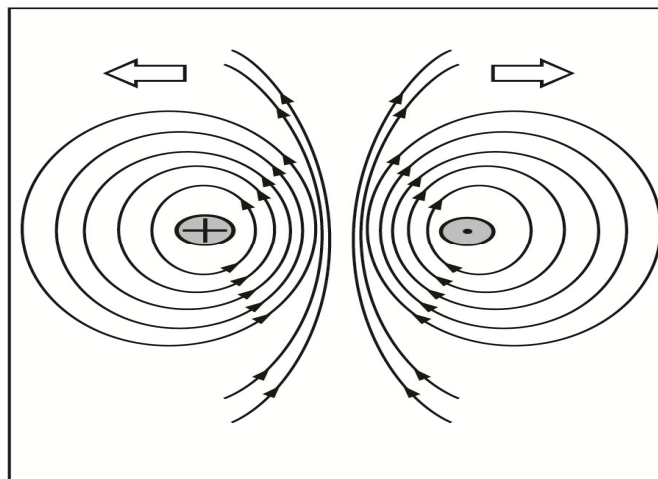
Fig. 6.14
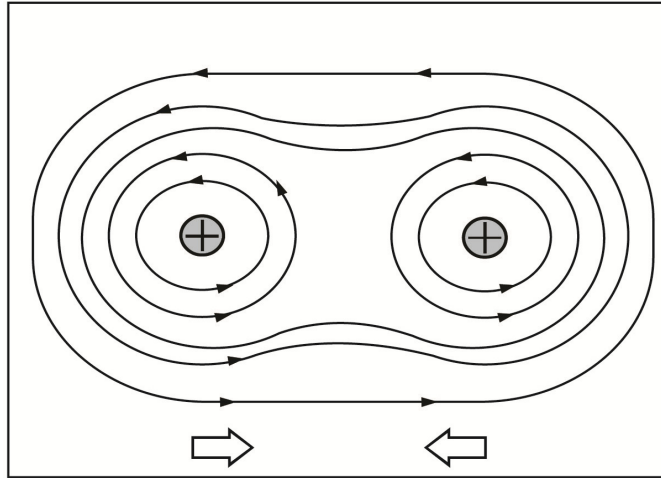
Fig. 6.15

When the conductor is a straight piece of wire, the magnetic field produced is of little practical use. Although it has direction, it has no North or South Pole, and unless the current is extremely high, the magnetic field has little strength. But if the shape of the wire is changed, we can greatly improve its magnetic characteristics.

A short piece of wire is twisted into a loop in Figures 6.16 and 6.17. By forming the loops, the magnetic characteristics of the wire are helped in three ways. First, it brings the flux lines closer together. Second it concentrates the majority of the flux lines in the center or core of the loop. Third, it creates north and south poles. The North Pole is the side where the flux lines come out; the South Pole is the side where they go in. This loop wire has the characteristics of a magnet. In fact, it's an example of a simple electromagnet.

DIRECTION OF CURRENT FLOW
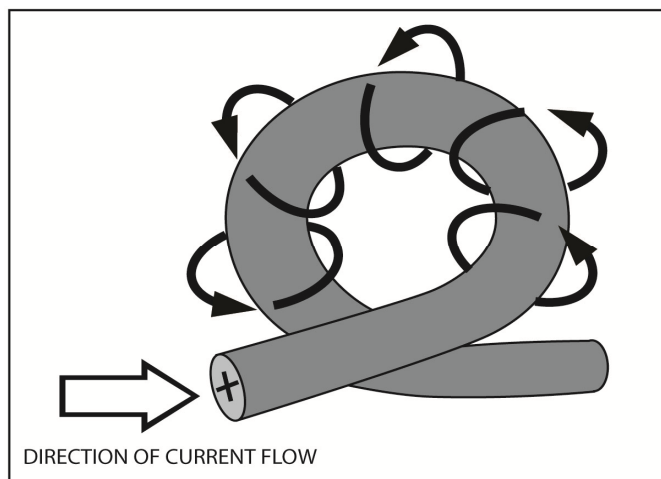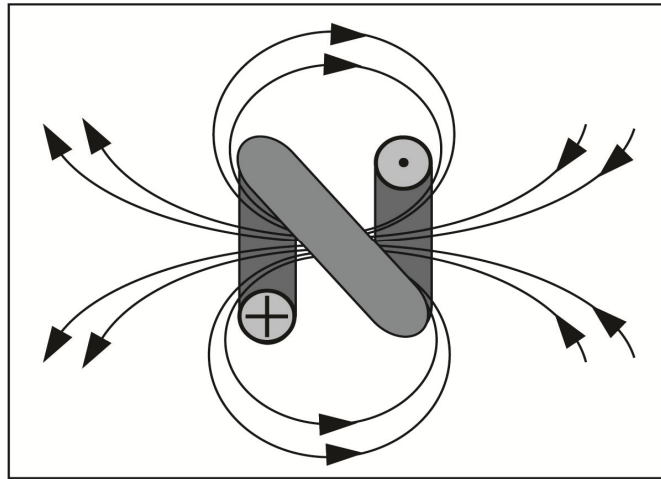
Fig. 6.16

Fig. 6.17

The Electromagnet

Electromagnetism is used in many different electronic devices. In its simplest form, the electromagnet is nothing more than a length of wire wrapped in coils as shown in Figure 6.18. When current passes through the wire as seen in the previous figures, a magnetic field is established. Because the turns of wire are very close together, the flux lines of the individual turns add together, to produce a very strong magnetic field.
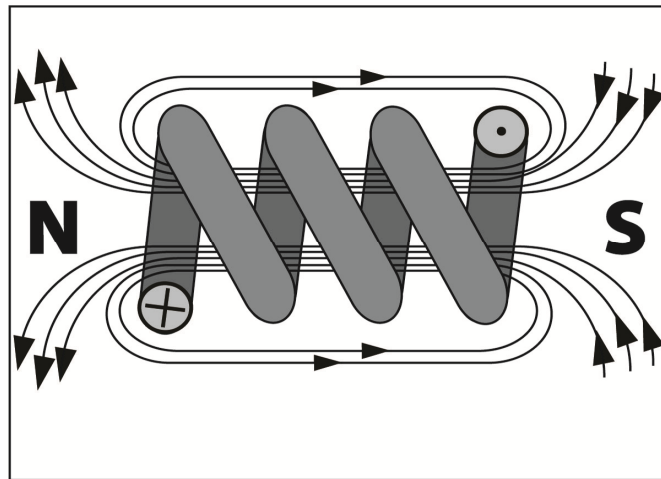
Fig. 6.18

The more turns there are in the coil, the more flux lines there are. Also, as more current flows through the coil, there will be more flux lines. So, the strength of the magnetic field is directly proportional to both the number of turns in the coil, and the amount of current going through the coil.

The coil's magnetic field has many of the same characteristics as the magnetic field around a permanent magnet. However, one important difference is that the field around the coil only exists when current flows through the coil. Also, you can change the amount of current that flows through the coil to vary the strength of the magnetic field around the coil.

We have already looked at two ways to increase the strength of the magnetic field around an electromagnet. One way is to increase the current. The other is to increase the number of turns. However, a third method and the most dramatic, involves adding a bar of ferromagnetic material,

called a core, to the center of the coil. Say for example an iron core is added. The iron core has a much higher value of permeability than air. Consequently, the iron core can support many times more flux lines than air. Thus, the strength of the electromagnet is increased. Most electromagnets are made by winding many turns of wire around a bar of ferromagnetic material such as iron.

Knowing the polarity of an electromagnet is very helpful. You can easily determine this if you know the direction of current through the coil. The rule is called the left-hand rule for coils. To apply this rule, you grasp the coil with your left hand in such a way that your fingers are wrapped around it in the same direction that current is flowing; your thumb will then point toward the north pole of the magnet.. Remember that current flows from negative to positive. In Figure 6.19, the current flows up the backside of the coil and down the front side. If you wrap your fingers in this direction, your thumb will points to the left. Thus, the left end of the electromagnet is the North Pole. In Figure 6.20, the coil is wrapped in the opposite direction and the North Pole is on the right.
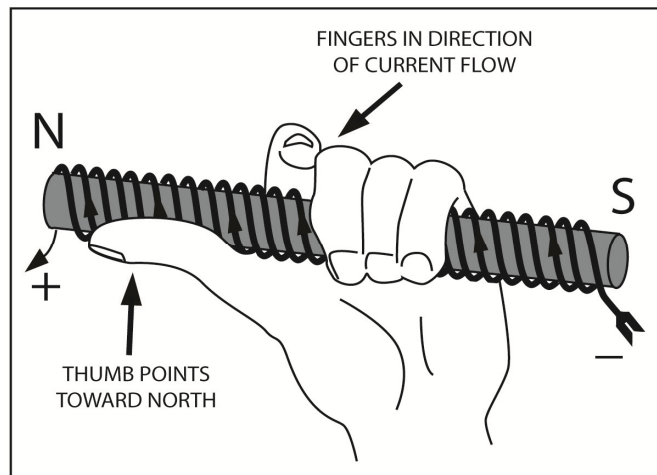
Fig. 6.19
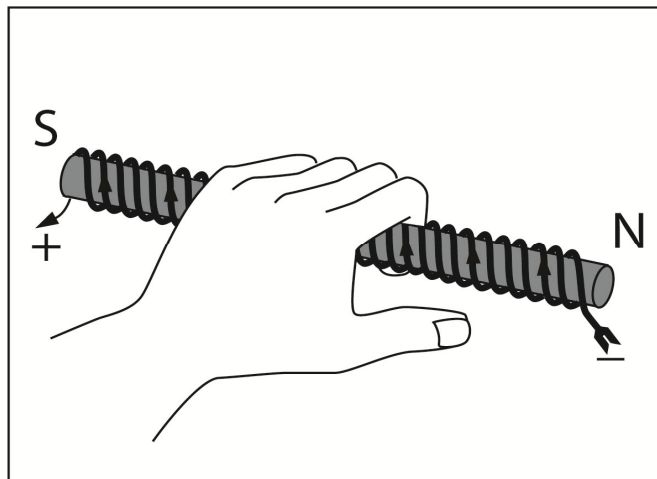
Fig. 6.20

If you know which end is the North Pole, you can use this same procedure to determine the direction of current flow. Assume that you know the North Pole is on the right, but you do not know the direction of current, you simply grasp the coil in your left hand with your thumb pointing toward the north pole of the coil. Your fingers now point in the direction of the current flow.

Magnetic Quantities

Electrical quantities such as voltage, current, resistance, conductance, and power are used in the study of electricity. In much the same way, studying magnetism requires that you learn several magnetic quantities. Of particular importance are the magnetic quantities: flux, flux density, magneto motive force, field intensity, reluctance, and permeability. While the definitions of these quantities are straight forward, the units of measure for these quantities often become confusing. The reason for this is that three different systems of measurements have been used over the years. The first is the English system, which uses the familiar inches, pounds, etc. The other two systems are based upon metric units. One is called the cogs system. CGS stands for centimeter, gram and second. Another system based upon metric units is the MKS system. MKS stand for meter, kilogram, and second. Following, the English unit is used because this is probably the system with which you are most familiar. At the end of this section, the English units are compared with the metric units.

Flux

The complete magnetic field of a coil or a magnet is known as the flux. The flux represents the total lines of magnetic force. In units of measurement, the Greek letter phi (ø) denotes flux. In English system, flux is measured in lines. A coil magnet, which produces, 1000 lines of force has a flux of 1000 lines or kilo line, ø = 1K lines.

Flux Density

Flux density refers to the number of lines per unit of an area. In the English system, the unit of area is the square inch, so flux density is expressed as the number of lines per square inch. The letter B represents flux density. If a coil with a cross sectional area of two square inches has flux of 2000 lines, the flux density is 2000/2 or 1000 lines per square inch. So, $B = 1000$ lines/in^2.

Magnetomotive Force (MMF)

Magnetomotive force is the force, which produces the flux in an electromagnet or coil. As already mentioned, this force is directly proportional to the number of turns in the coil and the amount of current flowing through it. For this reason, the unit of MMF is the ampere-turn. This is the amount of force developed by one turn of the wire when the current is one ampere. For example, a coil that has 100 turns and a current of 4 amperes has a magnetomotive force of 100 x 4 = 400 ampere turns.

Induction

Induction is the effect of one body on another when they aren't physically touching each other. For example, in an earlier chapter, we discussed how a charged body can induce a charge in another body simply by just coming close to it. That is, a charge can be induced into a body without any physical contact. This is possible because an electrostatic field that surrounds every charged body. Thus, the field of a charged body can affect another body without the two bodies actually touching. This is an example of electrostatic induction.

Magnetic Induction

Magnetic induction occurs when magnets affect other objects without actually touching them. The objects are affected from a distance. A strong magnet can cause a compass needle to deflect from a distance of several feet. Another power of the magnet is to induce a magnetic field in a previously un-magnetized object. For example, a magnet can induce piece of iron to become a magnet.

In the Figure 6.21 below, a bar of soft iron is placed close to a permanent magnet. Part of the field from the magnet passes through the iron bar. Because of this, Magnetic lines of force enter the left

side of the iron and exist on the right. This magnetic field causes the magnetic domains in the iron to line up in one direction. Due to this, the piece of iron becomes a magnet, itself. The South Pole must be on the left because this is the end where the flux lines enter the iron. The North Pole is on the right because the flux lines exit at this point. Observe that the north pole of the permanent magnet is closest to the induced south pole of the iron bar. Because these opposite poles attract, the iron bar is attracted to the magnet. So, the attraction of a piece of iron to a permanent magnet is a natural result of magnetic induction.
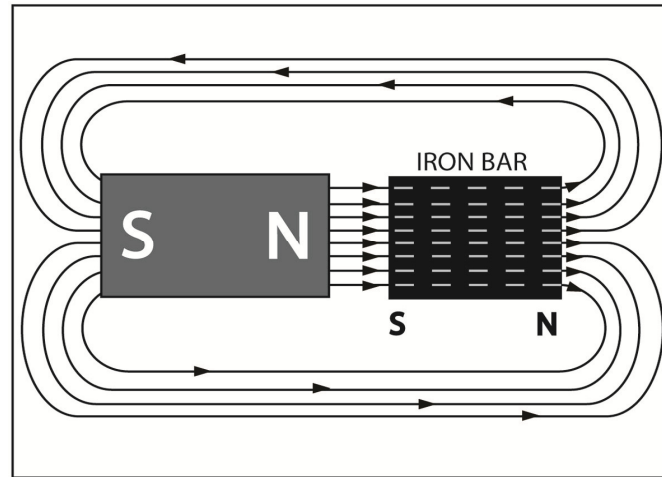
Fig. 6.21

Field Density or Magnetizing Force

MMF can be useful term, but it is limited in application. It doesn't take into consideration the length of the coil. Thus, a coil with 50 turns may be 1 inch long or 10 inches long and still have the same MMF; however, as we've already mentioned, the magnetic field becomes more concentrated in a smaller space with the shorter coils.

On the other hand, Field intensity takes into consideration not only the MMF but also the length of the coil. Field intensity is expressed as ampere turns per inch and is represented by the letter H. For instance, a 4-inch coil has an MMF of 400 ampere turns, the field intensity is 400/4 or 100 ampere turns per inch. H = 100 amp-turns/in. Field intensity is sometimes called magnetizing force which should not be confused with magnetomotive force.

Permeability

This important characteristic has already been mentioned. Recall that permeability is the ease with which material can accept lines of force. You can also think of it as the ability of material to concentrate a large number of force lines in a small area. For example, 1-inch column of soft iron can hold hundreds of times more flux lines than a comparable column of aluminum. The Greek letter (μ) represents permeability.

Reluctance

The opposite or reciprocal of permeability is called reluctance and is represented by the letter R. Reluctance is generally defined as an opposition to flux. Thus, a material with a high reluctance is reluctant to accept flux lines. Reluctance can be calculated by the following equation:

$$R = 1/\mu$$

If soft iron has a permeability of 2700, then it has a reluctance of 1/2700. Since air has a permeability of 1, it has a reluctance of 1/1 or 1. Flux lines tend to follow the path of least reluctance.

Ohm's Law for Magnetic Quantities

Three of the above quantities are related by an equation, which is very similar to the Ohm's Law equation. In fact, you can compare these three magnetic quantities to the electrical units of current, voltage, and resistance. In this correlation, current corresponds to magnetic flux (ø). Recall that flux is produced by magnetomotive force (MMF). So, MMF corresponds to voltage. Finally, the opposition to flux is called reluctance (R). Flux, MMF, and reluctance are related by the equation:

$$\emptyset = MMF/R$$

This states that the magnetic flux developed in a core material is directly proportional to the magnetomotive force and inversely proportional to the reluctance. Since this equation is similar to the Ohm's Law equation discussed earlier, it is often called the Ohm's Law for magnetic circuits.

Comparison of Units

As mentioned earlier, there are three systems of measurement in common use. The most familiar is the English system. However, the metric system is becoming more popular. Unfortunately, the units for the magnetic quantities are different in each system. Table 6.2 below compares the various units.

Term	Description	Symbol	English Units	CGS Units	MKS Units
Flux	Total Lines of Flux	Ø	Lines or Kilolines	Maxwell 1 Maxwell=1 Line	**Weber** **1 Weber= 100,000,000 Lines**
Flux Density	Lines Per Unit Area	B	Lilolines/In²	Gauss 1 Gauss=1 Maxwell/CM²	**Weber/M²**
Magneto motive Force	Total Force that Produces Flux	MMF	Ampere	Gilbert 1 Gilbert= 0.796 Amp-Turn 1 Amp-Turn= 1.25 Gilbert	**Ampere-Turn**
Field Intensity /Magnet izing Force	**Force Per Unit Length of Flux**	**H**	**Ampere-Turn/In**	**Oersted** **1 Oersted= 1 Gilbert/CM**	**Ampere-Turn/M**

Table 6.2

In the English system, flux is measured in lines or kilo lines; flux density is measured in kilo lines per square inch; MMF is measured in ampere-turns; and field intensity is measured in ampere-turns per inch. In the Centimeter-Gram Second, or CGS system, four new terms: Maxwell, Gauss, Gilbert, and Oersted are introduced. The Maxwell is equal to one line of force. The gauss is equal to 1 Maxwell per square centimeter. The Gilbert is equivalent to about 0.8 ampere-turns, or stated another way; an ampere-turn is equal to about 1.25 Gilbert. In the Meter-Kilogram-Second, or MKS system, the unit of flux is the weber. The weber is equal to 10^8 or 100,000,000 lines of force. Flux density is expressed as webers per square meter. As with the English system, the MKS unit is the ampere-turn. Finally, field intensity is expressed as ampere-turn per meter. This table ignores

permeability and reluctance, because neither of these properties has a measure of unit assigned to it in any of the three systems.

When the piece of iron, we have discussed earlier, is removed from the magnetic field, most of the magnetic domains return to random positions. However, a few of the domains remain aligned in the north-south direction. Thus, the iron bar retains a week magnetic field even after you remove it from the influence of the permanent magnet. The magnetic field, which remains in the iron bar, is called *residual magnetism*. The ability of material to retain a magnetic field even after you remove the magnetizing force is called retentivity. Soft iron has a relatively low value of retentivity, because it retains little residual magnetism. Steel has a rather higher value of retentivity. Consequently, its residual magnetism is higher.

Electromagnetic Induction

The action of electrons flowing in a conductor when the conductor moves through a magnetic field is called electromagnetic induction. When a conductor moves through the magnetic field, the free electrons are pushed to the right end of the conductor. This action is illustrated in Figure 6.22. This causes an excess of electrons at the right end of the conductor and a deficiency of electrons at the other end. This results in a potential difference between the two ends of the conductor. However, this potential difference exists only while the conductor is cutting the flux lines of the magnet. When the conductor moves out of the magnetic field, the electrons return to their original positions and the potential difference is gone. The potential difference also stops if the conductor stops in the magnetic field. Accordingly, the conductor must move with respect to the flux lines before a potential difference is developed.

DIRECTION OF
CONDUCTOR MOTION
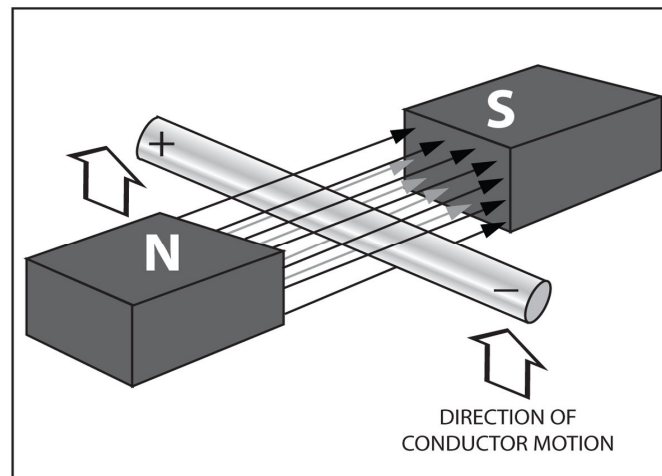
    Fig. 6.22

Motion is essential for electromagnetic induction. An outside force must be applied to cause the conductor to move through the magnetic field. This outside, often mechanical, force is converted to an electromotive force (EMF) by electromagnetic induction.   An EMF is brought into the conductor. The potential difference across the conductor is called an induced EMF or induced voltage.

The following four factors determine the amount of EMF induced into the conductor:

1. The strength of the magnetic field.

2. The speed of the conductor with respect to the field.

3. The angle at which the conductor cuts the field.

4. The length of the conductor in the field.

The induced EMF will be stronger if the magnetic field is stronger Also, the faster the conductor moves with respect to the field, the greater the induced voltage. Relative motion between the conductor and the field can be produced by moving the conductor, by moving the field, or by moving both. The angle at which the conductor cuts the field is also important. Maximum voltage is achieved when the conductor moves at right angles to the field. This is shown in Figure 6.23. Less voltage is induced when the angle between the lines of flux and the direction of motion of the conductor is less than 90°. Actually, if the conductor is moved parallel to the lines of flux, there is no EMF produced. The fourth factor is the length of the conductor in the field, which means the longer the conductor, the greater the induced EMF.

These factors are natural consequences of a basic law of electromagnetic induction. This law is *Faraday's Law*; the voltage induced in the conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of force. Meaning, the more flux lines cut per second, the higher the induced EMF will be.
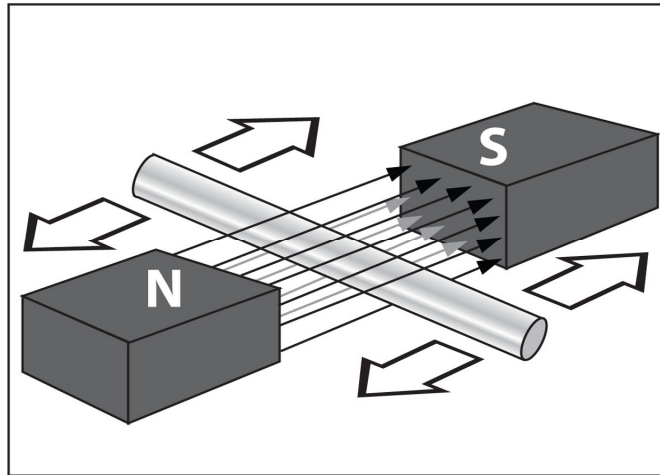
Fig. 6.23

There's another left-hand rule to determine the polarity of the induced EMF. This one is called the *left-hand rule for generators* and there's an example below in Figure 6.24. It involves your thumb and first two fingers of your left hand. Point your thumb in the same direction as the conductor is moving, and point your index or forefinger in the same direction as the flux lines. Now, point your middle finger straight out from your palm at a right angle to your index finger. Your middle finger now points to the negative end of the conductor. This is the direction that current flows if you were to connect an external circuit across the two ends of the conductor.
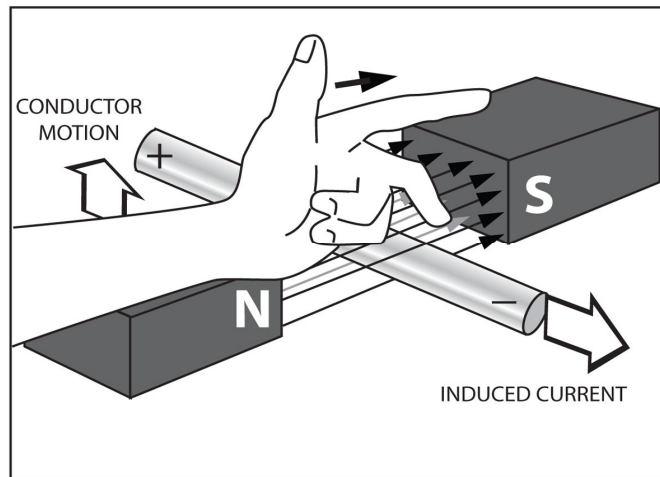
Fig. 6.24

The AC Generator

Most of the electrical power in the world today is supplied by electromagnetic. It is the most efficient way known to produce electricity. A very basic generator is shown in Figure 6.25. It uses electromagnetic induction to convert mechanical energy into electric energy. Mechanical energy is required to create relative motion between the magnetic field and the conductor, either the magnet or the conductor can be rotated. For an explanation of this, let's assume the conductor rotates in the counterclockwise direction. The conductor is shaped like a loop and is called an armature. When the loop or armature rotates, one half moves up through the field near the South Pole, while the other half moves through the field near the North Pole.

If the left hand generator rule is applied to the loop side nearest the South Pole, you find that the polarity of the induced voltage is negative at point A and positive at point B. When you apply the same rule to the conductor near the North Pole, you find that the induced voltage is negative at point C and positive at point D. Take note that the two induced voltages are series-aiding. If a meter is connected between points E and F, it will indicate the sum of the two induced voltages.
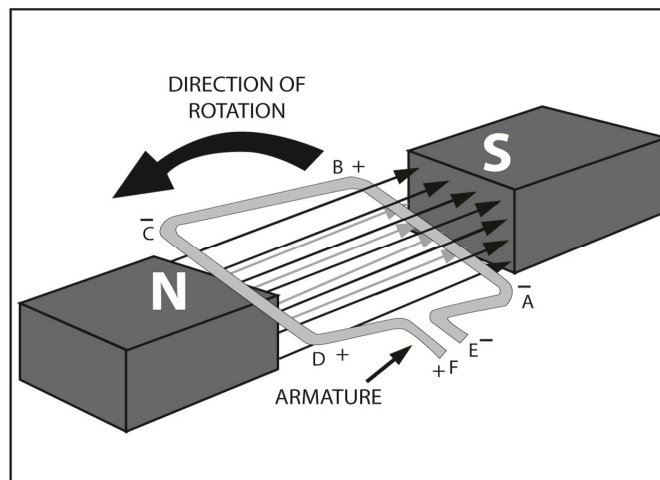
Fig. 6.25

The personality of the voltage, which is induced into the armature, is shown in Figure 6.26 below. You have to follow the armature through one complete revolution to understand how this voltage is produced. During this process, you must always consider the voltage at point A in comparison to

point B. Figure 6.26 shows the movement of the armature at 90^0 increments. At 0^0, the sides of the armature are moving parallel to the lines of flux. Thus, there is no induced voltage at this time.

However, this changes as the armature rotates. The loop begins to cut the lines of flux and a voltage is induced. Point A becomes positive with respect to point B. The voltage begins to rise and reaches its highest value at 90° of rotation. This is the maximum point of voltage, because the armature is cutting the flux at a right angle. Thus, it cuts the maximum number of lines at this point. Once it goes past 90^0, the voltage begins to decrease because fewer lines per second are cut. At 180^0, the induced voltage is again at zero because the armature is moving parallel to the lines. As the loop passes 180^0 and starts to cut the lines again, a voltage is once again created. However, this time point A becomes negative with respect to point B. You can apply the left-hand generator rule to prove this. The maximum negative voltage is produced at 270^0 when the armature is back where is started and the induced voltage is again zero.
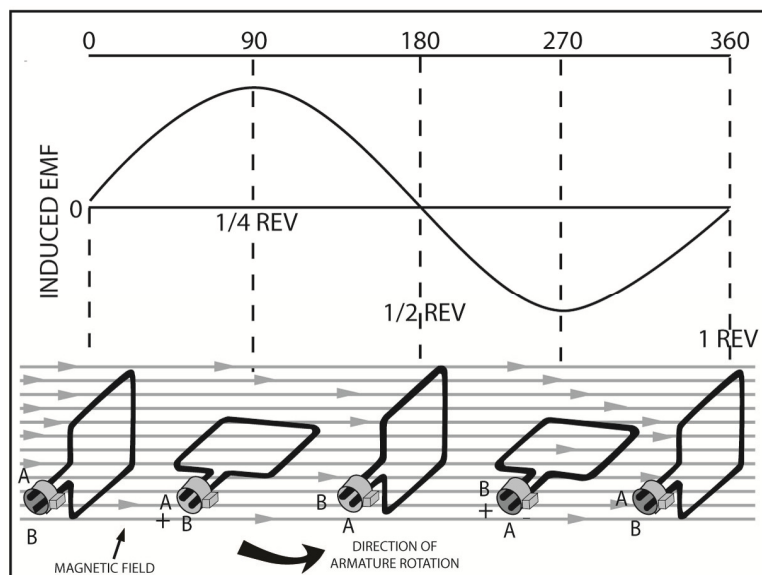
Fig. 6.26

The voltage shown in Figure 6.26 is known as a *sini-wave*. For each revolution of the armature, one cycle of the sine-wave is produced. If a load is connected across the armature between points A and B, current will flow through the load. For the first half cycle, current flows from B through the load to point A. However, during the next half cycle, current flows from point A, through the load in the opposite direction to point B. Thus, during each cycle, the current reverses direction-flowing in one direction half of the time and flowing in the opposite direction the other half of the time. This is called *alternating current* and is abbreviated as AC.

Our homes, offices, and factories are supplied with voltages called C voltages. The armature of the generator at the plant which provides our power rotates 60 times each second. Thus, the voltage supplied by these power stations goes through 60 cycles like the one shown in the Figure above each second. Most of the appliances in your home require 115 volts at 60 cycles.

The DC Generator

An AC generator or alternator can be converted to a DC generator. A device called a commutator converts the AC voltage produced by the rotating loop into DC voltage. Figure 6.27 shows how the commutator connects to the loop. A cylinder shaped conductor makes up the commutator. Two insulators are used to separate one half of the cylinder from the other half. Opposite sides of the loop are permanently connected to the opposite sides of the commutator. So, the commutator

rotates with the loop. Brushes make contact with the rotating commutator. The brushes are still and rest against opposite sides of the commutator. They are made of a conducting material so that the EMF produced by the loop is transferred to the brushes. In turn, wires connect to the brushes so that the EMF can be transformed to an external circuit.
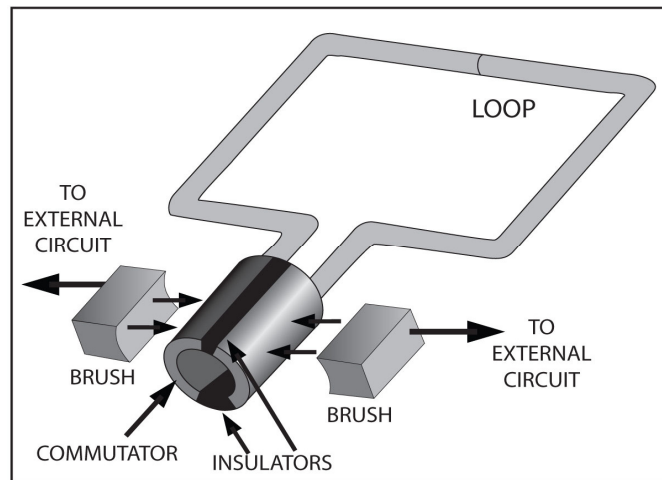
Fig. 6.27

Figure 6.28 displays a complete DC generator. It has four basic parts: a magnet to produce the magnetic field, a loop which produces the EMF, a commutator which converts the induced EMF to a DC voltage, and the brushes which transfer the DC voltage to an external circuit.
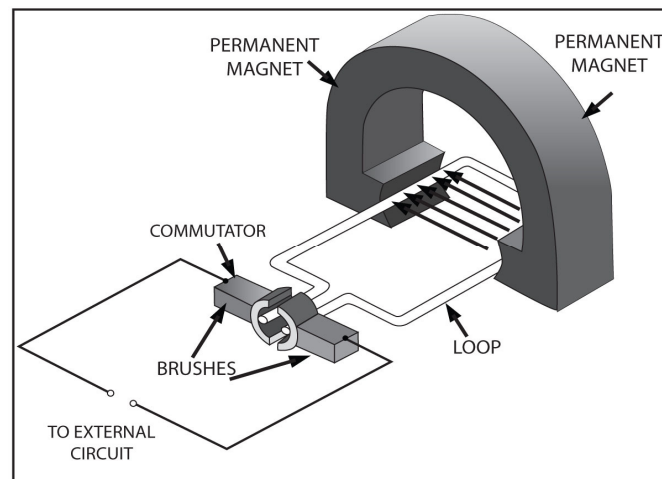
Fig. 6.28

The operation of the DC generator is shown in Fig. 6.29 below. The sides of the loop are moving parallel to the flux lines and 0 volts is produced at 0°, 1800°, and 3600°. This is also the case in an AC generator. At 900° and 2700°, the sides of the loop cut the flux lines at right angles, and maximum voltage is produced. However, unlike the alternator, the voltage is positive at point A with respect to point B at both 900° and 2700°.
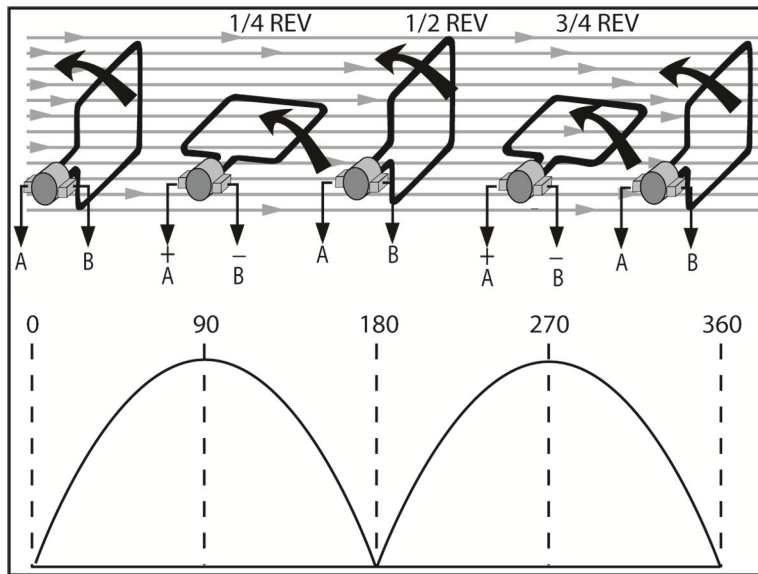
Fig. 6.29

This occurs due to the following reasons. Since the brushes are stationary and the commutator is rotating, each brush alternately connects to opposite sides of the loop. When the magnetic field is in the direction shown, the side of the loop, which is moving up through the field, produces a negative voltage at the commutator. Also, the side of the loop moving down through the field produces a positive voltage at the commutator. The brush on the right is always connected to the side of the loop, which is moving up through the field. Consequently, this brush is negative. On the other hand, the brush on the left is always connected to the side of the loop which moves down through the field. As a result, this brush is positive. Hence, if an external circuit is connected across A and B, current always flows in the same direction, i.e., from B to A.

An induced EMF is called a *pulsating DC voltage*, because the current always flows in the same direction, and pulsating because the level fluctuates. A pulsating DC voltage like this one has little use in this form. However, as you will see in a future section, this type of voltage can be smoothed out to form a constant DC voltage.

Magnetic and Electromagnet Application

Two important applications of electromagnetism are the alternator and the DC generator. The other applications of magnetic and electromagnetic devices are too numerous to list. However, there are examples all around us.

Relay

A very simple electromagnetic device is the relay. It is also one of the most useful. Figure 5.30 shows how a relay operates. When you close the switch, current flows from the battery through the relay coil. The current develops a magnetic field in the core, which attracts the armature, pulling it down. Due to this, the two contacts close and connect the generator to the load. When the switch is opened, the current through the relay coil stops, and the magnetic field collapses. The spring pulls the armature back up to open the contacts and disconnects the generator from the load. This entire process is shown in Figure 5.31.
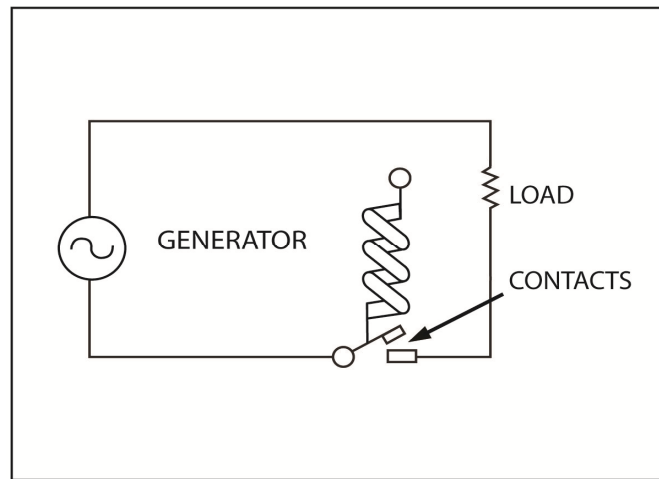
Fig. 5.30
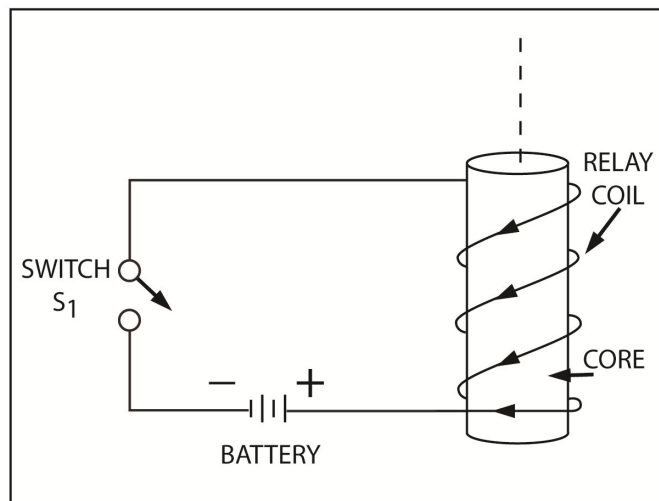
Fig. 5.31

When one circuit needs to control another, a relay is used. Because the relay circuit is electrically isolated from the generator circuit, a relay can be used to open and close high-voltage or high-current circuits with relatively little voltage and current in the coil circuit. They are also useful in remote controls where the switch is located at one point and the other circuit components are located at a distance. Also, a relay with several contact arms can open and close several circuits at once.

The doorbell is an interesting application of the relay as shown in Figure 5.32. When you close the switch, the current flows from the negative side of the battery through the switch, then the breaker contacts the two relay coils, and goes back to the positive side of the battery. The current flow through the relays and creates a magnetic field, which attracts the soft-iron armature and pulls it down. This pulls the hammer down and causes it to strike a bell. The lower breaker contact is attached to the armature. Consequently, when the coils energize, they break the current path for the coils. Thus, the relay de-energizes and releases the armature. The spring pulls the armature and the hammer upward. This closes the breaker contacts and once again completes the path for current flow through the relays. The operation repeats itself many times each second. Thus, the bell rings as long as the circuit is energized.
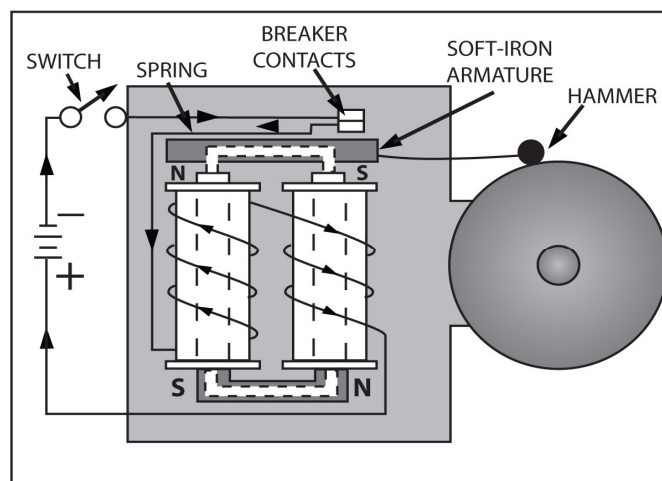
Fig. 6.32

Reed Switch and Relay

A magnetic reed switch is shown in Figure 6.33. It consists of two contacts in a sealed glass container. The contacts are made of a ferromagnetic material and are normally open. However, as shown in Figure 6.34, when you place a magnet next to the reed switch, the contacts close. This happens because a magnetic field is created in each contact by the flux lines from the magnet. So, each contact becomes a tiny magnet that has polarity. At the point where the two contacts are closest, opposite poles exist. These poles are attracted to each other, which closes the contacts. The reed switch allows you to turn a current on or off by changing the position of the permanent magnet. Practical applications for this device will be discussed later.
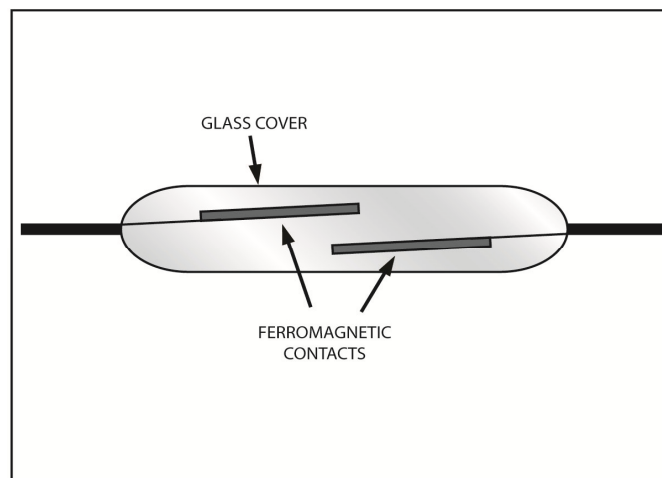
Fig. 6.33
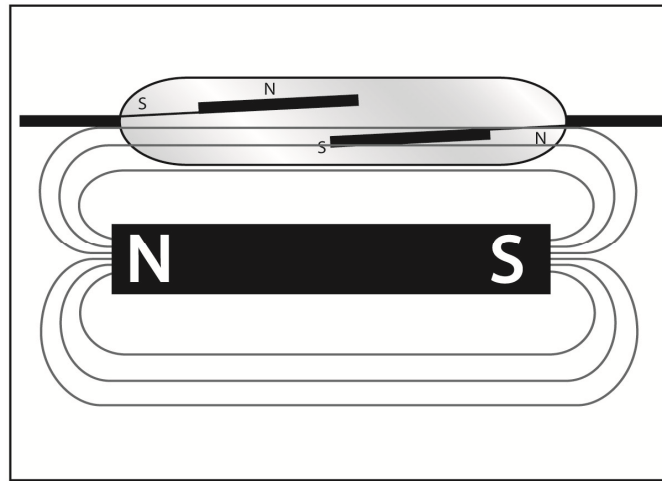
Fig. 6.34

A field from electromagnets can also be used to control the contacts. This is demonstrated in Figure 6.35. When the electromagnet is wound directly on the reed switch, the device is called a *reed delay*.
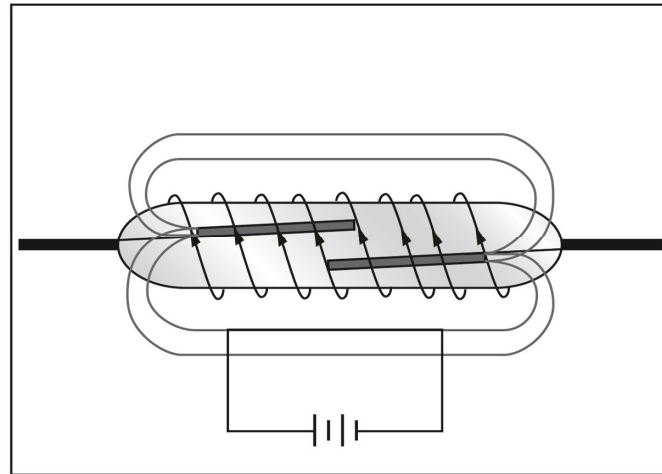
Fig 6.35

Record Pickup

Many types of recording and playback equipment use electromagnetic principles. The pickup cartridge used in the tone arm of many record players was an electromagnetic device. Figure 6.36 shows the constructions of a cartridge called a moving-coil or dynamic pickup. Here, a magnetic field is produced by a permanent magnet. A tiny coil is placed in this magnetic field. The core on which the coil is wound is attached to the stylus or needle. The coil is held in place by a flexible grommet. As the needle slips down the spiral groove on the record, it vibrates in response to the variations in the groove. These variations in the groove correspond to the audio tones recorded there. Thus, the needle vibrates at the same rate as the audio tones. Because the coil is connected to the needle, it also vibrates at this rate. The tiny movements of the coil in the magnetic field cause a minute of EMF to be induced into the coil. The induced EMF also varies at the audio rate. This EMF can be amplified and used to drive a loudspeaker so that the original audio tone is reproduced.
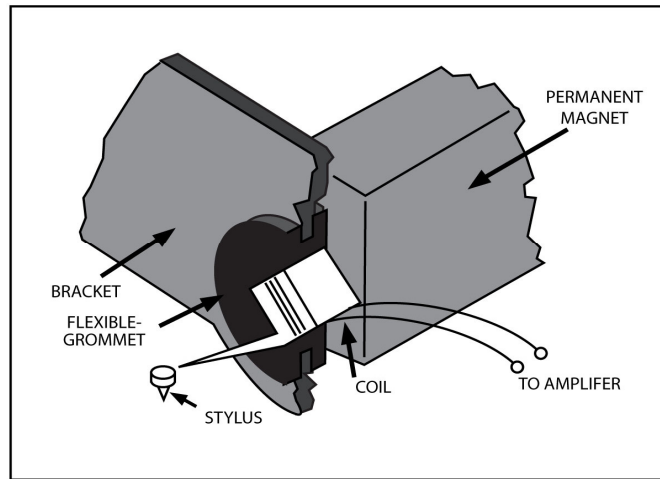
Fig. 6.36

Many Loudspeakers use a moving coil and a permanent magnet. Figure 6.37 depicts a cutaway diagram of a loudspeaker. A permanent magnet establishes a strong stationary magnetic field. A freely moving coil is placed in this magnetic field. A current, which varies at an audio rate, then passes through the coil. The varying current establishes a varying magnetic field around the coil. The varying magnetic field of the coil is alternately attracted and repelled by the stationary field of the permanent magnet. Thus, the coil moves back and forth at the same rate as the varying current. The moving coil is attached to a large cone or diaphragm. As the coil vibrates, the cone also vibrates setting the air around the cone in motion at the same rate. This reproduces the original sound.
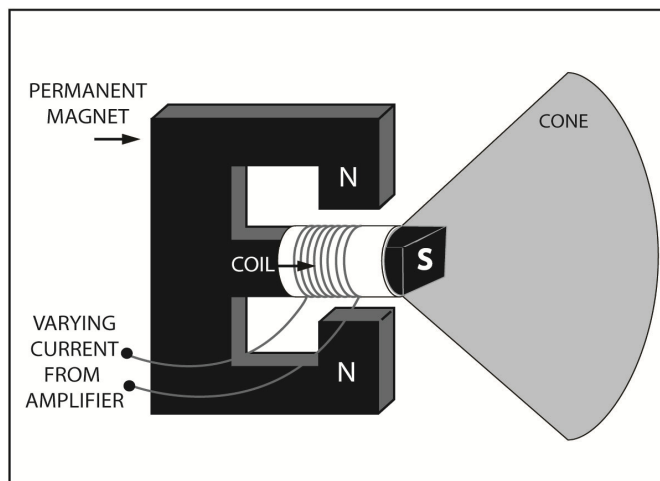
Fig. 6.37

Magnetic Tape

Electromagnetic principles are used by tape recorders to record electronic signals on magnetic tape. The device, which actually creates the signal on the tape and later, reads, it back is called a record-playback head. It is nothing more than a coil with a ferromagnetic core. Figure 6.38 depicts a recorder in record mode.
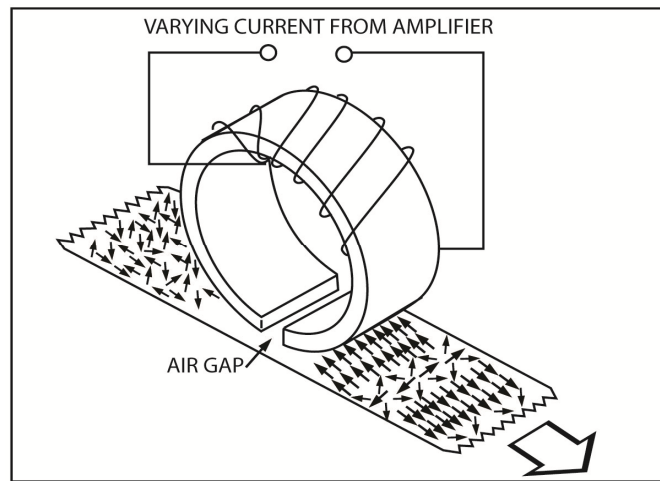
Fig. 6.38

A tiny air gap exists between the two ends of the core. A magnetic field is concentrated in this gap, when current is applied to the coil. A length of magnetic tape is pulled past the air gap. The plastic tape is covered with a ferromagnetic substance like iron oxide. The magnetic field that surrounds the air gap penetrates the tape and magnetizes it at this point. If the current applied to the coil varies at an audio rate, the magnetic field across the air gap varies at the same rate. Consequently, the magnetic pattern that is "written" onto the tape corresponds to the original audio signal.
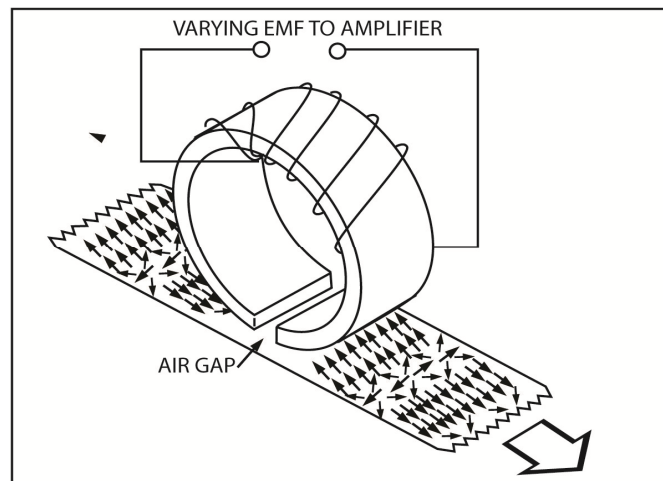
Fig. 6.39

To play back the tones recorded on the tape, the procedure reverses. This is shown in Figure 6.39 above. The tape is pulled past the air gap so that the core is subjected to the magnetic patterns on the tape. The changing magnetic field induces a tiny EMF into the coil windings. When this EMF is amplified and applied to a loudspeaker, the original audio tones are reproduced.

DC Motor

Earlier, we discussed how a generator converts mechanical energy to electrical energy. The opposite occurs with a motor; it converts electrical energy into mechanical energy. This principle which makes this possible is illustrated in Figure 6.40. Here, conductor carrying current is shown in a magnetic field. This is not an induced current; it flows because the conductor is connected across a battery. The current causes a magnetic field to be developed around the conductor in the direction shown. You can use the left-hand rule for conductors to verify this. The magnetic field around the conductor interacts with the field of the permanent magnet. On one side of the wire, the two

magnetic fields have the same direction and they add to produce a strong magnetic field. On the other side of the conductor the two magnetic fields have opposite directions. Thus, they tend to cancel and leave a weak resultant field on this side. As you can see, the flux lines are much more numerous on the one side of the conductor than on the other. In consequence, on one side, the lines bend and are forced very close together. These lines have a natural tendency to straighten and move further apart. However, the only way they can do this is by pushing the conductor out of the way. Thus, a force is developed which will push the conductor in the direction shown.
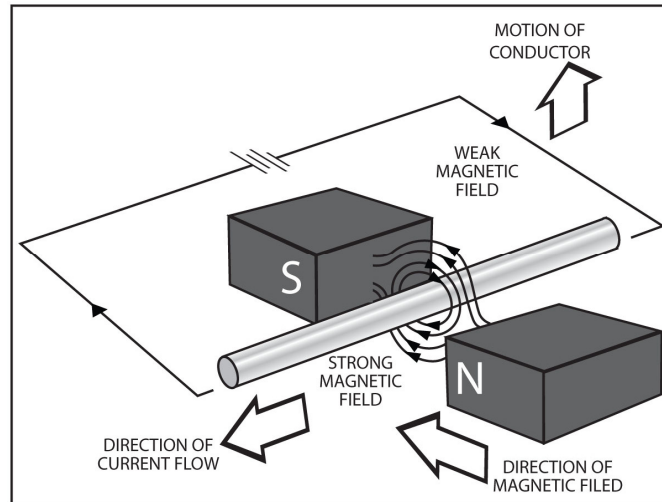
Fig. 6.40

The *right-hand motor rule* will help determine the direction that the wire will move. With your right-hand (not the left), point your index finger in the direction of the field of the permanent magnet. Point your middle finger in the direction of current flow through the conductor and at a right angle to your index finger. Your thumb now points in the direction that the conductor will move. You can apply this rule to see how a simple DC motor operates.
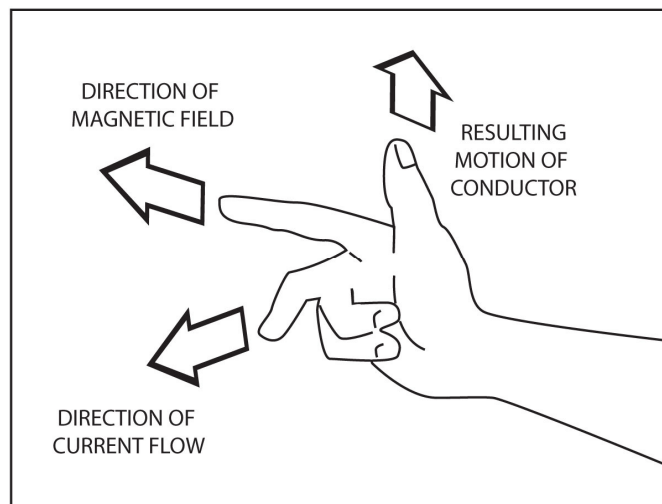
Fig 6.41

A DC motor is shown in a simplified diagram in Figure 6.42. Notice the similarity to the DC generator described earlier. However, there are two important differences. With the generator, the loop was turned on by an outside mechanical force. Here, the loop turns because of the motor action previously described. In the generator, a DC voltage was produced at the brushes. Here, an external DC voltage from a battery is applied to the brushes.
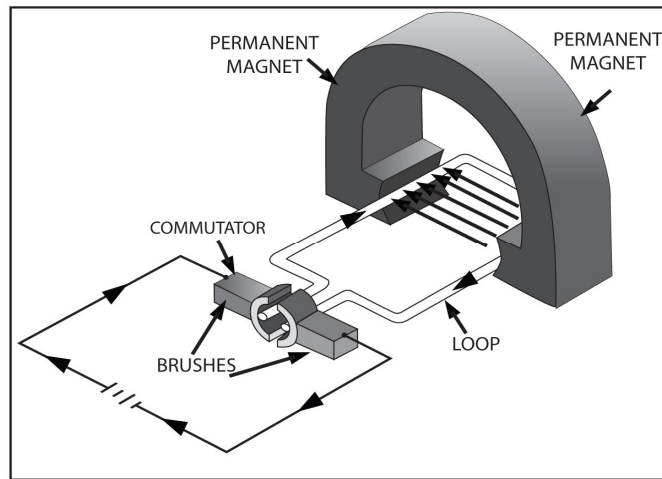
Fig. 6.42

The arrows indicate how the current flows through the loop.   You apply the right-hand motor rule to the side of the loop near the south pole of the magnet, you find that the conductor tends to move up. If you apply the same rule to the side near the North Pole, you find that this side tends to move down. Thus, the loop rotates in a counterclockwise direction. After one half of revolution, the two sides reverse positions. All the same, current still flows in the same direction through the side closest to the South Pole.

The simple motor shown here is not practical because a single loop of wire is used as an armature. Real motors use hundreds of turns of wire to develop a very strong twisting motion or torque.

Meter

A moving-coil meter uses the same motor action as described above. Fig 6.43 shows a simplified diagram of this device. Like the motor, it has an armature, which can freely revolve in the field of a permanent magnet. But, in the meter movement, one or more springs restrict the motion. When current flows through the coil, it establishes a magnetic field whose strength is directly proportional to the current. The motor action causes the coil to rotate.
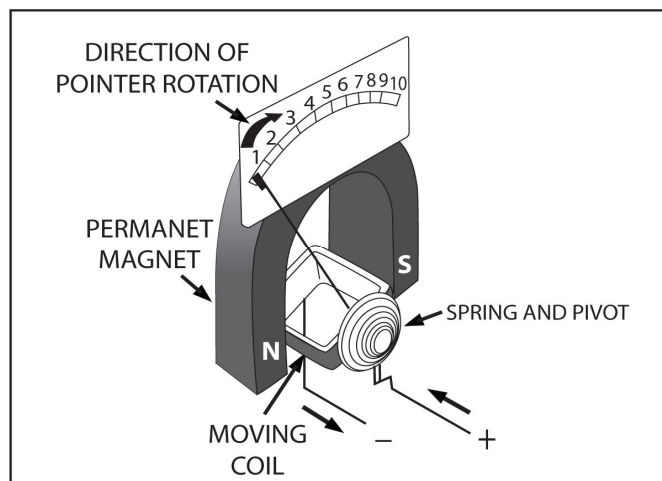
Fig. 6.43

However, the restraining springs keep the coil from rotating more than about 90 °. A pointer is attached to the coil that, as the coil rotates, moves the pointer in front of a scale. As more current flows, the coil will rotate further and the pointer will move further up the scale. The scale reading is

directly proportional to the amount of current that flows through the coil. Therefore, the scale can be marked off in amperes, mill amperes, or even microamperes. Most analog ammeters, voltmeters, and ohmmeters use this type of meter movement.

Computer Memories

Computers use a variety of electromagnetic devices to store information. In the beginning, most computers used storage techniques with magnetic cores. These were tiny little dough-nut shaped pieces of ferrite material, which could be magnetized in either of two directions. As shown in Figure 6.44, wires were strung through the holes in the cores. When current, going in the right direction, is applied to these wires, the cores could be magnetized in a certain pattern. A clockwise magnetic field can arbitrarily be called 1 while a counterclockwise field can be called 0. Patterns of 1's and 0's can be used to represent numbers, letters of the alphabet, and punctuation marks. One popular computer code uses seven digit patterns. The letter A is represented by 10000001; the number 6 by 0110110; and the question mark (?) by 01111111. So, if you were willing to use enough cores, you could use seven digit patterns of 1's and 0's to store the entire contents of this course in a core memory. Although not used much anymore, they could retain their memory even during a power outage or loss.
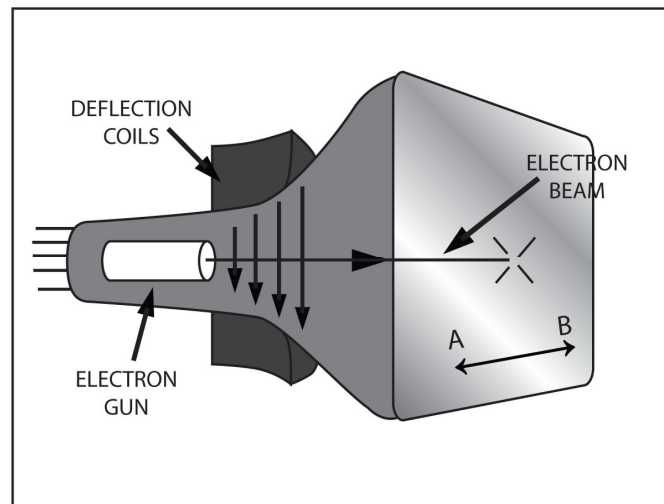
Fig. 6.44

Magnetic Deflection and Electron Beams

You have seen that a current–carrying conductor is deflected (moved) by a magnetic field. However, it is not the conductor, which is deflected, but the electrons traveling through the conductor. Since the electrons are confined to the wire, the conductor also moves.

In some cases, streams of electrons are not confined to a wire but travel through empty space. Such a beam can be deflected in the same way that a current-carrying conductor is deflected. There are many practical applications of this principle. The most familiar is the TV picture tube like the one shown in figure____. A device called an electron gun produces a beam of electrons, which is fired at the TV screen. Wherever the beam hits the phosphor screen, light is given off. By moving the beam over the entire surface of the screen while varying its intensity, a picture can be drawn.

Two magnetic fields are used to deflect the beam. One moves the beam back and forth across the screen over 15,000 times each second. Another moves the beam up and down the screen 30 times each second. The result is that 30 complete pictures which consist of about 500 lines are drawn each second.

The horizontal deflection coils are shown in fig____. When current flows in one direction through these coils, a magnetic field that has the direction shown is produced. You can use the right-hand motor rule to see that this field deflects the beam towards point A. If you reverse the direction of the field, the beam deflects towards point B. To deflect the beam in a vertical direction, vertical deflection coils are placed on the sides of the picture tube. This principle is used in radar sets and TV cameras as well as TV receivers.

Summary

In science, things that can't be observed because they are too small or large are often explained in terms of fields. Due to the fact that a magnet can affect objects at a distance, it appears to be surrounded by a magnetic field. This field is assumed to be made-up of lines of force called flux lines.

Magnets have north and south poles. The flux lines leave the magnet at the North Pole and enter the magnet at the South Pole and form complete loops. The flux lines cannot cross each other and tend to form the smallest possible loops. Like magnetic poles repel; unlike poles attract.

All materials are classified as ferromagnetic, paramagnetic, or diamagnetic. Ferromagnetic materials are strongly attracted by magnetic fields. However, paramagnetic materials are only slightly attracted by magnetic fields, and diamagnetic materials are somewhat repelled. Due to their non-attractive characteristics, paramagnetic and diamagnetic materials are considered non-magnetic.

A magnetic field is developed when an electrostatic charge moves. The electron spins on its axis and produces a magnetic field. In most atoms, electrons with opposite spins pair off so that their magnet fields cancel. However, in iron, nickel, and cobalt, the two valence electrons spin in the same direction and their fields add. These magnetic atoms bunch in tiny groups called domains. Normally, these domains are arranged haphazardly and their fields cancel. However, when they are subjected to a magnetic field, the domains align in the same direction to create a magnet.

Magnetism and electricity are closely related to each other. Current flow can produce a magnetic field, and a moving magnetic field can produce current flow.

You can use the left-hand rule for conductors to determine the direction of the magnetic field that is caused by current flow. To use this rule, grasp the conductor in your left hand with your thumb pointing in the direction of current flow. Your fingers now point in the direction of the flux lines.

The magnetic field around a conductor can be strengthened by winding the conductor as a coil. The result is called an electromagnet and has many of the characteristics of a permanent magnet.

The left-hand rule for coils help you determine the north pole of the electromagnet. To apply this rule, grasp the coil in your left hand with your fingers wrapped around it in the direction that current is flowing. Your thumb will point towards the north pole of the coil.

Magnetic have many quantities that are important. Permeability is the ease with which a substance accepts lines of force. Its opposite is called reluctance. Flux is the total lines of force around a magnet. Flux density refers to the amount of flux per unit of area. Magnetomotive force is the force, which produces the flux in a coil. Field intensity is the amount of MMF per unit of length of a coil.

Induction occurs when one body has an electrostatic or magnetic field and induces a change in another body without actually touching the other body. .A magnet can induce a magnetic field into a ferromagnetic body without touching it. This is called magnetic induction. When the magnet is taken away, a magnetic field remains in the ferromagnetic body. This called residual magnetism.

The ability of a substance to retain a magnetic field after you remove the magnetizing force is called retentivity.

An EMF is induced into the conductor when a conductor moves across a magnetic field. This is called electromagnetic induction. The magnitude of the created EMF is proportional to the rate at which the conductor cuts the magnetic lines of force. The more lines per second that are cut, the higher the created EMF will be.

The left-hand rule for generators helps you determine the polarity of the induced EMF. To use this rule, point your thumb in the direction of the flux lines. If you now place your middle finger at right angles to your thumb and index finger, it points in the directions in which current flows through the conductor.

A device which uses electromagnetic induction to convert mechanical energy to electrical energy is called a generator. A generator may produce AC or DC, depending upon how it is constructed. An AC generator is called an alternator. The DC generator uses commutators and brushes to convert AC to DC.

There are many different devices which use magnetic or electromagnetic principles. A relay uses an electromagnet to close switch contacts. A tape recorded uses an electromagnet as a record head.

Electrical energy is converted into mechanical energy in motors. Current passes through a coil to produce an electromagnetic field. This field interacts with a permanent magnet's field. As a result, the coil is forced to move. Proper design achieves a constant circular rotation.

A meter works on the same principle as the motor. Here, springs restrict the movement of the coil. A pointer that is attached to the coil moves in front of a scale to indicate the current through the meter.

The right-hand motor rule helps you determine the direction of movement of the coil in the motor or meter, or the direction of the deflection of the electron beam. To apply this rule you hold your thumb, index finger, and middle finger of your right hand at right angles to each other. If you point your index finger in the direction of the magnetic field and the middle finger in the direction of electron flow, your thumb will point in the direction in which the conductor (or electron beam) moves.

Chapter 7
Electrical Measurements

In this section, we will cover meter movement, construction, and operation. We will also discuss the ammeter, voltmeter, ohmmeter, and multimeter devices.

Meter Movement

Meter movement is the heart beat of the volt-ohm-milliammeter (VOM). This most widely used meter movement is the permanent-magnet, moving-coil movement that was described in a previous section. It's also named after its inventor, Arsene d'Arsonval and called d'Arsonval movement. It was first introduced in 1882, was called a galvanometer. It was delicate and somewhat crude. In 1888, an improved version was introduced by Edward Weston. Similar designs are still in use today.

Construction

The construction of the meter movement is shown in Figure 7.1 with several important parts listed. Each part will be detailed and explained, beginning with the permanent magnet.
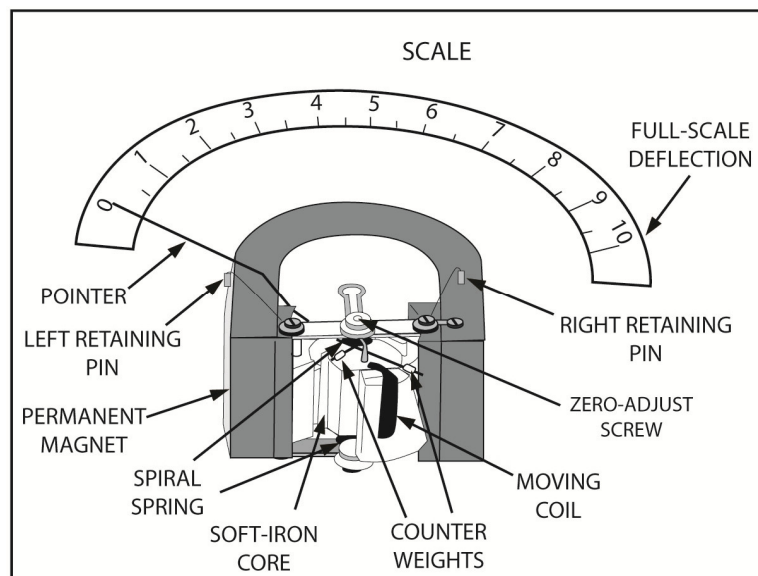
Fig. 7.1

The permanent magnet system is displayed in Figure 7.2. A stationary magnetic field is produced by a horseshoe magnet. To ensure the magnetic field is concentrated around the moving coil, pole pieces are added to the magnet. These are made of soft iron and have a very low reluctance. Consequently, the lines of the flux tend to concentrate in this area as shown. Also, a stationary soft-iron core is placed between the pole pieces. There's enough space left between the pole pieces and the core so that the moving coil can rotate freely in this space. Between the pole pieces and the core, most of the flux becomes concentrated in the area of the moving coil.
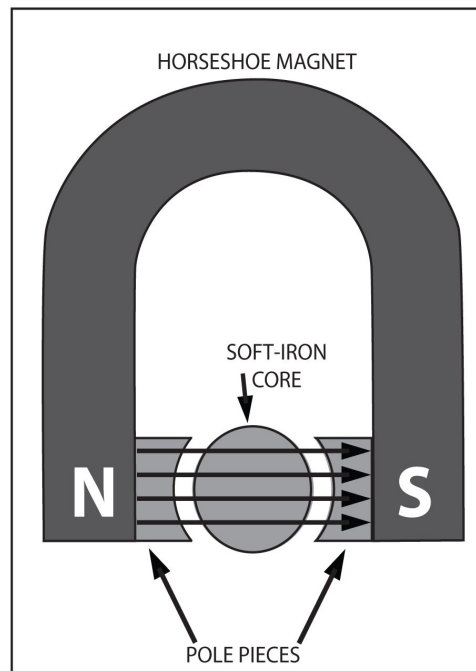
Fig. 7.2

In Figure 7.3, the moving coil is displayed as it fits around the soft-iron core. The coil is made of many turns of extremely fine wire on an aluminum frame. The aluminum frame is very light and requires little torque is to move it. The two ends of the coil connect to the leads of the ammeter voltmeter, or ohmmeter.
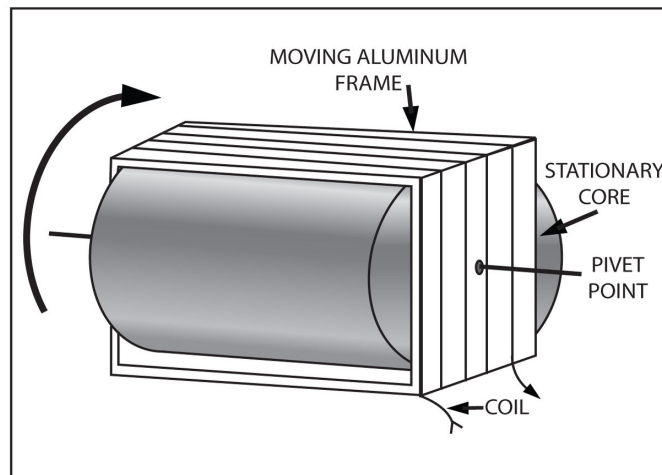
Fig. 7.3

The pointer assembly is shown in Figure 7.4 below. The pointer is attached to the moving coils so it moves when the coil does. Often, Counterweights are attached to the pointer so that a perfect balance is maintained. This also makes the pointer easier to move and helps the meter read the same in all positions. Whether you hold it vertically or horizontally, a well-balanced meter should read the same. Retaining pins on either side of the movement, limit the distance that the pointer and other rotating parts can move. Two spiral springs at opposite ends of the moving-coil force the pointer back to the zero position when no current flows through the coil. The coil two ends connect to the inner ends of the spiral spring. The outer end of the rear spring is fixed in place.

However, the outer end of the front spring connects to a zero-adjust screw. This allows you to set the pointer to exactly the zero point on the scale when no current flows through the coil.
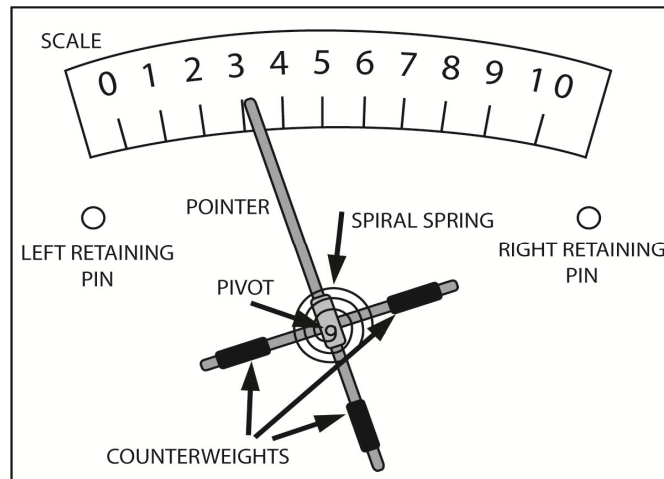
Fig. 7.4

The moving coil, pointer, and counterweight spin around a pivot point. This crucial point uses jeweled bearings to hold the friction to an absolute minimum.

Operation

Next, we'll discuss the meter's operation. In a previous section, you learned that a conductor is deflected at a right angle to a stationary magnetic field if current flows through the conductor. This is the principle behind the DC motor. The right-hand motor rule was also discussed. Figure 7.5 illustrates this rule and the motor action which causes the meter to deflect. The end view of one turn of the moving-coil is also shown. Current is forced to flow through the coil so that it flows, out of the page, to the left. Applying the right hand rule to the coil at this point, we find that the coil is forced up on the left and down on the right. This forces the pointer to move up scale or in clockwise direction.
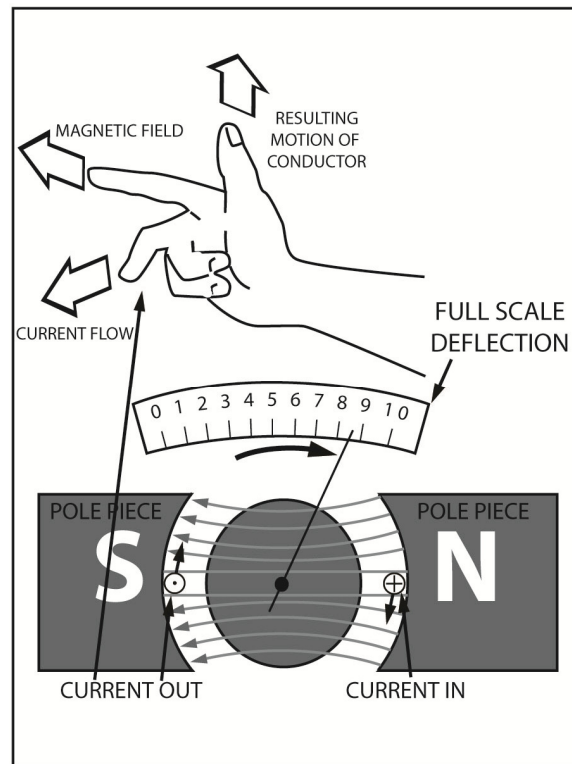
Fig. 7.5

The torque produced by this tiny motor is proportional to current's magnitude which flows through the moving coil. The more current, the greater the torque and the further the pointer deflects.

The amount of current required to produce a full-scale deflection is how meter movements are rated. For example, a 50 microampere meter movement deflects full scale when only 50 microamperes of current flows through it. Some other popular meter movements are the 50 μA and 200 μA.

In Figure 7.5, an important characteristic of the d'Asonval meter movement is illustrated. Let's assume that the current is always flowing in the same direction through the moving coil. That is, a direct current (DC) is applied to the coil. This movement works fine as long as the current is direct. But, the movement won't respond correctly to alternating current (AC). Whenever the current reverses, the coil attempts to reverse its direction of deflection. If the current changes direction more than a few times each second, the coil cannot follow the changes. Therefore, you must not apply AC to this type of meter movement.

Taut Band Movement

Taut-band movement is an important variation of the d'Arsonval movement. Figure 7.6 is a simplified diagram which shows the construction of this type of movement. Two tiny stretched metal bands hold up the moving coil. One end of each band connects to the moving coil while the other end connects to a tension spring. These springs keep the bands pulled tight. The bands replace the pivots, bearings, and spiral springs in the conventional d'Arsonval movement. This simplifies the construction of the meter, and reduces the friction to practically zero. Consequently, the taut-band movement is more sensitive than the movement described earlier. Taut-band instruments with 10 μA movements are available.
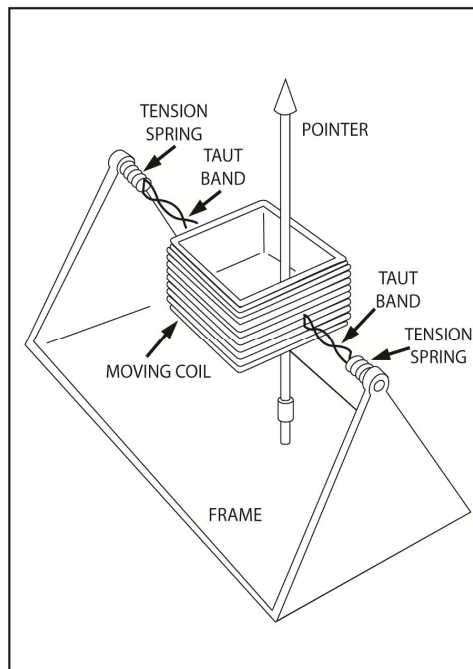
Fig. 7.6

The taut-bands serve several purposes. First, the coil is suspended in such a way that the friction is nearly zero. When current is applied, the coil rotates and the bands are twisted. When the current is removed, the bands untwist returning to the zero position. The bands also serve as the current path to and from the coil.

There are several advantages to taut-band movement when compared to the older d'Arsonval type. Taut-band movement is generally more sensitive. It is also more rugged and durable. Mechanical shocks simply deflect the tension springs which can then bounce back to their original positions. For this same reason, taut-band movement remains more accurate. Due to these advantages, the taut-band movement is the most popular meter movement today.

Ammeter

The meter movements just described are basically current meters. They deflect the current flows through them. In each case, the moving coil consists of many turns of extremely fine wire. Fragile spiral springs or the taut-bands of the movement carry current to the coil. Due to the delicate nature of the coil and the springs or bands, you must take care not to apply the excessive current through the movement. The current necessary for full-scale deflection does not harm the movement; however, a 100% overload might. It could cause the coil to burn out; a spring to be damaged; or the aluminum needle to become bent if it is driven too hard against the right retaining pin.

Care must be taken observe polarity when you use the meter movement. A reverse current causes the needle to deflect backwards. If the current is too great, the needle may bend when it bangs against the left retaining pin.

Measuring Current

Earlier in this manual, the rules for using the ammeter were overviewed. Please review those rules before moving forward.

1. First, you must connect the ammeter in series with the current to be measured. This means that you must break the circuit under test so that you can insert the ammeter. This is the prime disadvantage of the ammeter.

2. Second, you must observe polarity when you connect the meter. This simply means that you should connect the ammeter so that it deflects up scale. The terminals of the meters are generally marked with – and +. Simply connect the meter so the current flows into the – terminal.

3. Third, don't exceed the current ratings of the meter.

Range Increase in Ammeter

Every meter movement has a certain current rating. This is the current which causes full-scale deflection. An inexpensive meter movement may have a current rating of 1 milliampere. For a useable reading, the current through the movement cannot be more than 1mA. So this movement has a single usable range of 0 to 1 mA. Clearly, the meter would be more useful if it could measure currents greater than 1 mA, as well as those less than 1 mA. Fortunately, there is an easy way to convert a sensitive meter movement to a less sensitive current meter. You simply connect a small value resistor in parallel with the meter movement. The resistor is called a *shunt*. It acts as a low resistance path around the movement so that most of the current flows through the shunt and only a small current flows through the movement.

A 1 mA meter movement that is connected across a low resistance shunt to form a higher range ammeter is shown in Figure 7.7. The range is determined by how much current flows through the shunt. In Figure 7.7, the current applied to the ammeter is 10 mA, but only 1 mA of this flows through the meter movement. The other 9 mA flows through the shunt. So, to convert the 1 mA movement to a 0-10 mA meter, you must select the shunt so that 9/10 of the applied current flows through the shunt. After you do this, the full scale position on the scale indicates 10 mA, because this is the amount of current that must be applied before the meter reaches full-scale deflection.

If the value of the shunt is smaller, the meter will indicate even higher values of current. In Figure 7.7, the requirements necessary to measure 100 mA are shown in the bottom portion of the Figure. Here, 99 mA or 99 percent of the applied current must go through the shunt. Thus, the resistance of the shunt must be much smaller than the resistance of the meter movement.
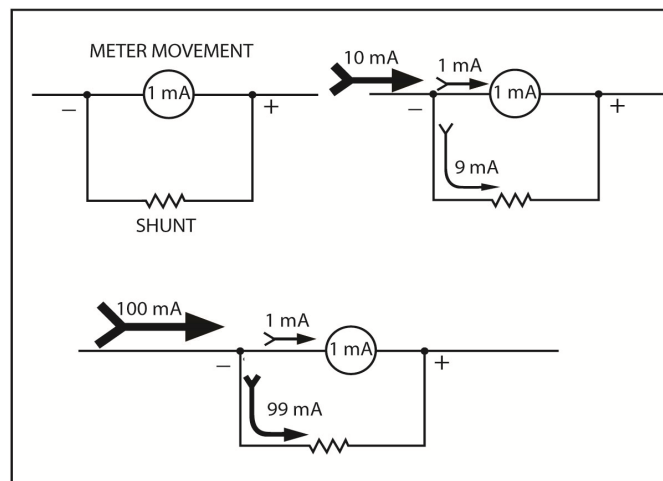
Fig. 7.7

Shunt Resistance Computing

For the proper value of the shunt resistor to be determined, you must first know something about the characteristics of the meter movement. From the earlier example, you know that full scale deflection requires 1 mA. However, you've also got know either the resistance of the meter movement or the voltage that is dropped by the movement when the current is 1 mA. Of course, if you know one, you can compute the other.

The resistance of the meter movement can be found in the manufacturer's literature, catalog, or operating instructions. It's often printed right on the meter movement itself. Assume that the 0-1 mA movement has the resistance of 1000 ohms or 1 kilohm. In this case, 1 mA of current causes a voltage drop across the meter movement of:

$$E = IR$$

$$E = 1 \text{ mA x } 1 \text{ k}\Omega$$

$$E = .001 \text{ A x } 1000\Omega$$

$$E = 1 \text{ volt}$$

If you refer back to Figure 7.7, you see that this voltage is developed across the meter movement in each of the examples shown. Since the resistance is connected in parallel with the meter movement, this same voltage is developed across the shunt. In the example shown in Figure 7.7, the 9 mA current develops 1 V across the shunt. You can use Ohm's Law to compute the value of the shunt, since the current and voltage are known. So, the value of the shunt should be:

$$R = E/I$$

$$R = 1 \text{ V}/ 9 \text{ mA}$$

$$R = 1 \text{ V}/ 0.009 \text{ A}$$

$$R = 111 \text{ ohms}$$

This is the resistance necessary to shunt 9 mA around the meter when a current of 10 mA flows in the circuit. However, the shunt works just as well when the movement indicates three-fourths scale or 0.75 mA. Again, you can Ohm's Law to calculate the voltage across the meter:

$$E = IR$$

$$E = 0.5 \text{ mA x } 1 \text{ k}\Omega$$

$$E = 0.0005 \text{ A x } 1000\Omega$$

$$E = 0.5$$

Given that, the voltage across the meter and the 111 ohm resistor are the same, the current through the shunt is:

$$I = E/R$$

$$I = 0.5 \text{ V}/ 111 \text{ } \Omega$$

$$I = .0045 \text{ A or } 4.5 \text{ mA}$$

Nine-tenths of the current still moves through the shunt while only one-tenth flows through the movement. So, the movement indicates the 0.5 mA when 5 mA of current flows in the circuit. The meter scale is marked off 0 through 10 instead of 0 through 1, and a 111 ohm resistor is connected across the meter movement. This process converts the circuit to a 0-10 mA current meter.

There's also another way to find the value of the shunt. Referring back to Figure 7.7, we know that 9 mA must move through the shunt so that the remaining 1 mA flows through the meter movement. For the shunt, to conduct 9 times as much current as the meter, its resistance must only be 1/9 that of the meter resistance. So, since the meter resistance is 1000 ohms, the shunt resistance must be 1000 Ω divided by 9 or 111 ohms.

Let's apply these two methods to the situation shown at the bottom of Figure 7.7. To review, the current through the meter movement is 1 mA. Thus, the voltage drop across the movement and across the shunt is still 1 volt. This allows you to compute the value of the shunt:

$$R = E/ I$$

$$R = 1 \text{ V}/99 \text{ mA}$$

$$R = 1 \text{ V}/.099 \text{ A}$$

$$R = 10.1 \text{ ohms}$$

The same answer can be computed by reasoning that the shunt resistance must be 1/99 that of the meter resistance, because the shunt moves 99 times as much current. Therefore, the shunt resistance must be:

$$1000 \ \Omega/99 = 10.1 \text{ ohms}$$
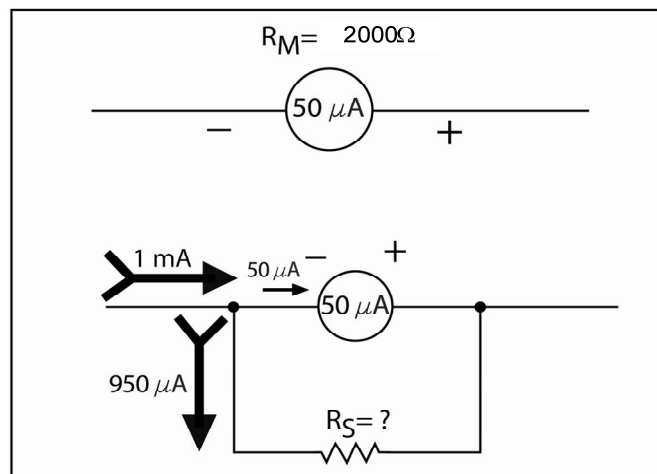
Fig. 7.8

Another example in Figure 7.8, shows a 0-50 µA meter movement with a resistance of 2000 ohms. What value shunt is required to construct a 0-1 mA meter? In this circuit, 1 mA or 1000 µA of current flows through, but only 50 µA can flow through the meter movement. The remaining 950 µA must flow through the shunt. Since you know the resistance of the meter movement, 2000 Ω, and the current going through it, 50 µA, the voltage across can be calculated.

$$E = IR$$

$$E = 50\mu A \text{ x } 2000$$

$$E = 0.00005 \text{ A x } 2000\Omega$$

$$E = 0.1 \text{ volts}$$

When the shunt is in parallel with the meter movement, the same voltage is developed across the shunt. So, you can compute the shunt value:

$$R_S = E/I$$

$$R_S = 0.1 \text{ V}/ 950 \text{ μA}$$

$$R_S = 0.1 \text{ V}/ 0.00095 \text{ A}$$

$$R_S = 105.26 \text{ Ω}$$

The same answer is arrived at because we reasoned that 95% or 19 times as much current moves through the shunt as through the meter movement. Because the shunt conducts 19 times as much current, the resistance of the shunt must be 1/19 that of the meter movement. So, the shunt resistance must be:

$$2000 \text{ Ω}/19 = 105.26 \text{ Ω}$$

Ammeter Accuracy

Accuracy is associated with and very important to every meter movement. The accuracy is specified as a *percentage of error at full-scale deflection.* Good quality instruments often have accuracies of ±2% or ±3% of full-scale. Figure 7.9 illustrates what ±3% of full scale means. The scale shown is a 100mA current scale. Remember, the meter accuracy refers to full scale deflection. At full scale, ±3% equals ±3 mA. So, with this meter, a current of exactly 100mA, could read anywhere between 97 mA to 103mA. So, a meter reading of exactly 100 mA could be caused by an actual current between 97 mA to 103 mA.
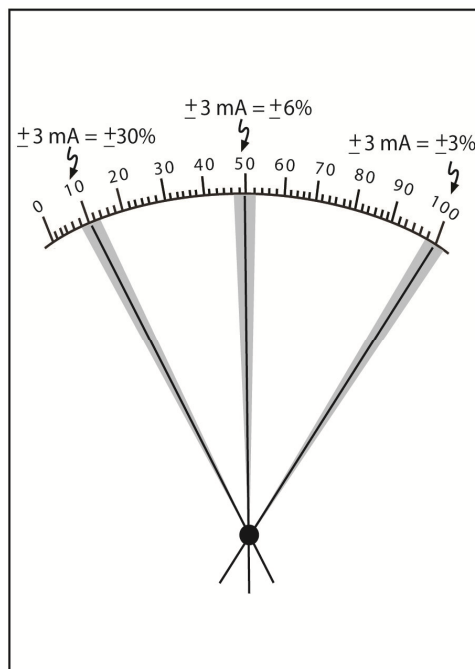
Fig. 7.9

More importantly, it means that the reading may be off by as much as ±3 mA at any point on the scale. For example, when the meter indicates 50 mA, the actual current may be anywhere from 47 mA to 53 mA. Thus at half-scale the accuracy is no longer ±3%; it is now ±6%.

The accuracy gets progressively worse as you move down the scale, because it's specified in this manner. For this reason, current measurements are most accurate when you select a current range that causes near full-scale deflection of the meter. The nearer to full scale, the more accurate the reading will be.

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Voltmeter

You can use the basic movement to measure voltage as well as current. Every meter movement has a certain voltage rating and a current rating. It's the voltage that causes full scale deflection. Of course, the voltage rating is actually determined by the current rating and the meter resistance. So, a 50 μA meter movement which has a resistance of 2000 Ω deflects full scale when it is connected across a voltage of:

$$E = IR$$

$$E = 50 \text{ μA x } 2000 \text{ Ω}$$

$$E = 0.1 \text{ volt}$$

This means the meter movement alone could be used to measure voltages up to 0.1 volt. Therefore, the meter scale is calibrated from 0 to 0.1 volt. However, when the meter movement is connected across a much higher voltage such as 12 volts, it can be damaged. So, the voltage range of the basic meter movement needs to be extended.

Range Extension in Voltmeter

We have already seen that a 50 μA, 2000 ohm meter movement can withstand a voltage of 0.1 volt without exceeding dull scale. For this range to be extended, you must ensure that the voltage across the meter does not exceed 0.1 volt when the meter movement is connected across a higher voltage. This is done by connecting a resistor in series with the meter movement. As shown in Figure 7.10, the resistor is called a *multiplier*, because it multiplies the range of the meter movement. This is how a voltmeter is formed by connecting a multiplier resistor in series with a micrometer
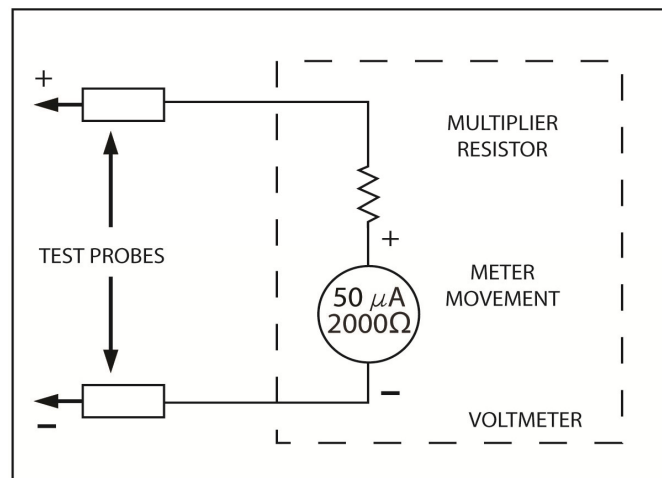
Fig. 7.10

The current which flows through the meter movement is limited by the multiplier resistor. For example, in the voltmeter shown in Figure 6-10, the current through the meter movement must be limited to 50 μA. This means the multiplier must drop all the voltage applied to the voltmeter except the 0.1 volt allowed across the meter movement. For example, if the range is to be extended to 12 volts, then the multiplier must drop 12 V – 0.1 V = 11.9 volts. Some voltmeters have very large multiplier resistors, so they can measure voltages up to 40,000 volts.

Calculating the Multiplier

The multiplier's value must be high enough to limit the current to the full-scale current rating of the meter movement for any applied voltage. If you keep this in mind, you can easily calculate the required value of the multiplier for any voltage range.

Let's say, we want to convert a 50 μA, 2000- ohm meter movement to a 12-volt voltmeter by adding a multiplier in series. Obviously, a current of only 100 μA must flow when the voltmeter is connected across 12 volts. Thus, the total resistance is:

$$R_{total} = E_{full\text{-}scale}/I_{full\text{-}scale}$$

$$R_{total} = 12 \text{ V}/ 50 \text{ μA}$$

$$R_{total} = 240,000 \text{ Ω}$$

Still, the meter movement itself has a resistance of 2000 ohms. Thus, the multiplier must have a value of 240,000 Ω = 238,000 Ω or 238 kΩ.

Based on this a basic 50 μA 2000 Ω meter movement can now measure 0 to 12 volts because 12 volts causes a full-scale deflection. From a voltage standpoint, the multiplier resistor drops 99% of the applied voltage. That is, for an applied voltage of 12 volts, the multiplier drops:

$$E = IR$$

$$E = 50 \text{ μA x } 238,000$$

$$E = 11.9 \text{ volts.}$$

The remaining 0.1 volt can cross the meter. Because, the total voltmeter resistance is 100 times larger than the meter resistance, the range of the meter is multiplied by 100. Now the meter scale should be re-calibrated from 0 to 12 volts.

Try to find the value of the multiplier that is required to convert the same meter movement to a 0-100 voltmeter. This time, the multiplier must limit the current to 50 μA when 100 volts is applied. So, the total resistance of the voltmeter must be:

$$R_{total} = E_{fullscale}/ I_{fullscale}$$

$$R_{total} = 100 \text{ V}/ 50 \text{ μA}$$

$$R_{total} = 2,000,000 \text{ ohms or 2 MΩ}$$

In this example, 2000 ohms are supplied by the meter movement. So, the value of the multiplier must be:

$$R_{multiplier} = R_{total} - R_{meter}$$

$$R_{multiplier} = 2,000,000 \text{ Ω - 2000 Ω}$$

$$R_{multiplier} = 1,998,000 \text{ Ω - 1,998 MΩ}$$

The 1,998 MΩ is very near to 2 MΩ. The difference is so small that you probably wouldn't notice any difference in a deflection regardless of which value you use. In this situation, you would probably use a standard value, 2 MΩ resistor rather than a 1,998 MΩ, which isn't as readily available for use.

Multiple Range Voltmeters

A practical voltmeter has many ranges. In Figure 7.11, one possible arrangement for achieving multiple ranges is shown. In this example, the voltmeter has four ranges which are selected by the range switch. Again, the 50 μA, 2000 Ω meter-movement is used. On the 0.1-volt range no multiplier is required since this is the voltage rating of the actual meter movement.

R_1 is switched in series with the meter movement on the 1 volt range. The value of R_1 is given as 20 kΩ. You can use the procedure outlined earlier to verify that this is the proper value multiplier required.

The 10-volt and 100-volt ranges, the multiplier values, e switched in series with the meter movement.
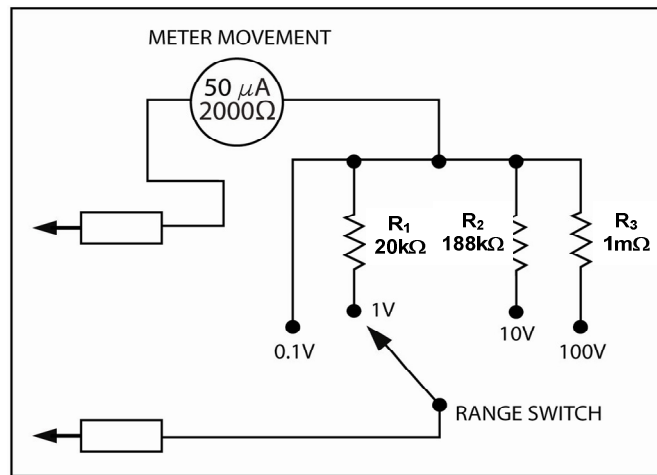
Fig. 7.11
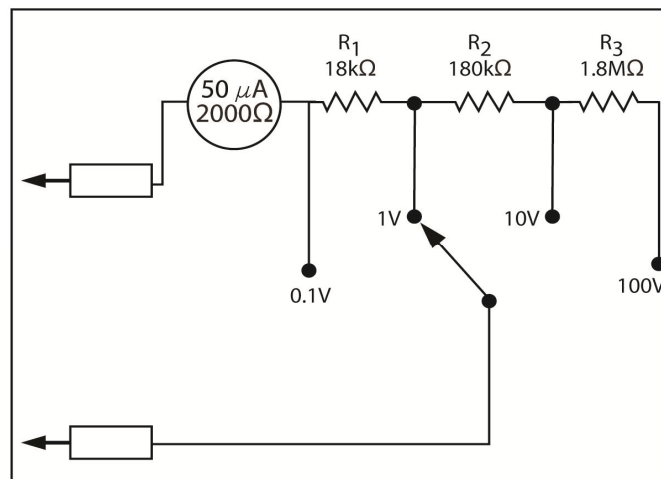
Fig. 7.12

Anther arrangement sometimes used when several ranges are required is depicted in Figure 7.12. No multiplier is required on the 0.1 volt range. The 1-volt range has an 18 kΩ multiplier that's switched in series with the meter movement. Up to this point, the arrangement is similar to that shown in Figure 7.11. However, the similarity ends on the 10-volt range. Here the R_2 is switched in series with R_1. In Figure 7.12, two resistors having a total resistance of 198 kΩ are used. On the 100-volt range, R3 is switched in series with R1 and R2. Thus, the total multiplier resistance is 18 kΩ + 180

kΩ + 1.8 MΩ = 1.998 MΩ. Recall that this is the exact multiplier value that you computed earlier for the 100-volt range.

Sensitivity (Ohms per Volt)

Sensitivity is an important characteristic of a voltmeter. Sensitivity is the amount of current that is required to produce a full-scale deflection of the meter movement. For example, a 100 µA meter movement is more sensitive than a 5 mA meter movement, because a smaller amount of current is required to create a full-scale deflection.

Often, sensitivity is defined in another way. It's normally expressed in ohms-per-volt, also written, ohm/volt. The more sensitive the meter is, the higher the ohms-per-volt rating. The full-scale current rating of the meter movement can be divided into 1 volt to determine the sensitivity in ohms-per-volt of any voltmeter.

$$\text{Sensitivity} = 1 \text{ volt}/I_{\text{full-scale}}$$

Therefore, a voltmeter which uses a 20 µA meter movement has a sensitivity of:

$$\text{Sensitivity} = 1 \text{ volt}/I_{\text{full-scale}}$$

$$\text{Sensitivity} = 1 \text{ volt}/20 \text{ µA}$$

$$\text{Sensitivity} = 50,000 \text{ ohms-per-volt}$$

This voltmeter has a total resistance of 50,000 ohms on the 1-volt range.

The sensitivity is solely determined by the full-scale current rating of the meter movement. Thus, it has the same sensitivity regardless of the range.

What is the sensitivity of a voltmeter which uses a 2 mA meter movement? Remember, you determine sensitivity by dividing the full-scale current into 1 volt. That is:

$$\text{Sensitivity} = 1 \text{ volt}/I_{\text{full-scale}}$$

$$\text{Sensitivity} = 1V/2 \text{ mA}$$

$$\text{Sensitivity} = 500 \text{ ohms per volt}$$

What would the total resistance of this voltmeter be on the 5-volt range? The resistance would be 500 ohms x 5 = 2500 ohms.

Voltmeters-Loading Effect

The very act of measuring an electrical quantity can unfortunately often change what's being measured. When you measure voltage, the voltmeter must be connected across the circuit under test. Since some current must flow through the voltmeter, the circuit behavior is somewhat changed when this happens. Frequently, you can ignore the effects of the voltmeter, especially if the meter has a high ohm/volt rating. But when the voltmeter has a low ohms/volt rating, or the circuit under test has a high resistance, it can't be ignored.
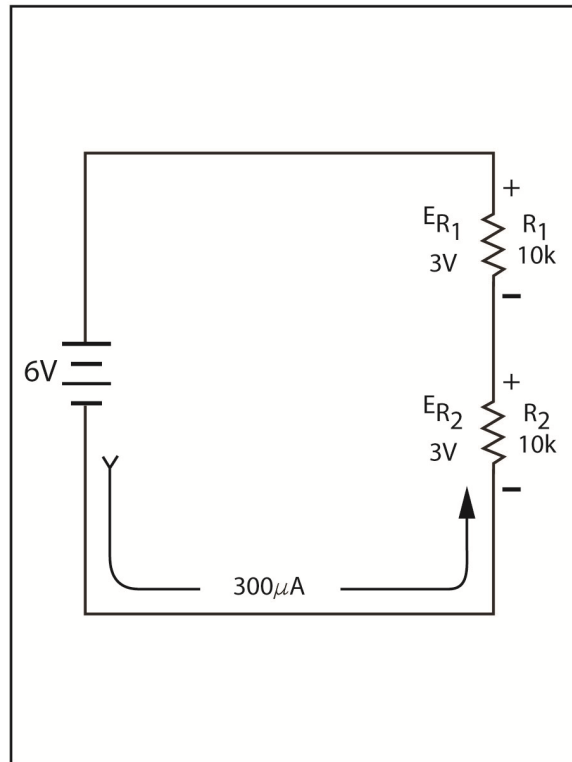
Fig. 7.13

Let's consider the circuit shown in Figure 7.13. Here two 10 kΩ resistors are connected in series across a 6-volt battery. The resistors are the same value and each drops one half of their applied voltage, 3 volts. Consequently, it's expected that a voltmeter will read 3 volts if it's connected across either resistor. However, if the voltmeter has a low ohms/volt rating, the actual reading may be very inaccurate.

Now what happens if the same circuit is connected across R_2 with a low-sensitivity voltmeter, a sensitivity of 1000 ohms/volt? Since you expect the voltage across R_2 to be about 3 volts, the voltmeter is set to the 0-10 volt range. Thus, its resistance, R_m, is 1000 Ω x 10 = 10,000 Ω. Now because, R_m is in parallel with R_2, the total resistance is reduced. As you learned in an earlier assignment, you can calculate the parallel resistance, R_A, of the meter and R_2:

$$R_A = R_2 \text{ x } R_{m/} R_2 + R_m$$

$$R_A = 10,000 \text{ x } 10,000/10,000 + 10,000$$

$$R_A = 100,000,000/20,000$$

$$R_A = 5,000 \text{ Ω or } 5kΩ$$
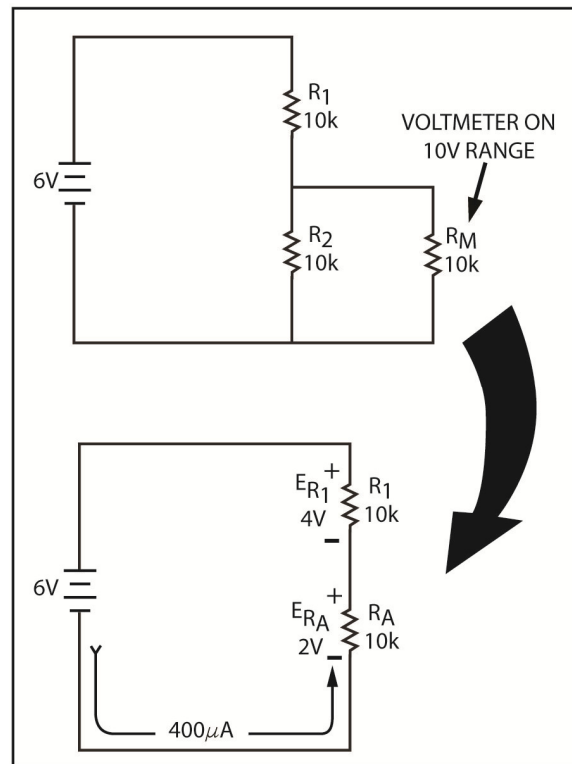
Fig. 7.14

Therefore, the circuit shown in Figure 7.14 on the top reduces to the circuit shown in Figure 7.14 on the bottom. Notice how this upsets the operation of the circuit. The total series resistance of R_1 and R_A is now only 15 kΩ, instead of 20 kΩ, which allows more current to flow:

$$I = E/R$$

$$6 \text{ V}/15{,}000 \text{ } \Omega$$

$$0.0004 \text{ A or } 400 \text{ } \mu A$$

The 1000 ohms-per-volt meter loads down the circuit and causes an inaccurate reading. Thus, the current increases from its previous value of 300 μA to a new value of 400 μA. The distribution of voltage also changes because R_1 is now larger than R_A. The voltage dropped by R_A is:

$$E_{RA} = I \text{ x } R_A$$

$$E_{RA} = 0.0004 \text{ A x } 5{,}000 \Omega$$

$$E_{RA} = 2 \text{ V}$$

The voltage dropped by R_1 increases to:

$$E_{R1} = I \text{ x } R_1$$

$$E_{R1} = 0.0004 \text{ A x } 10{,}000 \text{ } \Omega$$

$$E_{R1} = 4V$$

As a result, instead of reading 3 volts as expected the meter measures only 2 volts across R_2, which is an inaccuracy of 33%. This effect is called loading. The meter is loading down the circuit, which causes the voltage across R_2 to decrease. The loading effect becomes noticeable when the resistance of the meter approaches that of the resistor across which the meter is connected. For example, if the resistance of the meter were made 10 times that of R_2, the loading effect would barely noticeable.

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The loading effect is minimized when you use a voltmeter whose resistance is much higher than the resistance across which a voltage is to be measured.

The Ohmmeter

You can also use the basic meter movement to measure resistance. The resulting circuit is called an ohmmeter. Basically, the ohmmeter is nothing more than a meter movement, a battery, and a series resistance.

Basic Circuit

The basic circuit of the ohmmeter is shown below in Figure 7.15. The main goal here is for the ohmmeter to force a current to flow through an unknown resistance and then measure the current. For a given voltage, the current is determined by the unknown resistance. Meaning, the amount of current measured by the meter is an indication of the unknown resistance. So, the scale of the meter movement can be marked off in ohms.
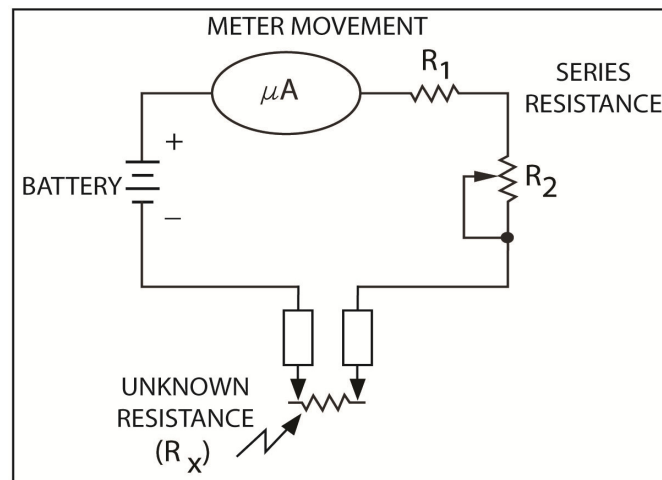
Fig. 7.15

The battery's purpose is to force current through the unknown resistance. Then the meter movement measures the resulting current. The test probes have long leads and simplify connecting the ohmmeter to the unknown resistor (Rx) simpler. The fixed resistor, R_1, limits the current through the meter to a safe level. Variable resistor, R_2, is called the ZERO OHMS adjustment. Its purpose is to compensate for battery aging.

Scale Calibration

With this type of ohmmeter, 0 ohms appears on the right side of the scale (at full-scale deflection). The reason for this is shown in Figure 7.16. Here, the two test probes are shorted together. As a result, the unknown resistance (Rx) between the probes is equal to 0 ohms. In this case, the meter should deflect full scale to the 0 ohms marking of the scale. Full-scale deflection for this meter is 50 μA. In order for the 1.5 volt battery to force 50 μA of current through the circuit, the total circuit resistance must be:
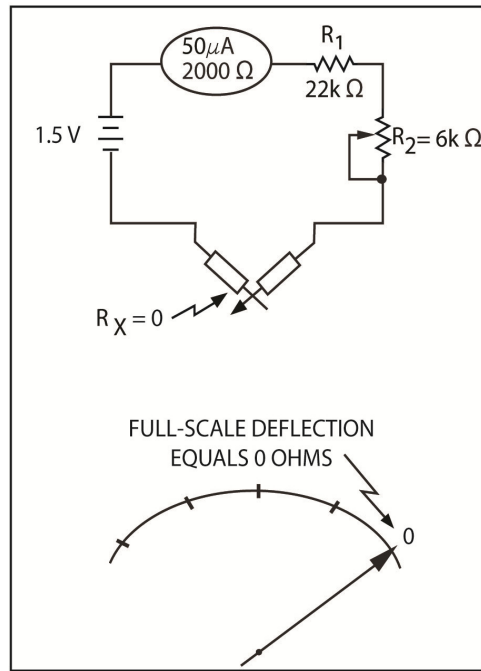
Fig. 7.16

$$R_T = E/I$$

$$R_T = 1.5 \text{ V}/.00005 \text{ A}$$

$$R_T = 30,000 \text{ } \Omega$$

2000 ohms are given by the meter, while R_1 provides 22,000. Thus, R_2 must be set to exactly 6,000 ohms to make sure a current of exactly 50 μA is achieved.

Are you wondering why R_2 isn't a fixed 6,000 ohms resistor, or why R_1 isn't a fixed 28,000 ohm resistor? Well, the battery voltage changes as the battery discharges. If the battery voltage drops to 1.45 volts, to achieve full-scale deflection, the circuit resistance must be reset to:

$$R_T = E/I$$

$$R_T = 1.45 \text{ V}/ .00005 \text{ A}$$

$$R_T = 29,000 \text{ } \Omega$$

In this situation, R_2 would have to be reset to 5000 ohms to compensate for the lower voltage. R_2 is called ZERO OHMS adjust. The first step in every resistance measurement is to adjust this resistance to "zero the ohmmeter".

You have seen that a full-scale deflection corresponds to an unknown resistance, R_x, of 0 ohms. So, at this point, the scale is marked 0. Now, what about the left side, no deflection, part of the scale? In Figure, 7.17, an open circuit exists between the two test probes. This corresponds to an infinite resistance. The meter movement has no current flow, and the pointer rests at the left side of the scale. Consequently, this point on the scale is marked with an infinity symbol (∞). Thus, you have a scale with 0 ohms on the right and infinite ohms on the left.
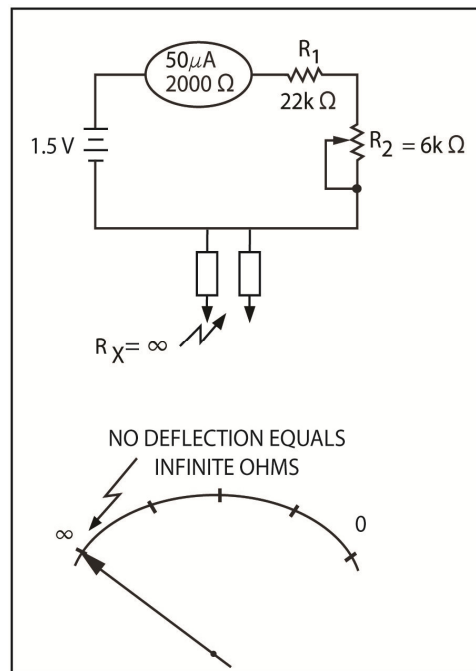
Fig. 7.17

Now what resistance is represented by the ½ scale deflection? The pointer will deflect to the center of the scale when the current is exactly 25 μA. This amount of current is caused by a total resistance of:

$$R_T = E/I$$

$$1.5 \text{ V}/ .000025 \text{ A}$$

$$= 60,000 \ \Omega$$

R_1 and R_2 have a combined resistance of only 30,000 ohms; the unknown resistance R_x supplies the other 30,000 ohms. Meaning, the meter deflects to half scale (25 μA) when the unknown resistance has a value of 30 kΩ. Consequently, the ½ scale point is marked 30k as shown in Figure 7.18.
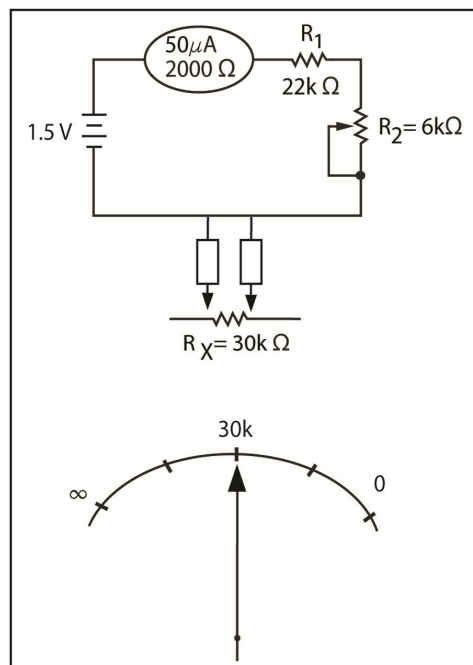
Fig. 7.18

This same process can be used to determine the amount of meter deflection for any value of R_x. Figure 7.19 show that 1/2 -full scale indicates an R_x of 60 kΩ, while 2/3-full scale indicates an R_X of 15 kΩ. To ensure this, notice what 1/3 of 50 μA or 16.66 μA flows in the circuit shown in Figure 7.19. Also, notice that 2/3 of 50 μA or 33.33 μA flows in the circuit shown in Figure 7.20.
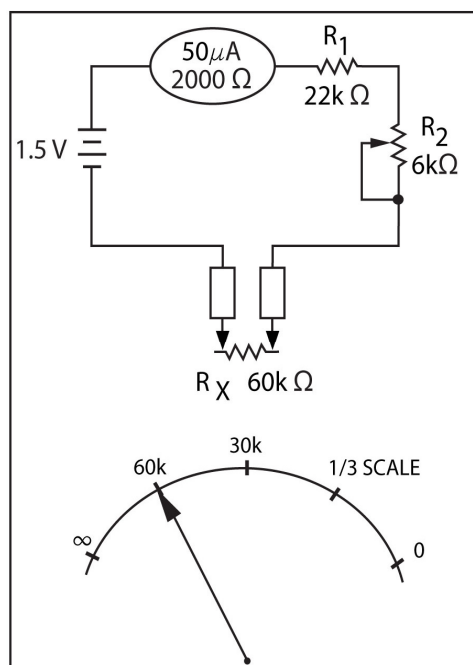
Fig. 7.19
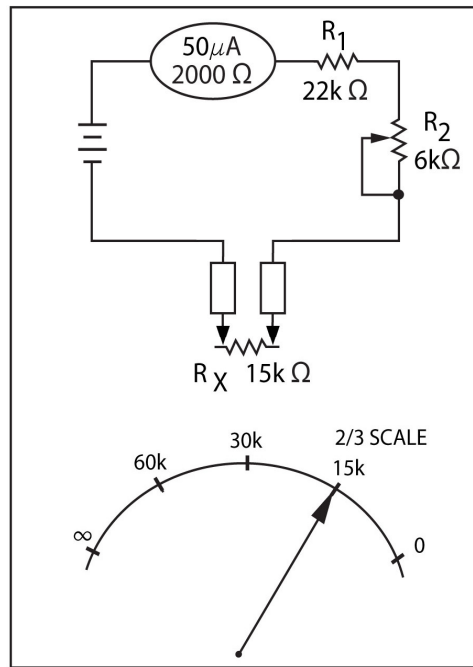
Figure 7.20

If enough points on the scale are found, the scale will look like the one found in Figure 7.21. Two important differences exist between this scale and the ones used for current and voltage. First, the ohms scale is reversed with 0 on the right. Second, the scale is non-linear. So, the entire upper half of the scale is devoted to a range of only 30 kΩ; from 0 to 30 kΩ. However, notice that the second 30 kilohms, from 30 kΩ to 60 kΩ, takes up less than ¼ of the scale. These markings are squeezed closer together on the left side of the scale. On ammeters and voltmeters, the scale is linear. It's marked off in equal increments of current or voltage.
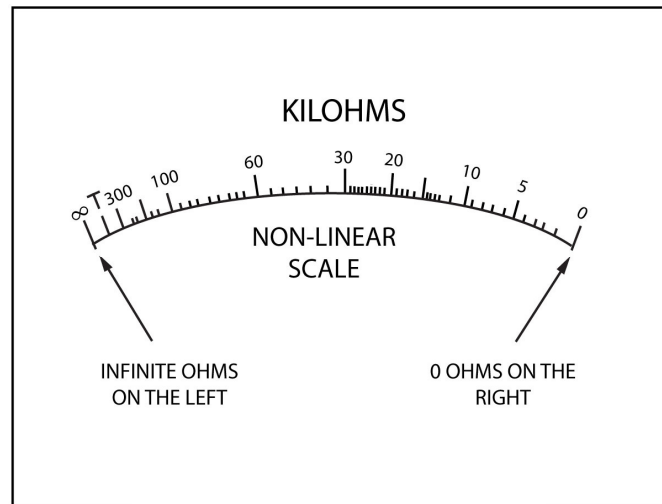
Fig. 7.21

Higher Range Creation

A single-range ohmmeter would not be very useful. For this reason, multi-range ohmmeters have been developed. Two techniques have evolved for creating additional ranges and are used in some ohmmeters.

To implement a higher resistance range, a switch is added to allow a choice between the two ranges. Next, a higher voltage battery is added. Finally, a higher value series resistor is required. To increase the range by a factor of 10, both the voltage and the total series resistance must be increased by a factor of 10. There's an example of this in Figure 7.22 below.
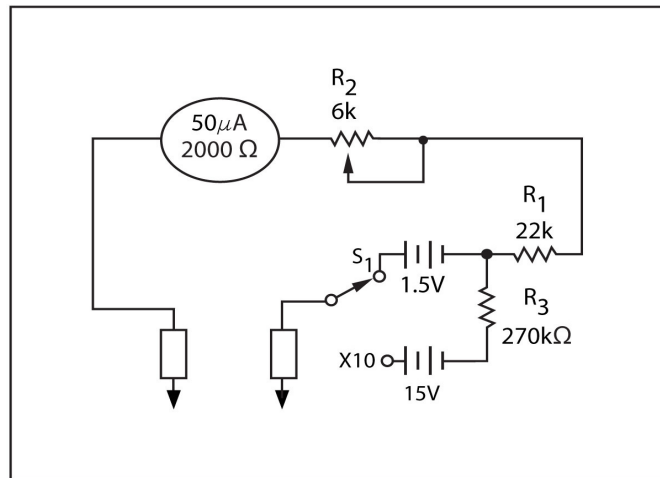
Fig. 7.22

When S_1 is in the position shown, the meter operates exactly like the one shown earlier in Figure 7.19 and 7.20. But when S_1 is set to the x 10 position, the 1-volt battery is in series with R_3, R_1, R_2 and the meter. The higher voltage does not cause excessive current through the meter because the series resistance has been increased by the addition of R_3. Note, the total resistance in the circuit is now 300 kΩ. Thus, when you short the leads together, the current is still:

$$I = E/R$$

$$15V/300 \text{ k}\Omega$$

$$I = 0.05 \text{ }\mu A$$

The right side of the scale still represents 0 ohms, but half-scale deflection (25 μA) now happens when the total resistance is:

$$R_T = 15 \text{ V}/ 0.25 \text{ }\mu A$$

$$R_T = 600 \text{ k}\Omega$$

On this meter, R_1, R_2 and R_3 supply 300 kΩ. This means the unknown resistance R_x must be 300 kΩ. Therefore, the center of the ohmmeter scale now represents 300 kΩ rather than 30 kΩ. The range has been increased by a factor of 10.

Of course, you cannot carry this technique much further because if you increase the range by an additional factor of 10, you would require a 150-volt battery. Fortunately, the range described above is sufficient for general purpose use. It can measure resistance values up to several megohms. Resistors larger than this are rarely used in most electronic applications.

Lower Range Creation

A basic ohmmeter can also be modified to measure lower values of resistance. To do this, you switch a small value shunt resistor in parallel with the meter and its series resistance.

When switch S_1 is in the position shown in Figure 7.23, the ohmmeter operates exactly like the one shown earlier in Figure 7.19. However, when you change the position of this switch, R_3 is

connected in parallel with the series combination of the meter, R_1 and R_2. The value of R_3 is 300 Ω or 1% of the combined series resistance of R_1, R_2 and the meter, 30,000 Ω. Therefore, 99% of the current flows through R_3 and only 1% flows through the meter circuit. Remember that 25 μA of current is required for half-scale deflection of the meter. Figure out what value of R_x will cause this amount of current to flow through the meter.
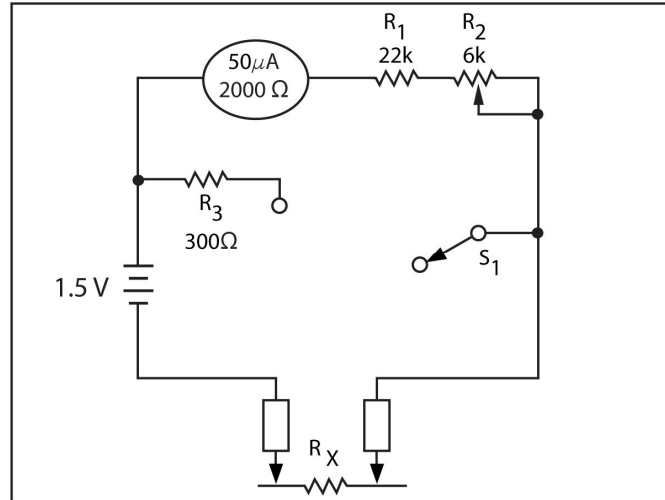
Fig. 7.23

The meter circuit's resistance is at about 300 ohms. If you connect an unknown resistance R_x of 300 ohms between the probes, the current form the battery becomes:

$$I = 1.5 \text{ V}/ 600 \text{ } \Omega$$

$$I = 2.5 \text{ mA}$$

But remember, 99% of this current, 2.475 mA, flows through R_3. Only 1%, 25 μA, flows through the meter movement. Thus, a half-scale deflection now represents an unknown resistance of 300 ohms instead of 30 kΩ. This technique can be used create lower ohmmeter ranges.

Shunt Ohmmeter

The ohmmeters described up to this point have been called series ohmmeters because the unknown resistance is always placed in series with the meter movement. You can recognize a series ohmmeter by its "backwards" scale, 0 ohms is on the right while infinite ohms in on the left.

The other type of ohmmeter is shown in Figure 7.24 and is called a shunt ohmmeter. This instrument gets its name from the fact that you place the unknown resistance in parallel (shunt) with the meter movement. This completely changes the character of the ohmmeter. Take notice that when an open, infinite ohms, exists between the probes, 50 μA of current flows through the meter movement. This produces a full-scale deflection. Consequently, an infinite ohm is on the right side of the scale or at full-scale deflection. Note that this is just the opposite of the series ohmmeter.

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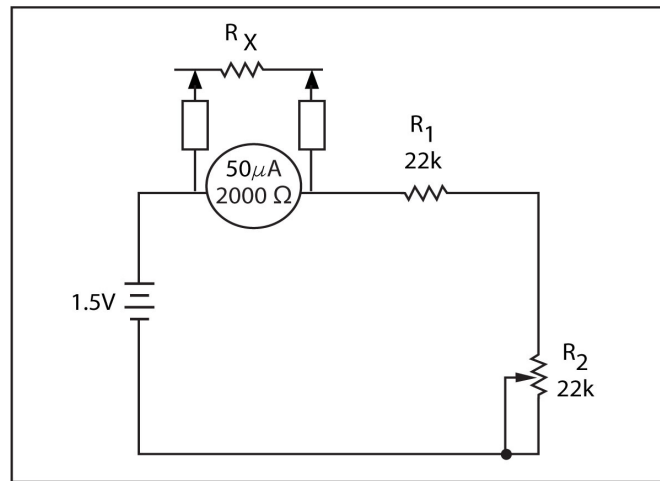
Fig. 7.24

When you short together the probes on the shunt ohmmeter, which represents an R_x of ohms, this shorts out the meter movement and produces no deflection. Thus, 0 ohms is on the left.

With the series ohmmeter, the half-scale reading was 30,000 ohms for the 50 µA, 2000 Ω meter movement. However, with the shunt ohmmeter, this is also different. With the shunt ohmmeter, 25 µA of current flows through the meter movement when R_x is the same resistance as the meter movement, thus, half-scale deflection on the shunt ohmmeter is marked 2000 ohms.

The shunt ohmmeter has disadvantages. The battery discharges any time the ohmmeter is turned on. With the series ohmmeter, it draws current from the battery only when you measure a resistance or touch the leads together. Also, the meter movement in the shunt ohmmeter is more easily damaged if you inadvertently connect the meter across a voltage source. In the series meter, the 28,000 ohms that is in series with the meter movement tends to limit the current. Even so, you should never connect either type of ohmmeter to a live circuit. Finally, it is more difficult to accurately measure high resistance values on the shunt meter, because the half-scale reading of the shunt ohmmeter is much less than that of the series ohmmeter. But, it is easier to read low resistance values on the shunt meter for the same reason.

Multi-meters

The voltmeter, current meter, and ohmmeter are usually combined into a single instrument referred to as a multi-meter. There are many reasons for this. First, it's easier to carry a single instrument than it is to carry three separate ones. Second, it is much cheaper to buy a single multi-meter than to buy three separate single-function meters.

Basic Circuit

A very basic schematic diagram of a multi-meter is shown in Figure 7.25. This meter has three DC voltage ranges, two ohmmeter ranges, and three current ranges. A function switch, S_2, determines if the multi-meter acts as an ammeter, a voltmeter, or an ohmmeter. The range switch, S_1 determines the range of the meter.
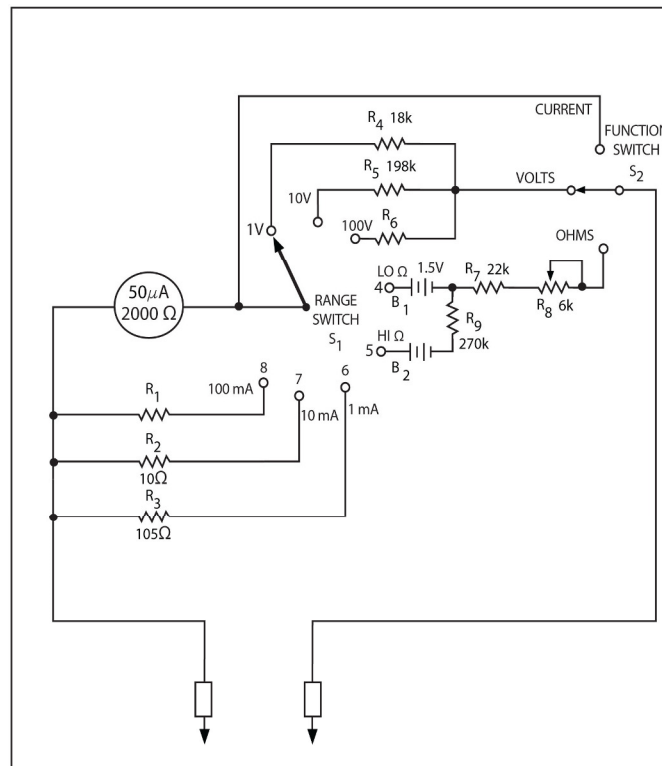
Fig. 7.25

To use the multi-meter as a voltmeter, put S_2 in the VOLTS position and S_1 in one of the voltage positions (1 V, 10 V or 100 V). In the circuit above, the multi-meter is set up to measure DC voltages up to 1 volt.

There are only two ranges in the ohmmeter portion of the multi-meter. On the LO Ω range, B_1 supplies the current which causes the meter to deflect when S_2 is in the OHMS position and a resistance is connected between the two test probes. In the HI Ω position, a higher voltage battery and a larger value series resistor increase the resistance range.

When function switch, S_2, is in the current position, the two test probes are connected directly to opposite ends of the meter movement. When range switch S_1 is set to one of the current ranges, a resistor is placed in parallel (shunt) with the meter movement. On the 1 mA range, 50 µA flows through the meter movement when 1 mA flows through the circuit under test. Thus, 950 µA flows through the shunt R_3. Since 19 times as much current flows through R_3 as through the meter movement, R3's resistance much be 1/19th that of the meter movement.

$$R3 = 2000\Omega/19 = 105\Omega$$

This same reasoning shows that the value of R_2 must be about 10 ohms.

Electronic Multimeters

All the meters, we have covered to this point, are classified as electrical meters, consisting of a meter movement, precision resistors, and a battery for the ohmmeter. But there's another family of meters called electronic meters. They have electronic circuits which can amplify small voltages and currents. They use devices like integrated circuits, transistors, and vacuum tubes which have not yet been covered. Due to this, their circuitry is described in this course. Generally, the electronic meter is used in the same way as the electrical meter. But one big difference is that the electronic meter has a much higher resistance than the electrical meter. A good electrical meter has a sensitivity of

20,000 ohms-per-volt. Thus, on the 10-volt range, its resistance is 20,000 Ω x 10 = 2000 kΩ. By contrast, most electronic meters have a resistance of 10 or 11 megohms on all DC ranges. Consequently, the electronic multi-meter has very little loading effect on most circuits.

Measurement Inaccuracies

There are several ways in which inaccuracies can slip into your measurements when using a multi-meter. Some of the causes of inaccurate measurements have already been described. Voltmeter loading is a good example. This can be minimized when you use a voltmeter which has a high resistance compared to the circuit resistances.

In a similar way, the ammeter introduces an error when you use it to measure current. Because the ammeter has a finite value of resistance, it increases the overall circuit resistance when it is connected in series with the circuit. Of course, this reduces the current flowing in the circuit. As a result, the ammeter reads a value of current lower than the accrual value without the meter. To reduce this error, you need to use an ammeter with a very low resistance value. The lower the ammeter resistance with respect to the circuit resistance, the lower the error.

If you know the resistance value of the ammeter, you can take its loading effect into consideration and make a more accurate interpretation of the reading. The resistance of the ammeter is often provided in the manufacturer's literature. If this value is not given, you can use the procedure shown in Figure 7.26 to determine the value. First, you set the ammeter to the desired scale. Next, you connect in series with a variable resistor and a voltage source. You adjust it R_2, until the meter indicates exactly one half scale deflection. At this point, half of the current flows through R_2 and half flows through the meter. Thus, the resistance of R_2 and the meter must be equal. Now, you can remove R_2 and measure its value with the ohmmeter section of the multi-meter to determine the resistance of the meter. You may wonder why you do not measure the resistance of the ammeter directly with an ohmmeter. On high current ranges, you can do this if a separate ohmmeter is available. However, when the ammeter is set to a low current range, the ohmmeter may produce enough current to harm the ammeter. Earlier, you saw that the resistance of a meter movement is an important factor when you design meter circuits. The technique that was outlined above can be used to determine the resistance of any meter movement as well as that of an ammeter.
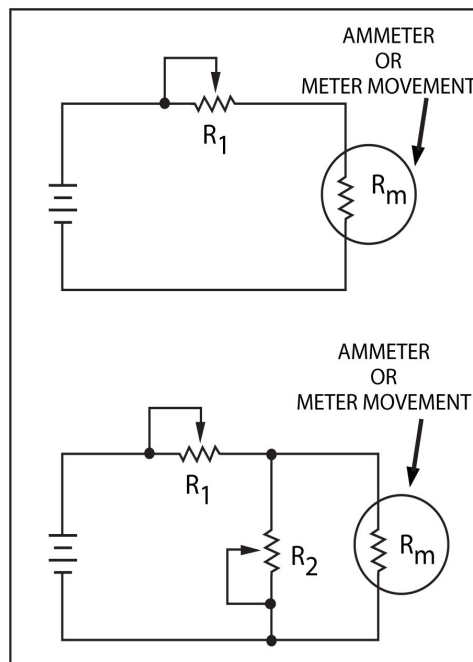
Fig. 7.26

The prime source of measurement inaccuracies is the characteristics of the meter itself. The meter movement may have an inaccuracy of ±2% or ±3% of full scale. Also, multiplier and shunt resistances may have a tolerance of 1%. When all these inaccuracies are taken into account, a typical multi-meter may have an overall accuracy if ±3% to ±4% for DC voltage and current ranges.

Another error that can affect measurements is caused by improperly reading the meter. *Parallax* causes the most common error. Figure 7.27 demonstrates what parallax is. When you view the meter straight on, as shown in the top Figure 7.27, it indicates exactly 5 volts. If you move slightly to the right of the meter, the needle appears to point to the left of 5 volts as shown in the middle drawing of Figure 7.27. Also, if you view from the left of center, the needle appears to point to the right of 5 volts as shown in the bottom drawing of Figure 7.27. To get a correct reading, you should always read the scale "straight on" from directly in front of the meter. However, because you have two eyes, one eye will be to the right of center while the other will be to the left of center. To prevent errors in reading the meter, you should close one eye, and read the scale, straight on, with the other eye. Some meters have a mirror on the scale to help eliminate parallax errors. You close one eye and align the needle with the reflection of the needle in the mirror. This ensures that the open eye is directly in front of the needle.
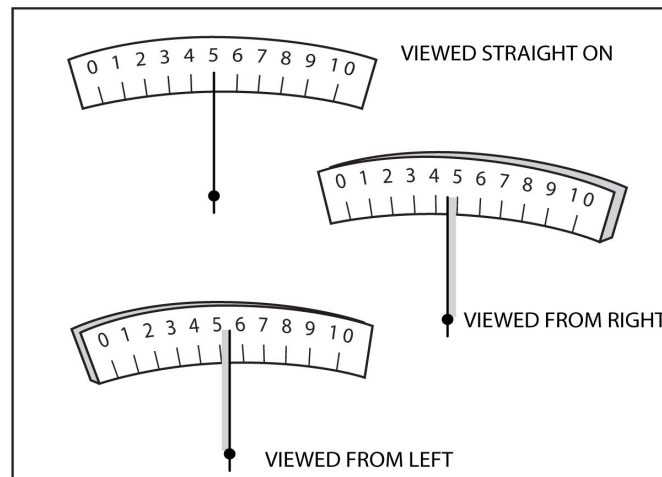
Fig. 7.27

Summary

The most popular type of meter is the d'Arsonval. This meter has a permanent magnet and a moving-coil. It develops a magnetic field when current flows through the coil. This interacts with the permanent magnet's field. The coil rotates as is described by the right-hand motor rule. The amount of rotation is proportional to the current.

The main parts of the d'Arsonval meter movement are the moving-coil, the permanent magnet, the scale pivots bearing, springs, retaining pins, counter weights, and a zero adjust mechanism.

The taut-band movement is a variation of the d'Arsonval device. In this movement, thin metal bands replace the pivots, jeweled bearing, and spiral springs. This makes a more sensitive and more rugged meter.

You can use a sensitive meter movement to construct a multi-range ammeter. A 50 µA movement can be used to measure a much higher current value by connecting a small value resistor (called a shunt) in parallel with the movement.

You must know the resistance of the meter movement to determine the proper value of a shunt. If the resistance of the meter movement is 1000 ohms, you can double the current range by connecting a 1000 ohm resistor in parallel. In the same way, if the shunt is to carry 9 times as much current as the meter movement, the shunt resistance must be one-ninth that of the meter movement.

The accuracy of a meter movement is specified as a percentage of error a full-scale deflection. If a 100 mA has an accuracy of ±3%, the reading may be off by as much as ±3 mA at any point on the scale.

To measure voltage, use a current-operated meter movement. A 1 mA, 1000 Ω meter movement indicates full scale when the applied voltage is:

$$E = 1 \text{ x } R = 1 \text{ mA x } 1\Omega = 1V$$

To extend the voltage range, you connect a voltage dropping resistor (called a multiplier) in series with the meter movement. To extend the range of the above meter to 10 V, the multiplier must drop 9 V when the current is 1 mA. Thus, its value must be:

$$R = E/I = \ \ 9V/I \text{ mA} = 9 \text{ k}\Omega$$

The sensitivity of a meter movement is specified in ohm-per-volt. To determine sensitivity, you divide the full-scale current rating into 1 V. So, a 1 mA meter has a sensitivity of:

$$1V/1mA = 1000 \text{ ohms-per-volt}$$

The ohms-per-volt rating is important because it indicates the loading effect of a voltmeter, the higher the sensitivity, the less the loading effect.

The series ohmmeter consists of a battery, a meter movement, and a resistance that are all connected in series. Zero ohms is indicated by a full-scale deflection while infinite ohms are indicated by no deflection. The internal series resistance of the ohmmeter circuit must allow a full-scale current to flow when the test leads are shorted together. Thus, a 50 μA meter movement and a 4.5 volt battery require an internal resistance of:

$$R = E/I = 4.5 \text{ V}/50 \text{ μA} = 90 \text{ k}\Omega$$

A multi-meter is a combination voltmeter, ohmmeter, and ammeter in a single case, and uses a single meter movement. To measure voltage, multiplying resistors are switched into series. To measure current, shunt resistors are switched in parallel. To measure ohms, a battery and zero ohms adjust are switched in series with the meter movement.

Chapter 8
DC Circuits

This chapter discusses series circuits, Kirchhoff's Voltage Law, and Kirchhoff's Current Law.

Simple Circuits

In the field of electronics, you will see certain circuits repeated constantly. Some of these most commonly used circuits are also very simple and easy to understand. We have already studied the characteristics of several simple circuits. These included the series circuit, the parallel circuit, and the series-parallel circuit. In this section, the characteristics of these circuits will be reviewed and then some advanced concepts will be covered.

Series Circuit

Current moves through all of the components in the circuit in a series, as shown in Figure 8.1. With a series circuit, you may want to out the current, the voltage dropped by any resistor, or the power dissipated by any resistor.
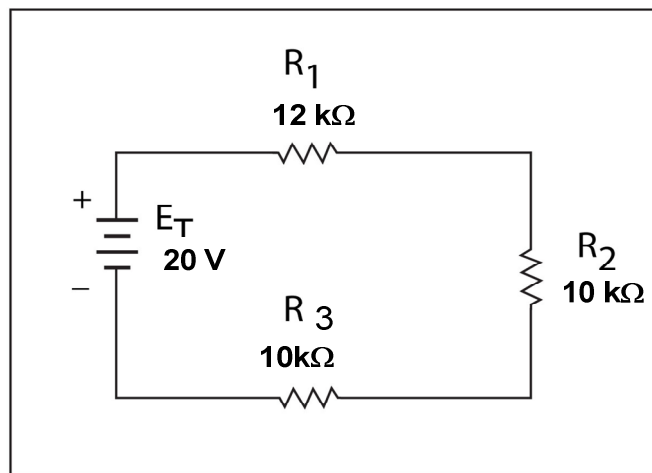
Fig. 8.1

The current is the same in all of the resistors. It can be calculated by dividing it by the total resistance into the applied voltage. The total resistance, R_T, in a series circuit is equal to the sum of the individual resistances. So, in Figure 8.1:

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 12k\Omega + 10k\Omega + 10\ k\Omega$$

$$R_T = 32\ k\Omega$$

Now the total resistance is known, current can be calculated:

$$R_{T=}$$

$$I = 20\ V/32\ k\Omega$$

$$I = 20\ V/32,000\ \Omega$$

$$I = 0.0006\ A = 0.625\ mA$$

The current is the same in all of the resistors; so you can determine the voltage drop across any one resistor by multiplying the current times the value of the resistor. To figure out the voltage across R_1:

$$E_{R1} = I \times R_1$$

$$E_{R1} = 0.000625 \text{ A} \times 12,000 \text{ } \Omega$$

$$E_{R1} = 7.25 \text{ volts}$$

E_{R2} is figured the same way:

$$E_{R2} = I \times R_2$$

$$E_{R2} = 0.000625 \text{ A} \times 10,000 \text{ } \Omega$$

$$E_{R2} = 6.25 \text{ volts}$$

So, the same process is used to compute E_{R3}:

$$E_{R3} = I \times R_3$$

$$E_{R3} = 0.000625 \text{ A} \times 10,000 \text{ } \Omega$$

$$E_{R3} = 6.25 \text{ volts}$$

Next, the voltage drops across the three resistors is calculated to demonstrate another important characteristic of series circuits. The applied voltage, E_T, is equal to the sum of the voltage drops.

$$E_T = E_{R1} + E_{R2} + E_{R3}$$

$$E_T = 7.25 + 6.25 \text{ V} + 6.25 \text{ V}$$

$$E_T = 20 \text{ V}$$

Last, the power dissipated by any resistor is equivalent to the current times the voltage drop across the resistor. So, the power dissipated by R_1 is:

$$P_{R1} = I \times E_{R1}$$

$$P_{R1} = 0.0006 \text{ A} \times 7.2 \text{ volts}$$

$$P_{R1} = 0.0043 \text{ W or } 4.3 \text{ mW}$$

The above equations must be reviewed, until you can compute any of the electrical quantities in the circuit.

Parallel Circuit

Figure 8.2 shows a simple parallel circuit. In this type of circuit, the same voltage is applied to each branch. So, in Figure 8.2, the voltage is the same across each resistor:
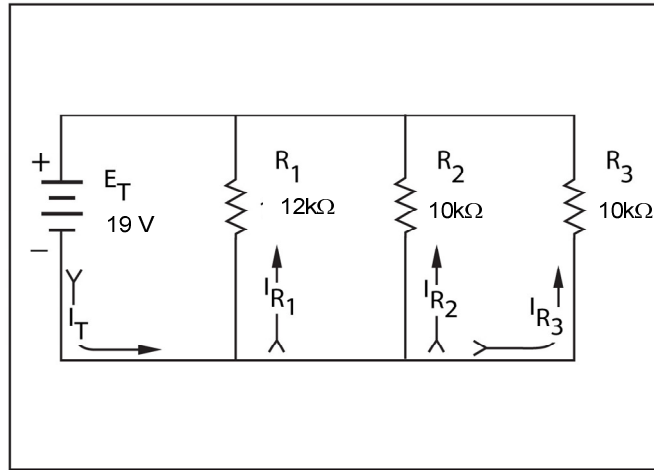
Fig. 8.2

$$E_T = E_{R1} = E_{R2} = E_{R3} = 19.2 \text{ Volts}$$

This means 19 volts is dropped across each resistor.

You divide the voltage by the resistance value of the resistor to find the <u>current</u> through any resistor. To find the current through R_1:

$$I_{R1} = E/R_1$$

$$I_{R1} = 19V/12 \text{ k}\Omega$$

$$I_{R1} = 19V/12,000 \ \Omega$$

$$I_{R1} = 0.0016 \text{ A} = 1.6 \text{ mA}$$

Based on this, the current for R_2 is:

$$I_{R2} = E/ R_2$$

$$19V/10,000 = 0.0019 = 1.9 \text{ mA}$$

And I_{R3} is:

$$I_{R3} = E/ R_3$$

$$19V/10,000 = 0.0019 = 1.9 \text{ mA}$$

To compute, the total current just sum the currents of the branch:

$$I_T = I_{R1} = I_{R2} = I_{R3}$$

$$I_T = 1.6 \text{ mV} = 1.9 \text{ mA} + 1.9 \text{ mA} = 5.4 \text{ mA}$$

Another way to determine the total current can be done by dividing the total resistance, R_T, into the applied voltage. To find the total resistance, you must use the equation for parallel circuits:

$R_T=$	1
	$1/R_1 + 1/R_2 + 1/R_3$
$R_T=$	1
	$1/12,000\Omega_1 + 1/10,000\Omega + 1/10,000\Omega$
$R_T=$	1

$$0.000083\Omega_1 + 0.0001\Omega + 0.0001\Omega$$

$$R_T = \frac{1}{0.000283}$$

$$R_T = 3534 \text{ ohms}$$

With the value of R_1, find the total current:

$$I_T = E/R_T = 19V/3534 = 0.0054A = 5.4 \text{ mA}$$

Notice how this total current agrees with the value found the individual branch currents were summed on the previous page.

The power dissipated in any resistor can be found by multiplying the current through the resistor by the voltage dropped by the resistor. In R_1, the power dissipated is:

$$P_{R1} = I_{R1} \text{ x } E_{R1} = 0.0016 \text{ A x } 19 \text{ V} = 0.0304 \text{ W} = 30.4\text{mW}$$

Series Parallel Circuit

Frequently a circuit will have both series and parallel current paths as shown in Figure 8.3. For electrical amounts to be calculated in this type of circuit, you must first simplify the circuit by redrawing it as shown in bottom drawing of Figure 8.3B. In the bottom schematic, the two parallel resistors, R_2 and R_3, have been replaced with an equivalent resistor called R_A. You can use the following equation to determine the value of R_A:

$$R_A = R_2 \text{ x } R_3 / R_2 + R_3$$

$$R_A = 2,000 \text{ x } 2,000/2,000 + 2,000$$

$$R_A = 4,000,000/4000$$

$$R_A = 1000 \text{ } \Omega = 1 \text{ k}\Omega$$

In the bottom schematic of Figure 8.3, the resulting circuit is just like any other series circuit.
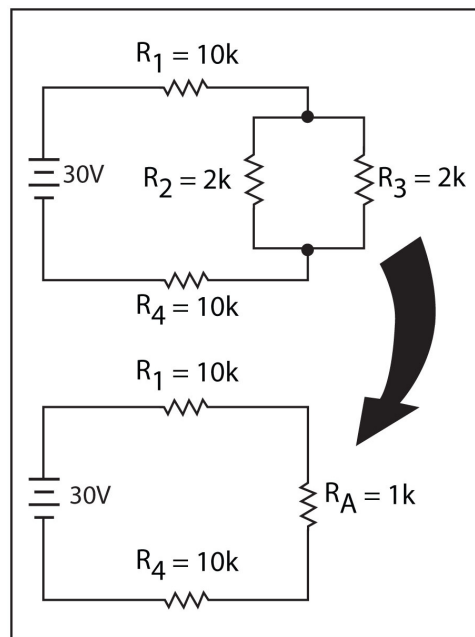
Fig. 8.3

Kirchhoff's Law

The techniques described earlier can be used analyze many simple series-parallel circuits. But they can't always be used to analyze more complex circuits. Often, a circuit will have several interconnected series-parallel branches and two or more voltage sources. There are many methods to help analyze circuits of this type. These techniques are generally grouped together under the name, network theorems.

A *network* is simply a circuit made up of several components like resistors. So, the series-parallel circuits described earlier could be referred to as a network. A network theorem is simply a logical method of analyzing a network. One of the most useful tools for analyzing a network is Kirchhoff's Law.

A form Kirchhoff's Law, described earlier, it <u>explains the relationship between the voltage rises and the voltage drops around a closed loop in a circuit.</u> Remember, the sum of the voltage drops is equal to the sum of the voltage rises. This fact is referred to as Kirchhoff's voltage law. The voltage law is seems very simple, but this law is a powerful tool when you use it properly.

Kirchhoff's Voltage Law

There are several different ways to explain the voltage law. Up to now, it has been stated: around a closed loop, the sum of the voltage drop is equal to the sum of the voltage rises as illustrated in Figure 8.4, part A.
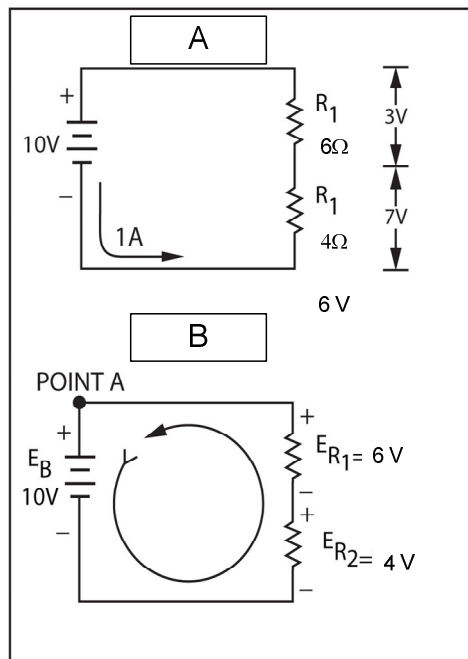
Fig. 8.4

Another way of saying the same thing is: around a closed loop, the algebraic sum of all the voltages is zero. This statement becomes true as you trace around the loop shown in Figure 8.4, part B. Notice that this is the same circuit as shown above in Figure 8.4, part A. To keep the polarity of the voltages correct, it is helpful to establish a three step rule for adding the voltages:

1. Chose which direction you prefer to trace. Clockwise or counter-clockwise work equally well.)

2. Trace around the circuit in the direction you shoes. If you encounter the positive side of a voltage drop   (or voltage rise) first, consider that voltage drop (or rise) to be positive.

3. If you encounter the negative side of a voltage drop   (or voltage rise) first, consider the voltage drop (or rise) to be negative.

To begin, start at point A in Figure 8.4, part B and trace counterclockwise as shown. Record each voltage you encounter. The first voltage is E_B. Because you encounter the positive side of the battery first, record the voltage as +10 V. Next, comes E_{R2} next, it will be -4 V because you arrive at the minus side first, and E_{R1} as -6 V, for the same reason. Therefore, the sum of the voltages is:

$$+10 \text{ V} - 4 \text{ V} - 6 \text{ V} = 0 \text{ V}$$

As an equation, it would look the following:

$$E_B - E_{R2} - E_{R1} = 0 \text{ V}$$

So, the sum of the voltage drops around the loop is zero. In this example, we just chose to trace the loop in the counterclockwise direction, but if the clockwise direction had been chosen, the sum would still be zero. It doesn't matter which direction you trace from.

Applying Kirchhoff's Law

In Figure 8.5 below, we want to find the current at all points in the circuit and the voltage that is dropped by each resistor. You can try to Ohm's Law to solve this problem; however, you will face insurmountable difficulties. But just our luck, with Kirchhoff's Law, you can easily find the solution.
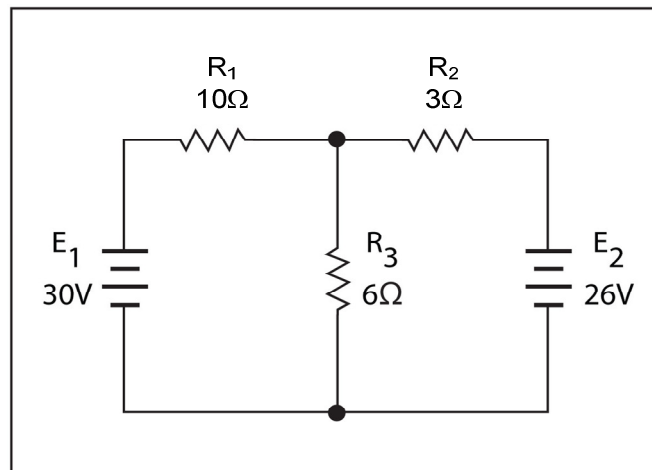
Fig. 8.5

To use Kirchhoff's Law, first, assume a direction of current through each loop. It won't matter if your assumption is incorrect, because the algebraic sign of your solution tells you if the direction you assumed is correct. If your answer works out to +3 amps, the direction you assumed is correct. If your answer works out to -3 amps, the direction you assumed is incorrect. A minus quantity of current indicates that the direction of current you assumed is reversed and incorrect.

With the batteries connected as shown, it appears that the loop current is in the direction shown by the arrow in Figure 8.6. Let's assume that this is the direction of current flow.
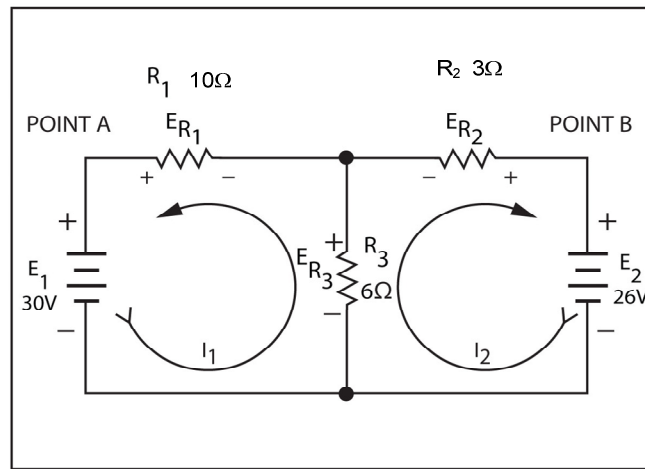
Fig. 8.6

Step two is to mark the polarity of the voltage drops across the resistors. To do this, mark negative polarity where current enters the resistor and positive polarity where current leave the resistor. If you use this procedure with the direction of current flow you assumed in the previous paragraph, the polarity of voltage drops are marked as shown in the Figure above.

Now, use Kirchhoff's voltage law to write an equation for each loop. To do this, you start at a given point and trace around the loop in the direction of current flow that was already chosen. You follow the procedure described earlier to record each voltage rise and voltage drop. Finally, you assume that the sum of all voltage drops and rises is equal to zero. So, let's trace out the loop through which I_1 flows. Start at the point labeled A in Figure 8.6. Your equation becomes:

$$+ E_1 - E_{R3} - E_{R1} = 0$$

We are assuming that E_1 to be positive because you encounter its positive terminal. In the same way, you assume the voltage drops across R_3 and R_1 to be negative since you encounter their negative terminals. You can assume the sum of the three term to be equal to zero in accordance with Kirchhoff's Law.

You can use this same procedure to develop an equation for the loop through which I_2 flows. Starting with point B and following the direction of current flow you assumed, the equation becomes:

$$+ E_2 - E_{R3} - E_{R2} = 0$$

So, at this point, two equations which describe the operation of the circuit are:

$$E_1 - E_{R3} - E_{R1} = 0$$

$$E_2 - E_{R3} - E_{R2} = 0$$

Each equation is made up of a voltage rise and two voltage drops. The value of the voltages rises, E_1 and E_2, are provided in Figure 8.5 If you substitute 30 volts for E_1 and 26 volts for E_2, your equation becomes:

$$30 \text{ V} - E_{R3} - E_{R1} = 0$$

$$26 \text{ V} - E_{R3} - E_{R2} = 0$$

Now, these equations need to be manipulated, so other known values can be plugged into them. Start with the equation:

$$30 \text{ V} - E_{R3} - E_{R1} = 0$$

The term E_{R1} is the voltage drop across R_1. Since this voltage drop is caused by I_1:

$$E_{R1} = R_1 \text{ x } I_1 = R_1 I_1$$

This means the term $R_1 I_1$ can be substituted for E_{R1} in our equation. The equation becomes:

$$30 \text{ V} - E_{R3} - R_1 I_1 = 0$$

E_{R3} is the voltage drop across R_3, and is caused by currents I_1 and I_2. Thus:

$$E_{R3} = R_3 \text{ x } (I_1 + I_2) = R_3 (I_1 + I_2)$$

With substitution, the equation becomes:

$$30 \text{ V} - R_3 (I_1 + I_2) - R_1 I_1 = 0$$

Next, you substitute the values of R3 and R1:

$$30 \text{ V} - 6(I_1 + I_2) - 10I_1 = 0$$

To eliminate the parentheses, multiply the -6 by each term within the parentheses:

$$30 \text{ V} - 6I_1 - 6I_2 - 10I_1 = 0$$

After you combine -6 I_1 and $-10I_1$ you have:

$$30 \text{ V} - 16 I_1 - 6 I_2 = 0$$

Now, it is convenient to have the voltage rise on one side of the equation, and the voltage drops on the other. To do this, subtract 30 V from both sides of the equation. This leaves:

$$-30 \text{ V} = -16 I_1 - 6 I_2$$

Let's leave this equation for a moment and go back to the equation for the second loop. Recall that the equation is:

$$26 \text{ V} - E_{R3} - E_{R2} = 0$$

Treating this equation the same as you did the first, the steps look like this:

$$26 \text{ V} - R_3 (I_1 + I_2) - R_2 I_2 = 0$$

Substitute values of R_3 and R_2:

$$26 \text{ V} - 6 (I_1 + I_2) - 3 I_2 = 0$$

Remove parentheses:

$$26 \text{ V} - 6 I_1 - 6 I_2 - 3 I_2 = 0$$

Combine I_2 terms:

$$26 \text{ V} - 6I_1 - 9 I_2 = 0$$

Now, Subtract 26 V from both sides of the equation:

$$- 6 I_1 - 9 I_2 = - 26 \text{ V}$$

Thus, your two original equations have been changed to:

$$-30 \text{ V} = -16 I_1 - 6 I_2$$

$$-26 \text{V} = - 6 I_1 - 9 I_2$$

Note that each equation has two unknowns, I1 and I2. Equations of this type are called *simultaneous equations*. There are several methods of solving simultaneous equations. With one of the simplest methods, you cancel or eliminate one of the unknowns. This method works because of two simple facts:

1. You can do almost anything you like to one side of an equation as long as you do the same thing to the other side. For example, you can add, subtract, multiply or divide both sides of an equation by a number without upsetting the equality.

2. You can add two simultaneous equations together   without upsetting the equality.

Look at the two simultaneous equations:

$$-30 \text{ V} = -16I_1 - 6I_2$$

$$-26V = -6I_1 - 9I_2$$

You can multiply both sides of the top equation by -6 so that your equations become:

$$-6(-30 \text{ V} = -16I_1 - 6I_2)$$

$$180 \text{ V} = 96I_1 - -36I_2$$

Now multiply the bottom equation by 4.

$$4(-26V = -6I_1 - 9I_2)$$

$$-104V = -24I_1 - 36I_2$$

By multiplying the bottom equation by 4, and the top equation by -6, you changed the terms containing I_2 in the both equations to the same magnitude but opposite sign as the term containing I_2 in the top equation. If you now add the two equations, the I_2 terms cancel:

$$180 \text{ V} = 96I_1 + 36I_2$$

$$-104V = -24I_1 - 36I_2$$

$$76V = 72I_1 + 0I_2$$

So after all that, you end up with a single equation:

$$76V = 72I_1$$

To solve for I_1, divide both sides of the equation by 72:

$$76V/72 = I_1 = 1.055 \text{ amps}$$

Now because you divided a voltage by a resistance, the result is a current. The positive value of current tells you that the direction of current you assumed was correct. Now, to find I_2, substitute +1.055 for I_1 in either of the above equations. That is:

$$-30V = -16I_1 - 6I_2$$

Substitute + 1.055 for I_1:

$$-30V = -16(1.055) - 6I_2$$

$$-30V = 16.888 - 6I_2$$

Add I_2 to both sides:

$$-13.111 = 6I_2$$

Divide by 6:

$$I_2 = 13.111/6$$

$$I_2 = 2.185 \text{ amp}$$

Thus, the currents in the circuit are as shown in Figure 8.7. Now you know the currents, you can use Ohm's Law to determine the voltage drops. When you compute the voltage drop across R_3 remember that both I_1 and I_2 flow through the resistor. Thus:

$$E_{R3} = R_3 (I_1 + I_2)$$

$$E_{R3} = 6 \ \Omega) \ 1.055A + 2.185 \ A)$$

$$E_{R3} = 6 \ \Omega \ (3.24 \ A)$$

$$E_{R3} = 19.4 \ V$$
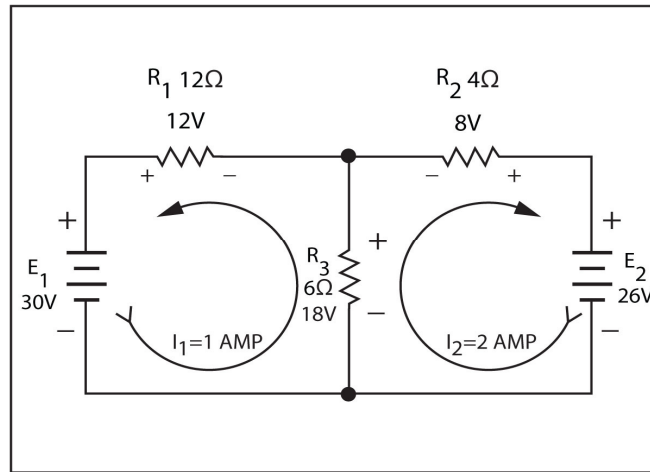
Fig. 8.7

Kirchhoff's Current Law

Current rather than voltage is the main focus in another form of Kirchhoff's Law involves. You can state Kirchhoff's current law in several different ways. In one form it states that in parallel circuits, the total current is equal to the sum of the branch currents. Another way is that the current entering any point in a circuit is equal to the current leaving that same point.

In Figure 8.8, it shows that this is simply two different ways of saying the same thing. Note, that 1 ampere flows through each of two branches. Thus, the total current is 2 amperes. Now look at point A, 2 amperes flow into this point. Consequently, 2 ampere must flow out of this point. One ampere flows up through R_1 while the other ampere flows over and up through R_2. Again, an important law is simply common sense. Nevertheless, you can use this simple law in much the same way as the voltage law to evaluate networks.
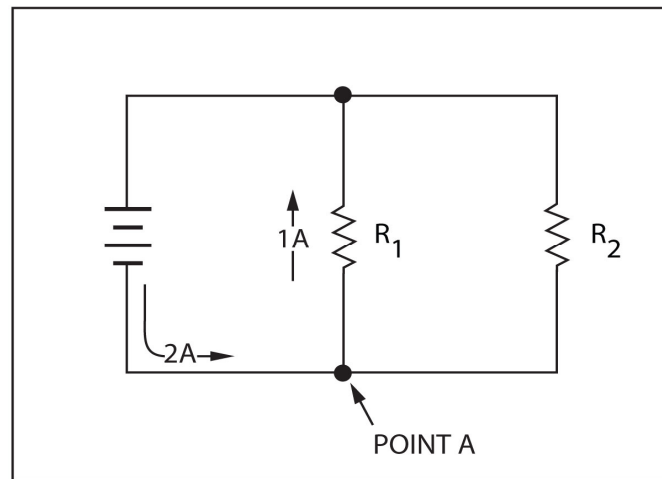
Fig. 8.8

Chapter 9
Inductance Capacitance

This chapter discusses the phenomenon of self-induction. Inductors and capacitors are also discussed.

Inductance

Earlier in the chapter on magnetism, we learned two rules that are very important to the study of inductance. First, when current flows through a conductor, a magnetic field builds up around the conductor. Second, when a conductor is subjected to a moving magnetic field, a voltage is induced into the conductor. These two rules form the basis for a phenomenon called self-induction.

Self-Induction

Before learning about self-induction, you must first differentiate between two different conditions which can exist in any DC circuit. The first is called the *steady-state condition* and the other is called the *transient condition*. Up to this point, only steady-state condition has been discussed. In most DC circuits, this condition is reached within a fraction of a second after power is applied. The current in the circuit has reached the value that you can compute with Ohm's Law. However, the current does not reach the steady-state value instantaneously. There is a short period of time called the transient time in which the current builds up to its steady-state value. So, the transient condition exists for an instant after power is initially applied to a circuit. In circuits that contain only resistors, the transient condition exists for such a short period of time, that only sensitive instruments can detect it. However, if you use inductors or capacitors in the circuit, the transient condition may be extended so that it is readily available and easier to detect.
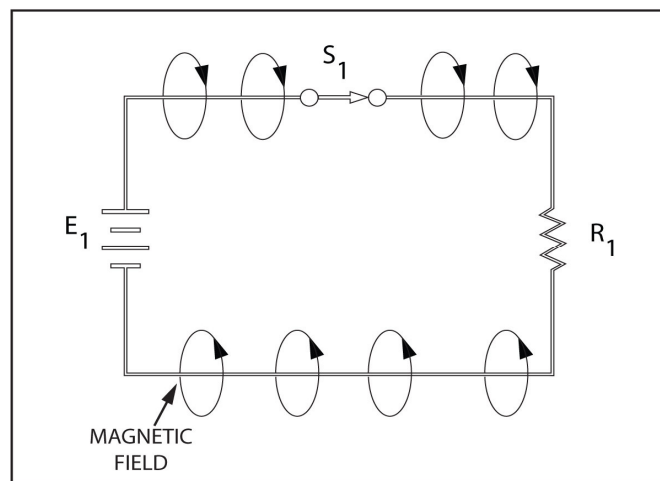
Fig. 9.1

When the current changes from zero to some finite value, during the transient time, a phenomenon called self-induction occurs. Remember that a magnetic field builds around any conductor when current flows. Also, when a conductor is cut by a moving magnetic field, a voltage is induced into the conductor. Keep these two facts in mind as we discuss what occurs during the transient time in the DC circuit shown in Figure 9.1. When S_1 is closed, current begins to flow and a magnetic field builds up around the conductor as shown. The magnetic field doesn't just appear from no-where; it

must buildup from the center of the wire. If you look at a cross section of the wire as shown in Figures 8.2, you see that the magnetic field builds up over a period of time.
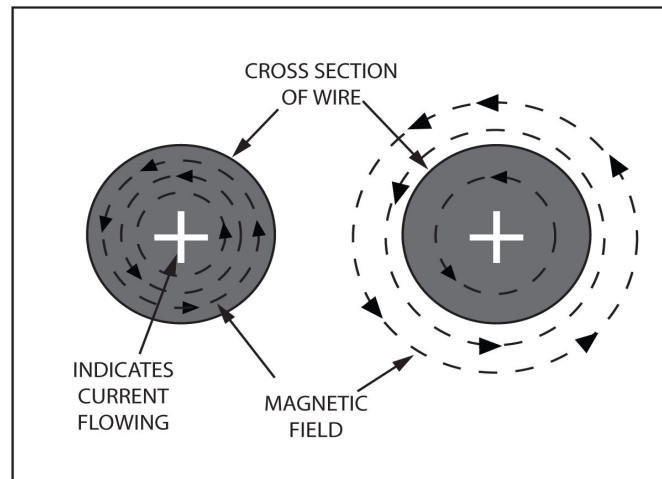
Fig. 9.2

While the magnetic field is expanding from the center of the wire, it cuts the wire. So, the requirements for inducting a voltage into the wire are fulfilled. Thus, the sequence of events is a follows:

1. The switch is closed

2. Current begins to flow through the wire

3. A magnetic field begins to build up around the wire

4. The moving magnetic field induces a voltage into the wire

If the left-hand generator rule, mentioned previously, is used, you can determine the polarity of the induced voltage and the direction of the induced current. Figure 9.3 shows the left-hand generator rule again. Apply it to the cross section of the wire shown on the bottom portion Figure 9.2. The tail of the arrow shows that current flows into the page. Thus, the direction of the magnetic field is counterclockwise around the wire. Consequently, on the right side of the wire, the general direction of the field is as shown in Figure 9.3. Also, as the magnetic field expands outward on the right, the relative motion is the same as if the conductor had moved to the left. Apply the left-hand rule by pointing your thumb and forefinger as shown. Notice that your middle finger, which indicates the direction of the induced current, points out of the page. Thus, the induced current flows in the opposite direction of the original current.
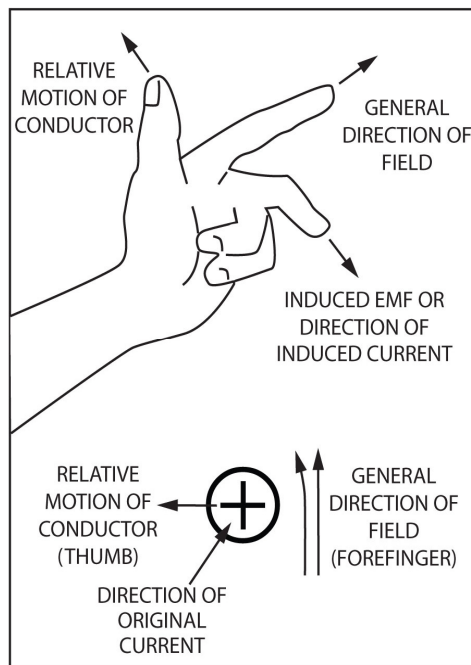
Fig. 9.3
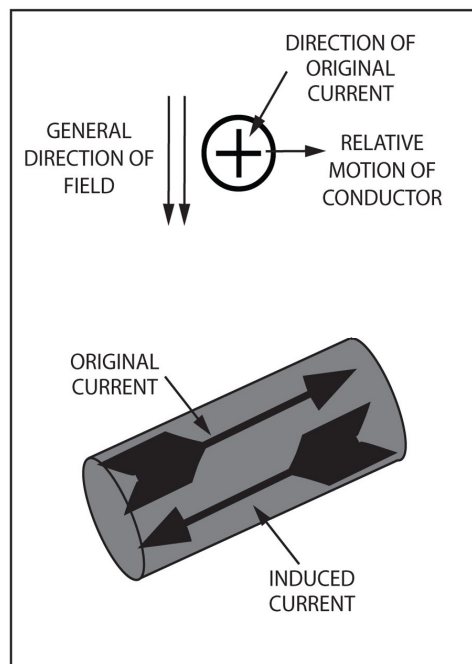
Fig. 9.4

The same result will be attained if you apply the left-hand rule to the field on the left side of the conductor. This is shown on the top of Figure 9.4. While it is true that the general direction of the field is reversed at this point, the relative motion of the conductor is also reversed, so that the induced current still flows out of the page.

The bottom section of Figure 9.4 shows the relationship of the original current and the induced current. The original current induces a lower reverse current. The net result is that the original current is initially less than you can account for with Ohm's Law.

The induced current is caused by an induced EMF. It tries to force current counter to the original current. For this reason, the induced EMF is often called a counter EMF.

This counter EMF exists for the period of time while the magnetic field expands. Thus, it exists from the time that the switch is closed until the instant that the current reaches its steady state. In DC circuits, it exists only during the transient time. However, a transient condition also exists when you open the switch.

The original current attempts to stop flowing when the current is broken, causing the magnetic field to collapse. As the field collapses, it again induces an EMF into the conductor. With the left-hand rule, you can determine the direction of the resulting induced current. Refer to the bottom section of Figure 9.3. The general direction of the magnetic field remains the same. As the field collapses inward, the conductor is cut by the flux lines as they move to the left. So, the relative motion is the same as if the conductor were moving to the right. You now find the induced current is in the same direction as the original current, when you apply the left-hand rule.

Obviously, the current cannot flow in an open circuit. Nevertheless, an EMF is created that tries to keep current flowing in the same direction. Sometimes, the induced EMF is high enough to ionize the air between the switch contacts. In very high current circuits, the arc-over caused by the induced EMF can actually damage the switch contacts.

This process by which the induced EMF is produced is called *self-induction*. <u>The effect of self-induction is opposition to changes in current flow.</u> If the original current attempts to increase, self-induction opposed the increase. If the original current attempts to decrease, self-induction opposes the decrease. <u>Self-induction is also defined as the action of inducing an EMF into a conductor when there's a change of current in the conductor.</u>

Inductance

<u>The ability of a device or circuit to oppose a change in current flow is inductance.</u> Inductance is also defined as the ability to induce and EMF when there is a change in current flow. Induction and inductance are easily confused, so you need to know the difference

Induction is the action of inducing an EMF when there is a change in current. Induction exists only when a change in current happens. Inductance is different. It is the ability to cause an induced voltage for a change in current. If a circuit (or device) has this ability, it has it with or without current flow. Thus, inductance is a physical property. Like resistance, inductance exists whether current flows or not.

The Henry, H, is the unit of measurement for inductance. It was named after Joseph Henry, a nineteenth century physicist who did important research in this area of science. A Henry is the amount of inductance which induces an EMF of 1 volt into a conductor when the current changes at the rate of 1 ampere per second. In most electronics applications, the Henry is an inopportunely large quantity. For this reason, the quantities millihenry (mH) and micro Henry (μH) are commonly used.

The symbol for inductance is L. Thus, the statement, the inductance is 10 millihenrys, can be written as an equation:

$$L = 10 \text{ mH}$$

Inductors

Every conductor has a certain value of inductance. However, with short lengths of wire, the inductance value is so small that you can measure it only with very sensitive instruments. Many

times in electronics, a specific amount of inductance is required in a circuit. A device which is designed to have a specific value of inductance is called an *inductor*.

Inductors are available in various values from microhenries to several henries. Inductor's have very simple construction. It's made of wire coiled around a core of some type. For this reason, the inductor is often called a coil.
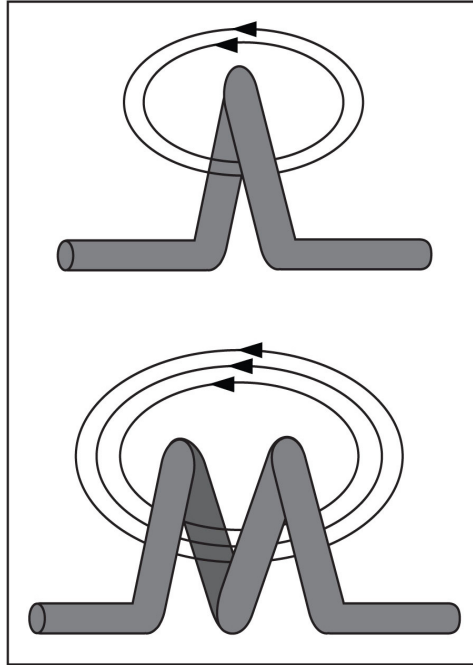
Fig. 9.5

The reason inductance of a wire increases when it is wound into a coil is shown in the top section of Figure 9.5. In the top section, a single loop is used. As the magnetic field expands or contracts, it cuts a single turn of wire and a small value of EMF is induced. In the bottom section of Figure 9.5, two loops are wound together. Notice that the field is twice as strong and that both turns are cut by the entire field. Because the filed strength and the number of turns are doubled, the induced EMF increases by a factor of 4. So, the inductance is four times as high. In the top section of Figure 9.6, three turns which produce a field strength three times as high as before is shown. Now, three times the number of flux lines cut three times the number of turns. Thus, the inductance and the induced EMF increase by a factor of 3 x 3 or 9. <u>These examples show that the inductance of the coil increase as the number of turns squared</u>.
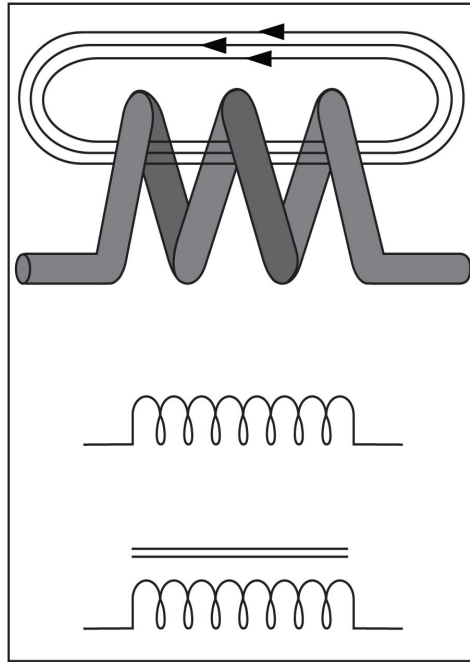
Fig. 9.6

Another way to dramatically increase the inductance is to wind the coil on a core material which has a high permeability. So, a coil wound on a soft iron core has many times the inductance of an air-core coil.   The middle section of Figure 9.6 shows the schematic symbol for the air-core or inductor, and the bottom section shows the symbol for the iron-core inductor. Although not indicated by the symbols, every inductor has certain amount of resistance because the wire that is used to construct it has resistance.

Inductor Time Constraint

When an inductance is in the circuit, the current cannot rise to its maximum value instantly. The time required depends upon the value of the inductance and the value of any series resistance. For a given value of resistance, the time required for the current to build to its maximum valued is directly proportional to the value of inductance. The higher the inductance, the more time is required for the current to reach maximum. On the other hand, for a given value of inductance, the time is inversely proportional to the resistance. The larger the resistance, the shorter time required. Mathematically, you can express this relationship with the equation below:

$$t = L/R$$

A circuit that has a 5 millihenry inductor and a 1 k ohm resistor, the time constant is:

$$t = .005/ 1000 = .000005 \text{ second or } 5\ \mu Sec$$

For this circuit, 5μSec is the length of time it takes for the current through the inductor to reach 63.2% of its maximum value. During each succeeding time constant, the current increases another 63.2% of the difference towards its maximum value. Look at the current through the example circuit after two time constants if the maximum current through the circuit is 100 amperes. The current after one time constant is:

$$100 \text{ amperes x } .632 = 63.2 \text{ amperes}$$

The current will have to increase another 36.8 amperes before it reaches maximum value. During the second time constant, when the current increases by 63.2% of the 36.8 amperes, the calculations look like this:

$$36.8 \text{ amperes x } .632 = 23.25 \text{ amperes}$$

Now:

$$63.2 \text{ amperes} + 23.25 \text{ amperes} = 86.45 \text{ amperes}$$

Above, we see the current through the inductor after two time constants. After five time constants, the current through the inductor is considered to be at its maximum value. Theoretically, the current through the circuit never reaches its maximum value.

Inductors in Combination

Like other electrical components, inductors can be connected in a series, parallel, or series-parallel combinations. No matter what the combination, there are times when it is necessary to determine the total inductance of a circuit. This is how it is done.

Inductors in Series. When two inductors, each with 100 windings, are connected in series, they have the same overall effect on the circuit as one inductor with 200 windings. The amount of inductance in the circuit increases as the number of windings increases. The inductance of inductors is additive. The formula below can be used to determine the inductance of any number of inductors in series:

$$L_T = L_1 + L_2 + L_3$$

Inductors in series are treated the same as resistors in series. The total inductance is equal to the sum of the individual inductances.

Inductors in Parallel. A single inductor in a circuit has a given amount of inductance or opposition to a change in current flow. The amount of inductance in the circuit decreases if you place another inductor of the same size in parallel with the first inductor. There's a simple reason for this occurrence. The change in current through the circuit is opposed by each inductor. However, because there are now two current paths, there is an overall decrease in opposition to current flow.

The formulas to determine inductance in parallel are essentially the same equations you use to determine resistance. They are:

$$L_T = L_1 \text{ x } L_2 / L_2 + L_2$$

or

$$L_T = \frac{1}{1/L_1 + 1/L_2 + 1/L_3}$$

or, for equal inductances in parallel:

LT Value of one inductor/Number of inductors in parallel

Inductors in Series-Parallel. If a number of inductors are connected in series-parallel circuit, you calculate the total of inductance using the same method as the total resistance in a resistive circuit. First, you determine the inductance of any parallel portion when this is added to the inductance of any portion of the circuit in series with the parallel inductance.

The Quality of an Inductor

Until now, this unit assumed that an inductor is perfect. A perfect inductor or a purely inductive circuit has no resistance. In a purely inductive AC circuit, the only opposition to current flow is the inductive reactance. However, perfect components do not really exist. Since the inductor is a coil of wire, it has resistance. The resistance of an inductor is the specific resistance of the wire that is used to manufacture the coil. It is not unusual for a choke (coil or inductor) to have a resistance of several hundred ohms.

In many circuits, the resistance of the inductor is so low that you can consider it as negligible. In these cases, it has little or no effect on the operation of the circuit. In other applications, the resistance of the inductor is higher; it can greatly affect the operation of the circuit.

Low resistance is a desirable characteristic of an inductor. The primary reason for this is that a resistance dissipates power. Therefore, power is dissipated by an inductor due to its resistance. An inductor's resistance basically determines the quality of an inductor. The quality or figure or merit of an inductor is called its Q. The Q of a coil is the ratio of the energy that is stored in the coil in the form of a magnetic field to the energy dissipated in its resistance. This is expressed as:

$$Q = \text{Energy stored}/\text{Energy dissipated}$$

Since the inductance and inductive reactance is a measure of the amount of energy that is stored in a coil, and because the resistance of a coil is a measure of the amount of energy dissipated, you can also express the Q of a coil as the ratio of the inductive reactance to the resistance.

$$Q = XL/R$$

Q is a figure of merit and is expressed as a numerical value without a unit of measure. It is simply a ratio. This relationship is widely used to indicate the quality of an inductor. For the most part, the higher the Q, the better the coil. A high level coil has a Q of approximately 20 or greater.

Since Q is directly proportional to the inductive reactance, Q increases as frequency increases. The reactance is essentially a constant at low frequencies. Due to certain electrical characteristics, the resistance of an inductor increases as frequency increases. However, the resistance does not increase as rapidly as inductive reactance. Therefore, Q increases with frequency.

Capacitance

Capacitance is the property of a circuit or device which enables it to store electrical energy by means of an electromagnetic field. A device designed to have a certain value of capacitance is called a *capacitor*. Capacitors have the ability to store electrons and release them at a later time. The number of electrons that it can store for a given applied voltage is a measure of its capacitance.

Capacitor

The word condenser was used instead of capacitor in the early days of electronics. But now, the word condenser is rarely used. An automobile mechanic may still call the capacitor in an ignition system a condenser but the more correct term is capacitor.

The main parts of a capacitor are shown in Figure 9.7. It consists of two metal plates separated by a non-conducting material called a dielectric. Metal foil is often used for the plates. The dielectric may be made of paper, glass, ceramic, mica, or some other type of good insulator.
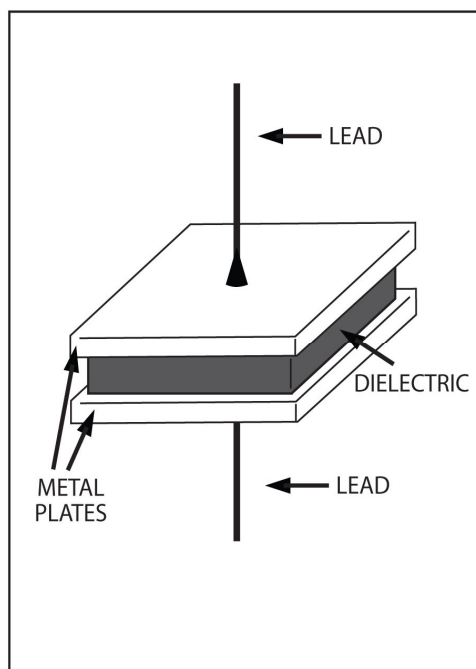
Fig. 9.7

The actual make-up of the capacitor may look very different from the one above. For example, Figure 9.8 shows how the paper dielectric capacitor is made. Two thin sheets of metal foil are separated by a sheet of paper with more sheets of paper are placed on the top and bottom of the foil sheets. The sheets are then wound together into a compact cylinder. Leads are attached to each of the foil sheets. Finally, a wax or plastic case is added to seal the entire unit into a permanent package.
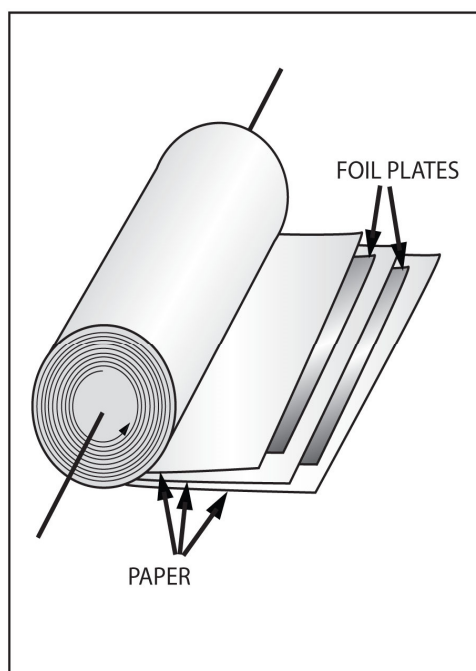
Fig. 9.8

Charging the Capacitor

The capacitor's ability to store an electrical charge is its most important property. The capacitor's charging action is shown in Figure 9.9 below. To keep things simple, the capacitor is shown as two metal plates. In Figure 9.9, the capacitor is not charged. So, the same number of free electrons is present in both plates. Naturally then, there is no difference of potential between the two plates and if you connect a voltmeter across the plates, it would read 0 volts. No current flows in the circuit because switch S_1 is open.
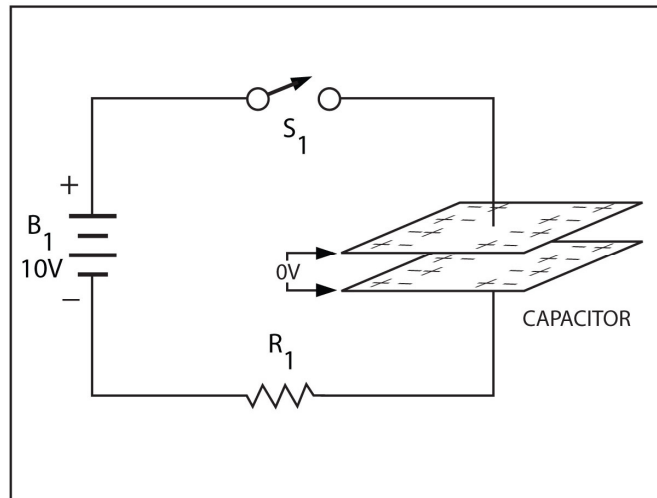
Fig. 9.9

If S_1 is closed, as depicted in Figure 9.10, the positive terminal of the battery connects to the upper plate of the capacitor; and the battery's positive charge attracts the free electrons in the upper plate. Thus, these electrons flow out of the upper plate to the positive terminal of the battery. At the same instant, the positive upper plate of the capacitor attracts the free electrons in the negative plate. But, because the two plates are separated by an insulator, no electrons can flow to the upper plate from the lower plate. Nevertheless, the attraction of the positive charge on the upper plate pulls free electrons into the lower plate. So, for every electron that leaves the upper plate and flows to the positive terminal; of the battery, another electron leaves the negative terminal and flows into the bottom plate.
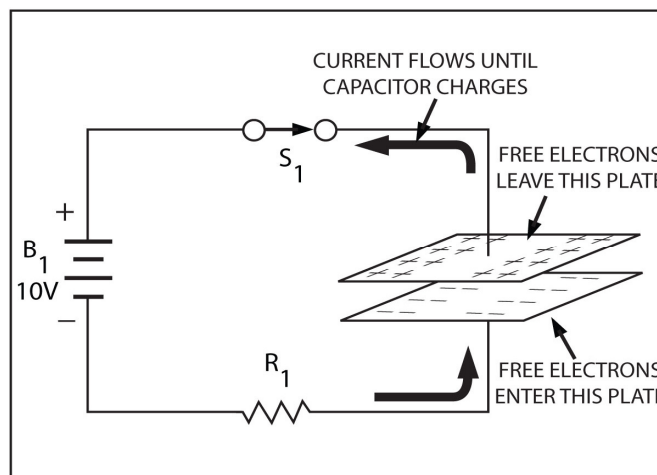
Fig. 9.10

A difference of potential begins to develop across the two plates as the capacitor charges. Also, an electric field is established in the dielectric material between the plates. The capacitor continues to charge until the difference of potential between the two plates is the same as the voltage across the battery. In the example shown, current flows until the charge on the capacitor builds up to 10 volts. Once the capacitor has the same EMF as the battery, no additional current can flow, because there is no longer a difference of potential between the battery and the capacitor.

Remember, although current flows in the circuit while the capacitor charges, current does not flow through the capacitor. Electrons flow out of the positive plate and into the negative plate. However, the insulating dielectric keeps electrons from flowing through the capacitor. Moreover, if electrons do flow through the dielectric, the capacitor would not develop a charge in the first place. It would simply produce voltage drop in the same way as a resistor.

Figure 9.11, shows that once the capacitor has been charged, you can open the switch, and a good capacitor can retain a charge for a long period of time.
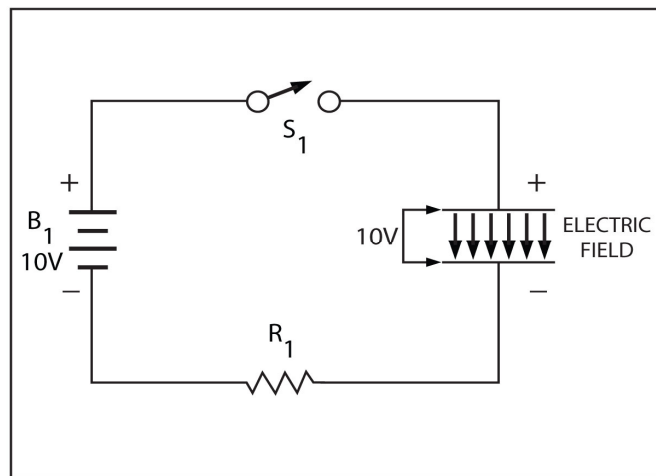
Fig. 9.11

Discharging the Capacitor

Hypothetically, all the energy that is stored in a capacitor can be recovered. Thus, a perfect capacitor dissipates no power. It would simply store energy and later release the energy. Its, of course, impossible to build a perfect capacitor, but you can try to get as close as possible. The act of storing the energy is called charging the capacitor. The act of recovering the energy is called discharging the capacitor.

This charge and discharge cycle of the capacitor is illustrated in Figure 9.12. The arm of S_1 connects the capacitor, C_1, placed directly across the battery. Notice the schematic symbol that represents the capacitor. A current flows as shown and charges the capacitor to 10 volts.

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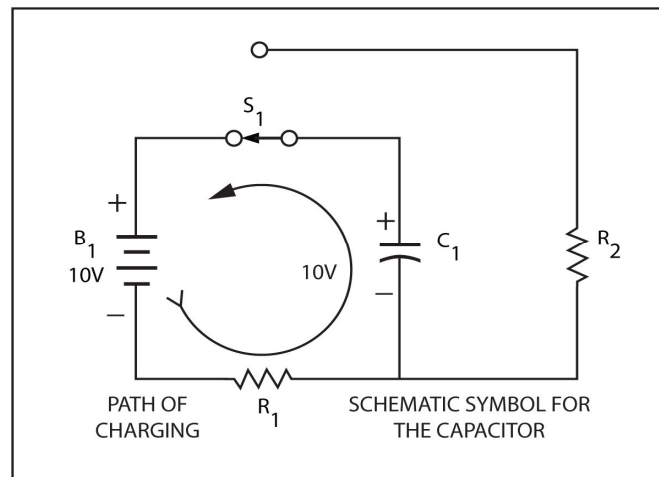
Fig. 9.12

When the capacitor is charged, move the arm of S_1 to its other position as shown in Figure 9.13. This removes C_1, from across the battery and places C_1 across R_2 instead. The free electrons on the negative plate now rush through R_2 to the positively charged plate. Electron flow continues until the two plates again reach the same potential. At this time, you can consider the capacitor to be discharged and the current flow in the circuit stops.

In many types of electronic equipment, a capacitor is used more often than any other type of component except the resistor. Thus, it is important that you learn as much as possible about these devices.
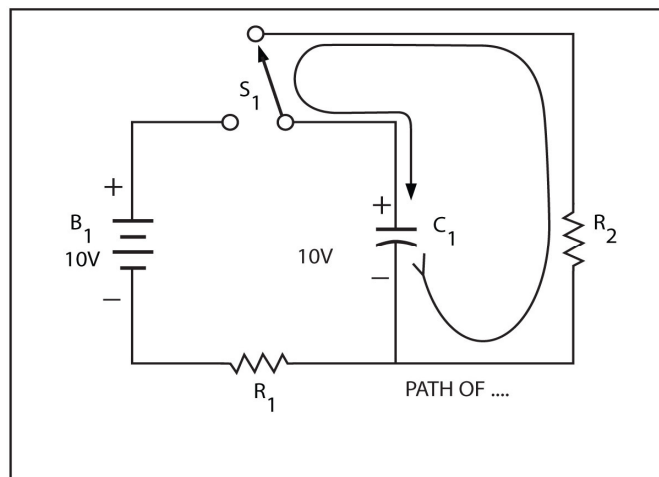
Fig. 9.13

Unit of Capacitance

The measure of how charge a capacitor can store for a given applied voltage is capacitance. Capacitance is measured the farad (F), named in honor of Michael Faraday. One farad is the amount of capacitance that will store a charge of one coulomb when an EMF of one volt is applied. One farad is an extremely large value of capacitance. For this reason, the unit microfarad, μF, meaning one millionth of a farad is used more often. Even the microfarad is frequently too large. In these cases, the unit micro-micro-farad, $\mu\mu F$, is used. The more modern name for the micro-micro-farad is the picofarad, pF). In Table 9.1 below, conversion rates between different units of capacitance are shown.

To sum up, the farad is the amount of capacitance that will store one coulomb of charge when one volt is applied. The microfarad is one millionth of farad. The picofarad is one millionth of a microfarad:

$$1/1,000,000,000,000 \text{ of a farad}$$

In powers of ten, the microfarad is 10^{-6} farad while the picofarad is 10^{-12} farad.

To Convert	To	Action
Farads	Microfarads	**Multiply by 1,000,000 (10^6) or move the decimal point 6 places to the right.**
Farads	Picofarads	**Multiply by 1,000,000,000,000 (10^{12}) or move the decimal point 12 places to the right**
Microfarads	Farads	**Divide by 1,000,000 (10^6) or multiply by .000001 (10^{-6}). Move the decimal point 6 places to the left**
Microfarads	Picofarads	**Multiply by 1,000,000 (10^6) or move the decimal point places to the right**
Picofarads	Farads	**Divide by 1,000,000,000,000 (10^{12}) or multiply by .000000000001 (10^{-12}) Move the decimal point 12 places to the left**
Picofarads	**Microfarads**	**Divide by 1,000,000 (10^6) or multiply by .000001 (10^{-6}). Move the decimal point 6 places to the left.**

Table 9.1

Factors for Determining Capacitance

Capacitance is determined by three factors:

1. The area of the metal plates.
2. The spacing between the plates.
3. The nature of the dielectric.

These points are illustrated in Figure 9.14. A capacitor, consisting of two 1-inch square plates which are separated by 0.001 inch is shown in the top section of Figure 9.14. The dielectric is air. Such a device has a capacitance of 225 pF. You will use this capacitor as a reference to see what happens when you change the area of the plates, the spacing of the plates, and the nature of the dielectric.
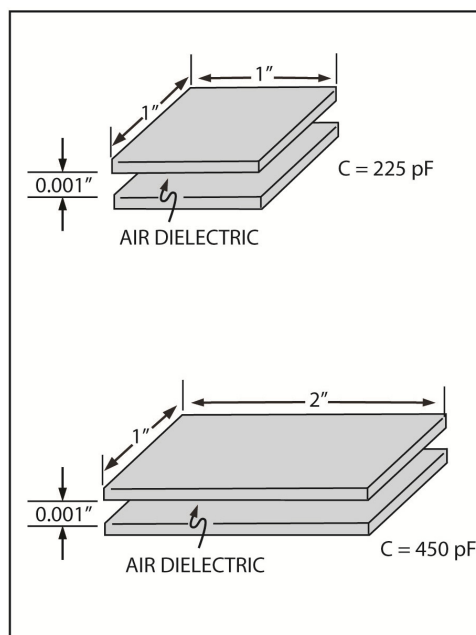
Figure 9.14

The bottom section of Figure 9.14 shows what happens when you double the area of the plates but keep all other factors the same. There is now twice as much area in which the electrostatic field can exist. This doubles the capacity or capacitance of the device. The capacitance value doubles to 450 pF. Thus, capacitance is directly proportional to the area of the plates.

The top section of Figure 9.15, illustrates how reducing the spacing between the plates to one half its former value can double the capacitance. The path of the electrostatic lines of force is cut in half. This doubles the strength of the field which, in turn, doubles the capacitance. Thus, capacitance is inversely proportional to the spacing between the plates.
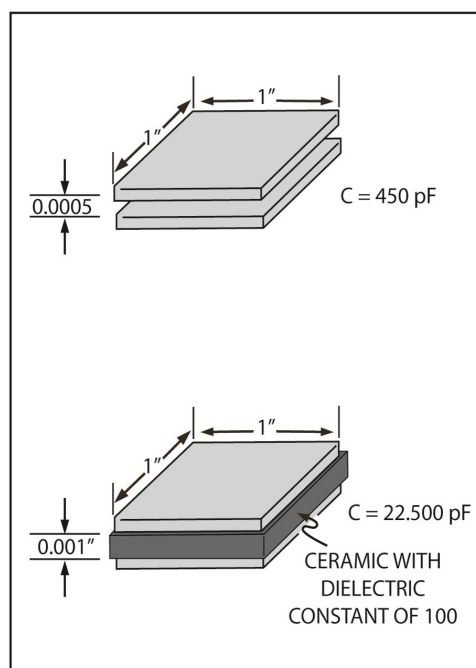
Fig. 9.15

The top section of Figure 9.16 shows that you can use a better dielectric than air to greatly increase the capacitance. Air is a very poor dielectric. Most insulators support electrostatic lines of force more easily than air. The ease with which an insulator supports electrostatic lines of force is indicated by its dielectric constant. Air is used as a reference, arbitrarily given a dielectric constant of 1. Most insulators have a higher dielectric constant. A sheet of waxed paper has a dielectric constant of about 3. This means that a sheet of 0.0001 inch waxed paper that is placed between the plates would triple the capacitance. This is illustrated in the bottom section of Figure 9.15.

Some typical dielectric constants for common types of insulators are shown in Table 9.1.

Material	Dielectric
Air	1
Vacuum	1
Waxed Paper	3-4
Mica	5-7
Glass	4-10
Rubber	2-3
Ceramics	**10-5000**

Table 9.1

Capacitance is directly proportional to the dielectric constant. The following formula combines the three factors described above:

$$C = 0.225 \ K \ A/D$$

C is the capacitance in picofarads; K is the dielectric constant; A is the area (in square inches) of one plate; and D is the distance (in inches) between the two plates.

Capacitors Types

Capacitors are available in many different shapes and sizes. But they all fall into one of two different categories: variable and fixed.
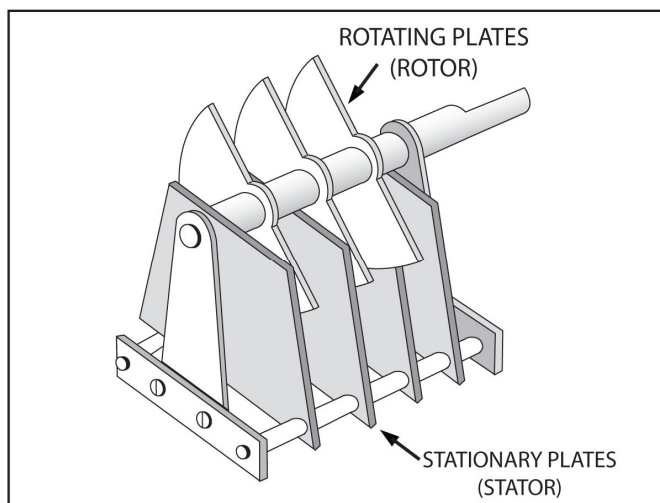
Fig. 9.16

Variable Capacitors.   Figure 9.16 shows the construction of an air dielectric variable capacitor. The capacitance value of this capacitor type changes when you rotate the shaft. The rotating plates change position in relation to the stationary plates. The rotating plates are electrically connected and form one plate of the capacitor. The stationary plates are also electrically connected. They form the other plate of the capacitor. The rotating plates and stationary plates mesh together but do not touch. When you move the shaft, the area of the plates across from each other changes from maximum when they are fully meshed (closed) to minimum when they are fully open. This changes the capacitance of the device.

Fixed Capacitors. Most fixed capacitors are constructed as in Figure 9.8. They consist of alternate layers of metal foil, called plates, and insulators, dielectric.

Capacitors are often named for their dielectric. So, we have paper, ceramic, and mica capacitors. They can also be classified according to their shape. So, there are disc capacitors, tubular capacitors, and chip capacitors.

A very popular type of fixed capacitor is the electrolytic capacitor. Its construction is illustrated in Figure 9.17. Sheets of metal foil are separated by a sheet of paper or gauze which has been saturated with the chemical paste called an electrolyte. The electrolyte is a good conductor and, therefore, the paper is not the dielectric.

The dielectric is created during the manufacturing process. A DC voltage is applied across the foil plates. As current flows, a thin layer of aluminum oxide builds up on the plate which is connected to the positive side of the DC voltage. As shown in 9.18, the oxide layer is extremely thin. Because the oxide is a fairly good insulator, it acts like a dielectric. The upper foil becomes the positive plate; the oxide becomes the dielectric; and the electrolyte becomes the negative plate. Note that the bottom layer of foil simply provides a connection to the electrolyte.
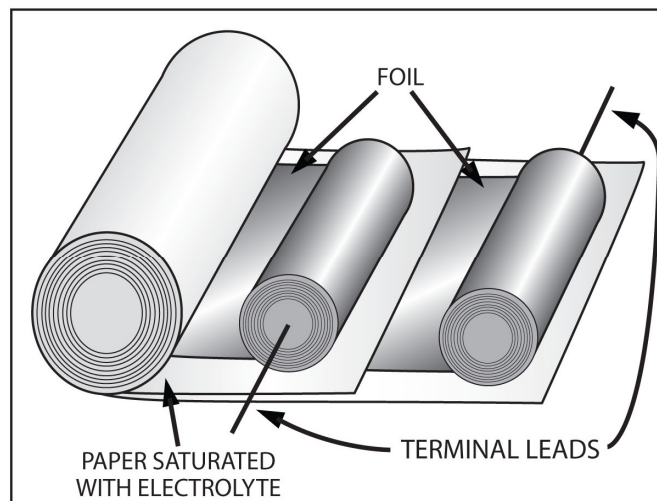
Fig. 9.17
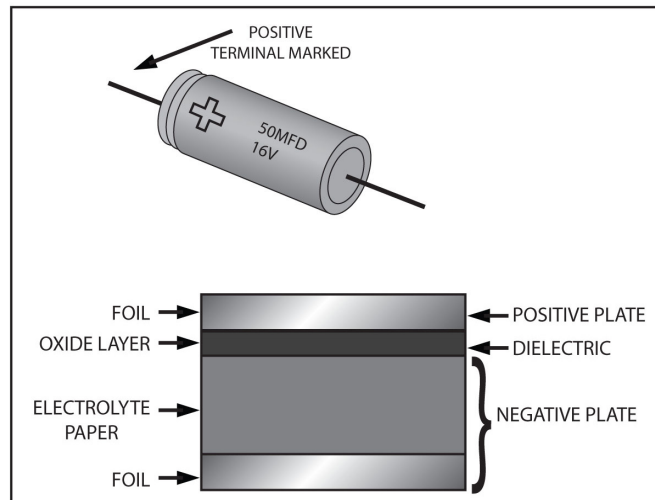
Fig. 9.18

Capacitance is inversely proportional to the spacing between plates. Due to the fact that the oxide layer is very thin, extremely high values of capacitance are possible with this technique. While other capacitors have values below 1 μF, an electrolyte capacitor may have values that range from about 1 μF up to thousands of microfarads.

The electrolyte capacitor is polarized, because of its construction. This means that the capacitor has a negative and a positive lead. However, many capacitors have only the negative lead marked.

The voltage rating of an electrolytic or any capacitor is very important. It indicates the maximum voltage that the capacitor can withstand without the dielectric breaking down or arching over. With electrolytic capacitors this value is generally printed on the capacitor along with its capacitance value.

Like resistors, there is another type of capacitor called a *chip capacitor*. It does not have leads. Instead, it has metal contacts on the ends that allow you to solder it directly to circuit board foils. Figure 9.19 shows an internal view of a chip capacitor.
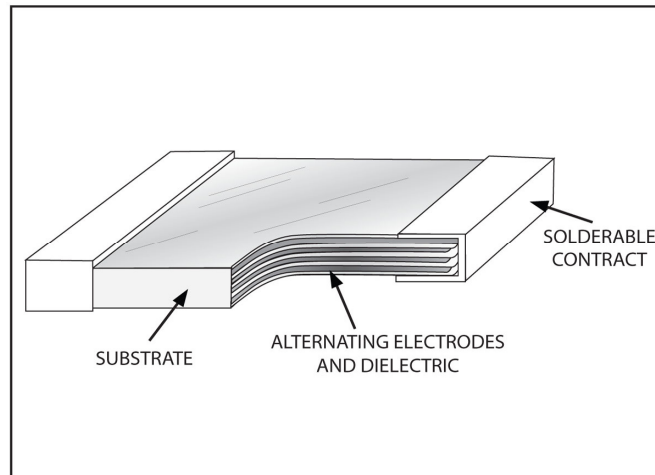
Fig. 9.19

Alternating layers of ceramic and thin films of metal make up a ceramic chip capacitors. These alternating layers are built up one-by-one with thin layers of liquid ceramic or dry ceramic tape. Conductive electrodes are screen printed over each ceramic layer before the next layer is added. If liquid ceramic is used during manufacture, it is allowed to dry before the electrode film is applied. The completed stack is then cut into individual chips.

These alternating electrode layers within the chip are connected together when the solderable contacts are applied to each end of the individual chips. The finished capacitor is completely sealed inside a protective ceramic and metal coating.

Two factors which determine the capacitance of a chip capacitor are the number of electrode layers and the dimensions of the capacitor. A third factor, which affects the capacitance of a chip capacitor, is the ceramic that separates the metal layers. The ceramic within a chip capacitor forms the capacitor's structural material as well as its dielectric. Higher values of capacitance have more alternating layers and are larger. Chip capacitors range from about 0.5 pF to 1.0 μF. Chip capacitor sizes vary from 0.080" to 0.225" long x 0.050" to 0.175" wide x 0.050" to 0.070" thick.

RC Time Constants

When you connect a capacitor across a DC voltage source, it charges to the applied voltage. If it then gets connected across a load, it will discharge through the load. You can compute the length of time that is required for a capacitor to charge or discharge if you know certain circuit values.

Two factors determine the charge or discharge time. These are the value of the capacitor and the value of the resistance through which the capacitor must charge or discharge. The time is directly proportional to both resistance and capacitance. To understand the relationship between resistance, capacitance and time, you must consider the idea of an RC time constant.

The time constant is the time that is required for a capacitor to charge to 63.2 percent of the applied voltage. On the other hand, if the capacitor is being discharged, the time constant is the length of time that is required for the voltage across the capacitor to drop by 63.2 percent. You can use the following equation to express the time constant:

$$T = R \times C$$

Here t equals the time constant in seconds, time needed to reach 63.2 percent of full charge. R is the resistance in ohms; and C is the capacitance in farads. As you learned earlier, the farad is too large to be practical and capacitance is most often expressed in microfarads. In the above equation, if C is in microfarads and R is in ohms, then t is in microseconds. If C is in microfarads and R is in kilohms, then t is in milliseconds. Finally, if C is in microfarads and R is in megohms, then t is in seconds.

Here are some examples:

If C = 1 μF and R = 100 Ω:

$$t = R \times C$$

$$t = 100\Omega \times 1 \ \mu F$$

$$t = 100 \text{ microseconds}$$

If C = 1 μF and R = 10 kΩ

$$t = R \times C$$

$$t = 10k \times 1 \ \mu F$$

$$t = 10 \text{ milliseconds}$$

If C = 1 μF and R = 2 MΩ

$$t = R \times C$$

$$t = 2 \ M\Omega \times 1 \ \mu F$$

$$t = 2 \text{ seconds}$$

Remember, the time constant, t, is not the time that is required to fully charge or discharge the capacitor. Rather, it is the time that is required to charge the capacitor to 63.2 percent of the applied voltage. To see how a capacitor charges, consider the example in Figure 9.20. A 1µF capacitor is connected in series with a 1 MΩ resistor. Thus, the time constant is 1 second. Initially, top schematic, the capacitor is completely discharged and the voltage across it is 0 volts. Note how the capacitor charges when you move the arm of the switch up so that the 100-volt power supply is connected to the R-C network.
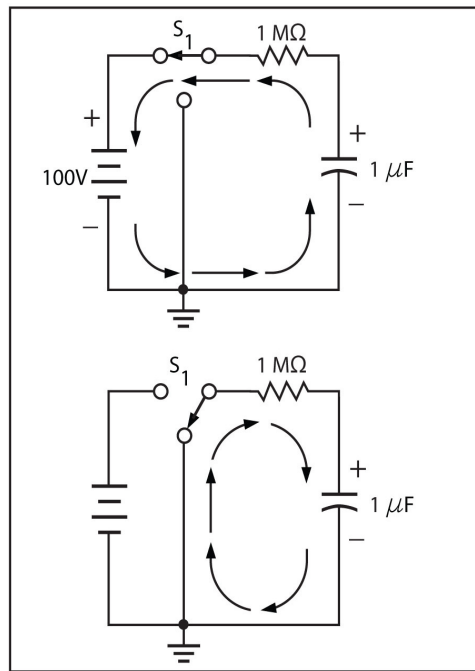
Fig. 9.20

When the capacitor is connected across the voltage source, it attempts to charge to the level of the applied voltage. However, the capacitor does not charge instantaneously. The time constant of the circuit is:

$$t = R \text{ x } C$$

$$t = 1 \text{ MΩ x } 1 \text{ µF}$$

$$t = 1 \text{ second}$$

So, after 1 second, 1 time constant, the capacitor charges to 63.2 percent of the applied voltage or to 63.2 volts.

Two important curves which are helpful when you work with time constants are illustrated in Figure 9.21. Curve A shows how a capacitor charges. Initially, the capacitor charges rapidly, charging to 63.2 percent of the applied voltage during the first time constant. However, as time passes, the capacitor charge slows down.

During the second time constant, the capacitor charges to 63.2 percent of the remaining voltage. In our chart, the remaining voltage, after 1 time constant, 1 second, is:

$$100 \text{ V} - 63.2 \text{ V} = 36.8 \text{ V}.$$

Now, 63.2 percent of 36.8 V is about 23.3 V. Thus, at the end of the second time constant, after 2 seconds have elapsed, the voltage on the capacitor has risen to:

6.2 V + 23.3 V = 86.5 V.

This is 86.5 percent of the applied voltage.
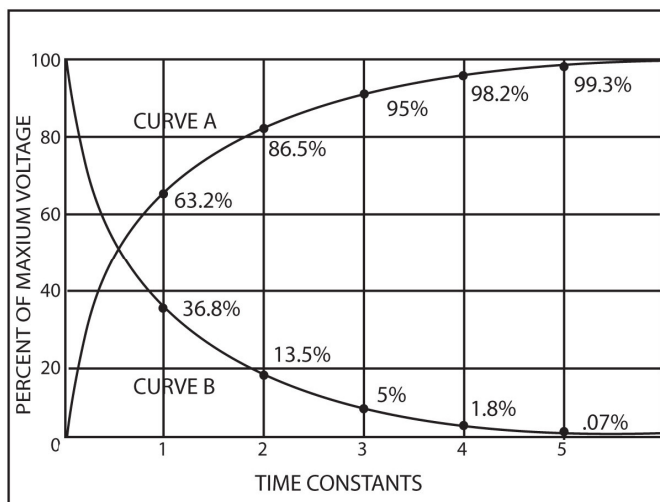
Fig 9.21

During the third time constant, the capacitor once again charges to 63.2 percent of the remaining voltage. After 3 time constants, 3 seconds, the capacitor has charged to 95 percent. After 4 time constants, 4 seconds, it has charged to 98.2 percent; and after 5 time constants to more than 99 percent. For most purposes, after five time constants, the capacitor is considered to be fully charged. You may recognize this mathematical progression from the previous discussion of inductors. The percentages on the curves shown in Figure 9.21 are the same as with inductors. Therefore, you can apply this Figure to current calculations with inductors. Curve A is an exponential curve and show that this capacitor charges exponentially.

The capacitor's discharge is shown by Curve B in Figure 9.21. At the first instant, the capacitor is fully charged. During the first time constant, the voltage drops by 63.2 percent to 36.8 percent of its original value. During the second time constant, the voltage drops an additional 63.2 percent or to only 13.5 percent of its original value. The voltage drops to about 5 percent after three time constants and to only 1.8 percent after four. After five time constants, the charge is less than 1 percent of its original value. For most practical purposes, you can consider the capacitor to be fully discharged after five time constants.

In top section of Figure 9.20, the capacitor charges to approximately 100 volts in 5 second. The bottom section of Figure 9.20 shows the capacitor being discharged. According to curve B, the charge on the capacitor is:

100 volts initially

36.8 volts after 1 time constant (1 second)

13.5 volts after 2 time constants (2 second)

5 volts after 3 time constants (3 seconds)

1.8 volts after 4 time constants (4 seconds)

0.7 volts after 5 time constants (5 seconds)

Capacitors in Combination

Capacitors can be connected in various combinations, similar to resistors.   It's important to understand the behavior of capacitors when they are connected together.

Capacitors in Parallel. The dimensions of the 225 pF capacitor that was described earlier are shown in Figure 9.22. The bottom section shows, two of these capacitors are connected in parallel. In this situation, only one the three factors which determine capacitance has changed. The dielectric constant and the spacing between the plates are the same as before. However, the effective area of the two plates has increased. In fact, the area has doubled. Recall that capacitance is directly proportional to the area of the plates. Therefore, the total capacitance is twice that of the single capacitor.
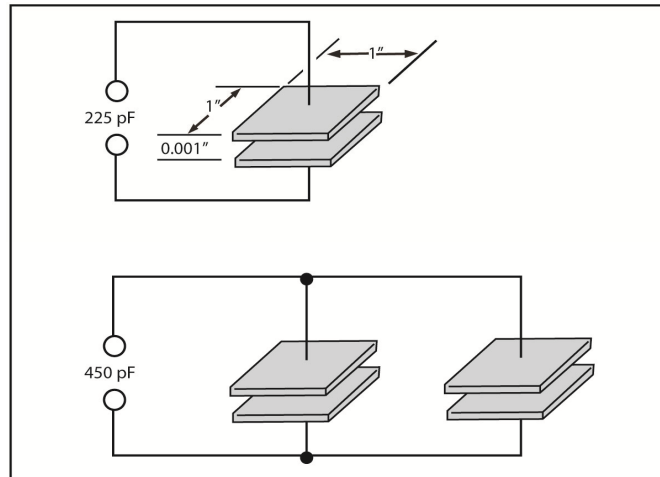
Fig. 9.22

This shows that connecting capacitors in parallel is equivalent to adding the plate areas. Consequently, the total capacitance is equal to the sum of the individual capacitance values. If three capacitors are connected in parallel, you add the individual values to find the total capacitance (C_T):

$$C_T = C_1 + C_2 + C_3$$

If $C_1 = 5$ μF, $C_2 = 10$ μF, and $C3 = 1$ μF; then $C_T = 16$ μF. Notice that the capacitors in parallel add like resistors in series. Capacitors that are connected in parallel all charge to the same voltage. The voltage is the same across every section of a parallel network.

Capacitors in Series. A comparison between a standard capacitor and two standard capacitors that are connected is shown in Figures 9.23 and 9.24. As shown this is equivalent to doubling the thickness of the dielectric. That is, two series capacitors act like a single capacitor which has a dielectric thickness equal to the sum of the individual dielectric thicknesses. Since capacitance is inversely proportional to the spacing between the plates, doubling the thickness of the dielectric cuts the total capacitance value to one half that of the standard capacitor.
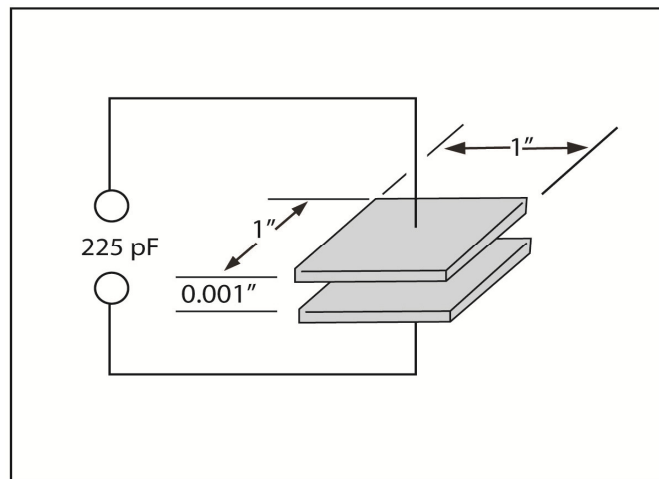
Fig. 9.23
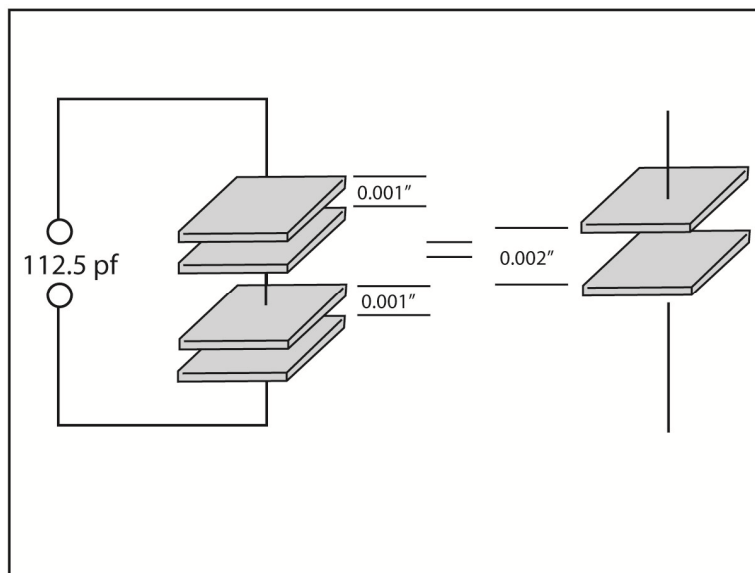
The total capacitance of a group of series capacitors can be calculated in the same way as you calculate the total resistance of resistors in parallel. Simply; capacitors in series combine in the same way as resistors in parallel. You can use the following formula to calculate the total capacitance of two capacitors in series:

$$C_T = C_1 \times C_2 / C_1 + C_2$$

This equation has the same form as the equation for calculating two resistors in parallel.

When more than two capacitors are connected in series, you use the following formula:

$$C_T = \frac{1}{1/C_1 + 1/C_2 + 1/C_3}$$

Again, we see the equation has the same form as the one for calculating total resistance in parallel circuits.
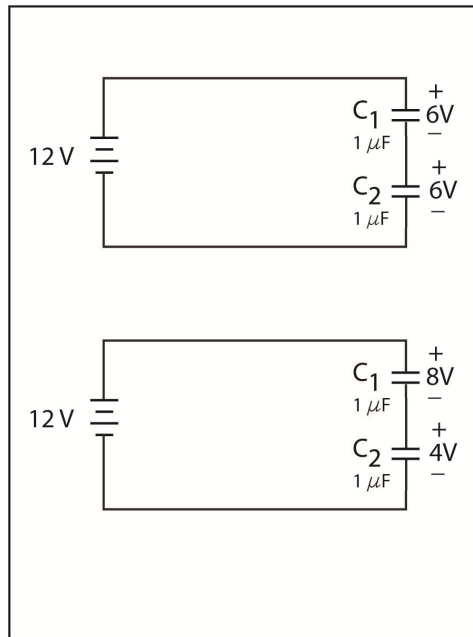
Fig. 9.24

Two capacitors connected in series across a 12-volt battery are shown in the Figure above. An interesting thing about capacitors in series is the way in which the applied voltage is distributed across the capacitors. If two capacitors have the same value, the applied voltage is distributed evenly between the two. In the top schematic, each capacitor charges to one half the applied voltage, 6 volts.

However, when the capacitors have different values, the smaller capacitor charges to higher voltage, than the larger capacitor. In the bottom schematic, C_2 is twice as large as C_1. So, C_1 charges to twice the voltage. Since the total voltage across both capacitors must be 12 volts. C_1 must drop 8 volts while C_2 drops 4 volts.

To understand why the voltage is distributed in this way, you can use the equation which expresses capacitance in terms of charge and voltage. The equation is:

$$C = Q/E$$

Where C is the capacitance in farads, Q is the charge in coulombs, and E is in volts. You can rearrange this equation like this:

$$E = Q/C$$

In this form, the equation states that the voltage across the capacitor is directly proportional to the charge on the capacitor, but inversely proportional to the size of the capacitor. In the bottom schematic of Figure 9.24, the two capacitors are in series. As a result, the charging current is the same at all points in the circuit. For this reason, the two capacitors must always have equal charge. Since the charges are equal, the voltage is determined solely by the value of the capacitor. And because voltage is inversely proportional to the capacitance value, the smaller capacitor charges to a higher voltage.

Capacitors in DC Circuits

When you use capacitors in circuits that involve DC voltages, they exhibit certain properties and operational characteristics. In AC circuits, capacitors have different properties and characteristics. Since capacitors are usually considered to be AC components, most of this unit is devoted to the

operation of capacitors in AC circuits. However, many AC circuits also use DC voltages. For that reason, you will first study the operation of capacitors in DC circuits.

Since there is no direct electrical connection between the plates of a capacitor, a capacitor represents essentially an open circuit, infinite resistance, to a DC voltage. There is no direct path for electrons to flow through the capacitor. However, when a capacitor charges or discharges, movement of electrons takes place within the circuit. This movement of electrons constitutes current flow, but this charging or discharging action is transient or short-time duration in nature. Once the capacitor has charged or discharged, current ceases to flow. While electrons do not cross between two plates of a capacitor, the charging and discharging action does cause movement of electrons in the external circuit. If a component (such as a resistor) is connected in series with the capacitor, it will have a voltage drop developed across it as the capacitor charges and discharges. The voltage dropped across the resistor reverses polarities due to current moving in one direction during charging and moving in the opposite direction during the discharge cycle.

A simple series resistor-capacitor (RC) circuit connected to a DC voltage source with the switch open and the capacitor initially discharges no current flows in the circuit. However, when you close the switch, the capacitor starts to charge. Electrons from the negative terminal of the battery flow through the switch and the resistor to the right-hand plate of the capacitor. Once the capacitor is fully charged, current flow ceases. During the charging time, electrons flow through the resistor. This results in a voltage drop across resistance with the polarity as indicated. This voltage appears only momentarily as the capacitor charges. When the switch is initially closed, electrons begin to flow immediately and a peak voltage appears across the resistor. As the capacitor charges, the voltage drop across the resistance decreases. The voltage across the resistor is zero when the capacitor is fully charges or completely discharged.

There are many variations and applications for this simple circuit. The most important characteristic of this RC combination is the time it takes to charge or discharge the capacitor. This time is referred to as the time constant, T. The time constant is the period of time it takes for a capacitor to charge to approximately 63.2% if applied voltage. This time is the product of the circuit's resistance and capacitance value.

Capacitors in AC Circuits

When an AC voltage is applied to a capacitor, alternating current flows in the circuit. As the AC voltage varies, the current in the circuit follows a sinusoidal variation. Electrons do not pass directly through the dielectric, from one plate of the capacitor to the other. Although electrons do not pass from one plate to the other through the dielectric, electrons do flow in the circuit external to the capacitor as if they do. As the applied AC voltage rises and then falls, the capacitor charges and then discharges. The frequency of the input voltage and the circuit's time constant determine the charge and discharge rate of the capacitor. Even though there isn't a physical resistor, all circuits contain a finite resistance. The current flows, first in one direction and then reverses and flows in the other direction. This oscillating current is also the definition of a sine wave.

The effect that an applied AC voltage has on the atoms within the dielectric of a capacitor is very interesting. At this point, the external applied voltage is zero, and the electrons contained in the atoms of the dielectric rotate normally about their nuclei. When the capacitor charges, the upper plate is made negative with respect to the lower plate. The electrons that orbit the nucleus in the dielectric are repelled by the negative plate and attracted by the positive plate. This distorts the orbit of the electrons. The amount of voltage applied to the capacitor determines the amount of orbit distortion.

While the amount of electron shift, orbit distortion, is small, it nevertheless constitutes a movement of electron within the dielectric. While none of the electrons actually break loose from their orbits and flow in the external circuit, you can say that the movement of electrons constitutes current flow. As the AC voltage charges and discharges the capacitor, the movement of electrons onto one plate and off the other in the external circuit represents current flow. When the applied voltage is a sine wave, current flow in the circuit is also sinusoidal.

Current-Voltage Relationships in Capacitive AC Circuits

The relationship between current and applied voltage in a capacitive circuit is different than it is in purely resistive AC circuits. Due to the way that a capacitor functions, current and voltage in a capacitive AC circuit are not in phase with each other. In a circuit where an AC voltage is applied to a resistance, current through the resistor follows the voltage that is applied to it. In this case, current and voltage are in phase. In other words, the positive and negative half cycles of voltage and current in a resistive AC circuit are in step with each other.

In a capacitive AC circuit, the capacitor constantly charges and discharges at the rate of change of the applied voltage. Once the capacitor is initially charged, the voltage across it acts as voltage source. Its effect is to oppose changes in the external supply voltage. Since the capacitor must charge or discharge to follow the changes in the applied voltage. There is a phase shift between the voltage and current in the circuit. In a purely capacitive circuit, the phase shift is 90 degrees, so the current leads the voltage 90 degrees.

To understand the relationship between current and voltage is a capacitive AC circuit, you should first review the basic principles of capacitor operations when a DC voltage is applied. The capacitor is initially discharged and the switch is open. When you close the switch, the instantaneous voltage across the capacitor is zero. It might appear that the voltage across the capacitor is initially equal to the applied voltage, the instant the switch is closed, but it is zero because electrons have not had time to flow to and from the plates of the capacitor. In other words, on the initial closure of the switch, the capacitor is still uncharged. Immediately thereafter, electrons begin to flow. Electrons flow from the negative terminal of the battery to the right-hand plate of the capacitor, which gives that plate an excess of electrons and a negative charge. At the same time, electrons are drawn from the left hand plate of the capacitor to the positive terminal of the battery, which causes the left-hand plate to have a positive charge. As electrons begin to flow, a voltage builds up across the capacitor. The polarity of voltage across the capacitor at this time is in direct opposition to the applied voltage. When the capacitor is fully charged to the applied voltage, the two voltages are equal in amplitude and opposite in polarity. There is no difference of potential and current ceases to flow.

When the switch is initially closed, the capacitor voltage is zero while the current in the circuit is maximum. As the electron flow charges the capacitor, the capacitor voltage begins to build up. The capacitor voltage opposes the applied voltage, which reduces the amount of current flow in the circuit. When the capacitor becomes fully charged, the current in the circuit reduces to zero.

Once the capacitor becomes charged, the voltage across the capacitor is the same as the applied voltage. However, the current flowing in the circuit is out of phase with the voltage.

When the current is maximum, the voltage across the capacitor is zero. There is a phase shift between the current and voltage in the circuit. This phase shift is expressed in terms of degrees. Remember that one complete cycle of a AC sine wave contains 360°. The amount of phase shift in the capacitive circuit is one fourth of this or 90°. The current and voltage in a purely capacitive circuit are 90° out of phase with one another. Another important fact to note is that the change in current leads the change in voltage. The capacitor voltage charge follows the current change in time.

The current lead the voltage in a capacitive circuit; there is 90° leading phase shift in a purely capacitive circuit.

Capacitive Reactance

It is the basic nature of a capacitor to oppose changes in voltage. In a DC circuit, a capacitor charges to the applied voltage. If you increase the applied voltage, the capacitor then charges to the new higher voltage. If you decrease the applied voltage, the capacitor discharges until the voltage across it equals the new lower applied voltage. Keep in mind that it takes a finite period of time for a capacitor to charge or discharge to a new voltage level.

In an AC circuit, the capacitor constantly charges and discharges. The voltage across the capacitor is in constant opposition to the applied voltage. This constant opposition to changes in the applied voltage creates an opposition to current flow in the circuit. This opposition to AC current flow through a capacitor is called capacitive reactance. Capacitive reactance is represented by the symbol X_c, and, like resistance, it is measured in ohms.

The capacitive reactance of a capacitor is determined by its capacitance value and the frequency of the applied voltage. The amount of opposition to current flow in an AC circuit by a capacitor is a function of the capacitance and the frequency of the AC voltage. Capacitive reactance is inversely proportional to capacitance and frequency. Therefore, when you increase the capacitance or frequency, the capacitive reactance decreases.

The capacitive reactance is calculated by using the equation:

$$X_c = 1/2\pi fC$$

In this expression, X_c is the capacitive reactance is in ohms, f is the frequency in Hz, C is capacitance in farads and pi (π) is a constant that is approximately 3.14.

Summary

When current flows through a conductor, a magnetic field builds up around the conductor. As the magnetic field builds up, a voltage is induced into the conductor. The induced voltage opposes the applied voltage and is called a counter EMF. The process by which the counter EMF is produced is called self-induction.

The counter EMF's polarity always opposes changes in current. It opposes the increase in current which occurs when you apply power to a circuit. It also opposes the decrease in current which occurs when you remove power. Inductance is the ability of a device to oppose a change of current. The unit of inductance is the Henry.

A device designed to have a specific inductance is called an inductor. It consists of turns of wire that are wrapped around a core, the greater the number of turns and the higher permeability of the core, the greater the value of inductance.

A capacitor consists of two metal plates that are separated by an insulator called a dielectric. It has the ability to store an electrical charge. This ability to store a charge is called capacitance. When a capacitor is connected to a voltage source, it charges to the value of the applied voltage. If you then connect the charged capacitor across a load, it discharges through the load.

The unit of capacitance is the farad (F), although the microfarad (μF) and the picofarad (pF) are used most often. Three factors determine the value of a capacitor: the area of the plates, the spacing between the plates, and the dielectric constant.

There are many different types of capacitors. They are generally classified by their dielectric. The most popular types are air, paper, mica, ceramic, and electrolytic.

The capacitance and the resistance in the circuit determine the length of time that is required for a capacitor to fully charge. A time constant is the length of time that is required for a capacitor to charge to 63.2 percent of its applied voltage. The formula to find the time constant is:

$$t = R \times C$$

You use a time constant chart when you work with time constants. Its shows the manner in which capacitors charge and discharge. It plots the number of time constants against the percentage of applied voltage.

Capacitors may be connected in series or parallel. When they are connected in parallel, the total capacitance is equal to the sum of the individual capacitor values. The formula is:

$$C_T = C_1 + C_2 + C_3$$

When they are connected in series, you can determine the total capacitance with the following formula:

$$C_T = \frac{1}{1/C_1 + 1/C_2 + 1/C_3}$$

Chapter 10
Alternating Current

Alternating current is suitable for use in a variety of commercial, industrial, and military applications. To understand why AC, alternating current, is so widely used, you must understand its advantages and characteristics. This chapter describes AC, how it is used, and why it is used. This chapter also discusses AC generators and their construction.

What is AC

Alternating current flows first in one direction and then in the opposite direction. On the other hand, direct current, DC, only moves in one direction, alternating current periodically changes its direction of flow. Figure 10.1 illustrates the difference between DC and AC. It shows a resistor that has direct current flowing through it. The current that flows only in one direction is the result of the fixed or constant voltage that is applied to the circuit. This fixed voltage source, referred to as a DC voltage, could be a dry cell or storage battery. The DC voltage source and the resistor form an elementary DC circuit.
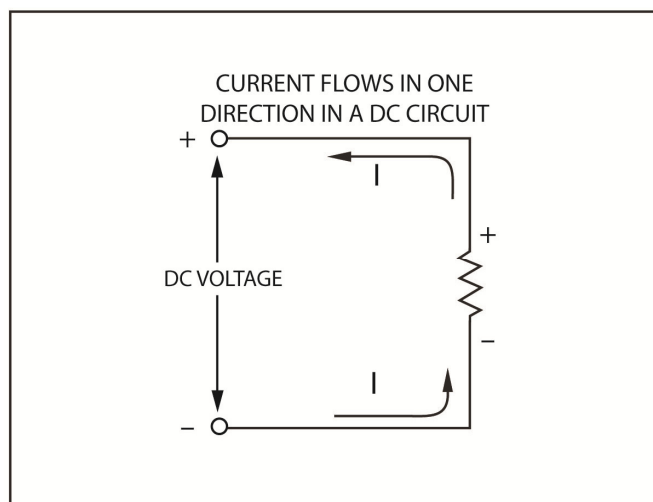
Fig. 10.1

The voltage source is fixed, so the polarity of the source does not change. Therefore, the polarity of the voltage drop across the resistor is also unchanged. Because the DC voltage source remains fixed, the current through this circuit only flows in one direction

In Figure 10.2, an alternating current flows through a resistor. In the top figure, current flows in a counterclockwise direction. In the bottom figure, current flows clockwise. Notice how the polarity of the source voltage as well as the polarity of the voltage drop across the resistor changes in these illustrations. The change in polarity of the voltage applied to the circuit creates a change in the direction of current flow and a change in the polarity of the voltage drop. Usually, the voltage source shown here is referred to as an AC voltage. The resistor and the voltage source form a basic AC circuit.
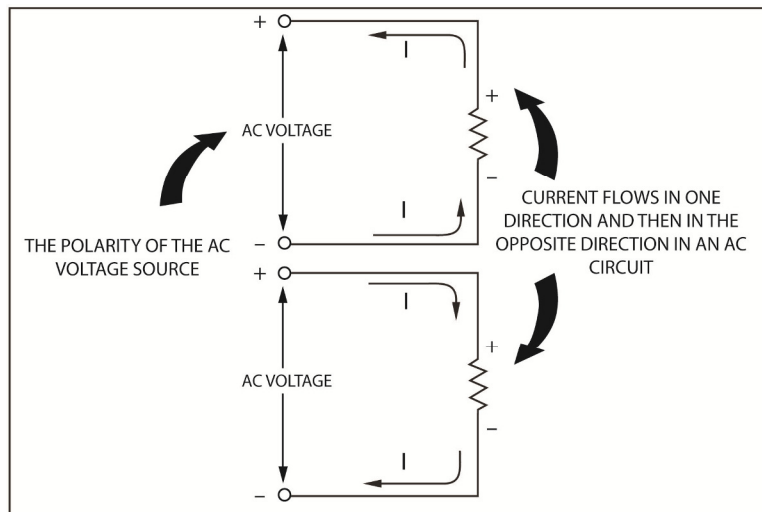
 Fig. 10.2

Generally, a direct current has a steady or constant value, because it is usually produced by a DC voltage that has a fixed value. However, momentary changes may result if, the DC voltage is adjusted to a higher or value or the circuit resistance changes in value. However, in most DC circuits you are concerned with a steady current which always flows in one direction. By comparison, with alternating current, there are changes in both value and direction. In other words, the current in an AC circuit increases from zero to some maximum value and then drops back to zero as it flows in one direction and then varies in the same manner in the opposite direction. But the exact manner in which the current increases and decreases in each direction can be controlled. This makes it possible to produce various types of AC signals. In fact, a variety of AC voltage sources are used to generate different types of AC voltages that are suitable for a variety of applications. Next, some of the basic types of AC signals that are commonly used will be discussed.

AC Uses

Alternating current is used widely because it's versatile. AC changes in both value and direction; therefore, it has characteristics that are usable in a wider range of applications than is possible with DC currents.

For example, when a large amount of electrical energy is required for a particular application, it is much easier to generate and transmit an alternating current then direct current. In applications where large amounts of power are required, devices such as batteries, which produce DC voltages suitable for low power applications, cannot be used. In these situations, electromechanical devices known as generators are used to generate the high voltages and currents required. Although generators can be used to produce both DC and AC electricity, AC generators are simpler, can be constructed in larger sizes, and are often more economical to operate. Therefore, AC electrical power is simply easier and cheaper to produce.

An AC voltage can be easily changed to a higher or lower voltage by passing it through a device known as a *transformer*. This voltage increase, step up, or decrease, step down, can be achieved with very little loss of power. In other words, the new voltage will provide approximately the same power to a load as you could obtain from the initial voltage. This is a very important feature can be used very successfully in many situations. Although it is true that DC voltages may also be stepped up or down, the process is much more complex and costly, and considerable power is lost during transformation of DC voltages. This makes the conversion of DC voltages less efficient.

Alternating current may be easily converted into direct current. It can then be used to operate various types of DC circuits or equipment. Although, it's also true that DC power can also be converted into AC power, the process is much more complex, expensive and less efficient. Therefore, when AC is used as the primary source of electrical power, you can still obtain DC when it is needed through a relatively simple conversion process.

Due to the, the characteristics and features just described, it may seem that AC is useful only because it can serve as a source of electrical power to operate electronic equipment. But, this is not the case. Alternating current is used extensively to transmit information from one location to another. This information carrying ability results because the characteristics of an alternating current or voltage can be made to vary in a desired manner. In other words, the magnitude or amplitude, maximum value in each direction, can be varied to represent intelligence or information. Even the rate at which the alternating current changes direction can be varied to represent intelligence. Because of this, information can be inserted within an alternating current or voltage, which makes it possible for the AC to carry information.

When alternating currents or voltages are used to carry information, they are often referred to as *AC signals*. AC signals are used widely in electronics to carry information from one point to another within an electronic circuit. These signals can also be transmitted over long distances with long wires or transmission lines.

Alternating current may also be converted into electromagnetic waves (also called radio waves) which can radiate or travel through space. This can occur, because a conductor which carries alternating current is surrounded by a magnetic field. As the intensity and direction of the current changes, the field expands and collapses. This means that AC signals, which contain information, can be sent from one location to another, without wires or transmission lines. This action can't be achieved direct current.

These points help to illustrate why AC is so widely used into today's world. Although there are many additional factors to consider, you can summarize by saying that AC is primarily used to either provide electrical power or to provide a means of transmitting information or intelligence from point to another.

Where is AC Used

Where large quantities of power are needed, alternating current is generally used. Most electrical energy supplied for domestic and commercial purposes is alternating current.

Large amounts of AC power can be generated at the power plant by extremely large generators which are driven by turbines. These are powered by stream of falling water. Power stations that utilize falling water are called hydro-electric stations and generally located near a dam where the water can be stored, and its rate of flow controlled. When using steam in the generation process, a source of heat is required to produce the steam. This heat can be produced by burning coal and some newer stations use nuclear energy. At one time, windmills were widely used in more remote areas, to generate AC power. Many windmills are still in operation today, but they are not considered suitable for supplying large amounts of power.

The AC electrical power produced by a power plant is distributed as shown in Figure 10.3. The generators at the plant produce a relatively high AC voltage, often 3,200 volts or more. This voltage is passed through power transformers which step it up to an even higher voltage, often as high as 275,000 volt. This extremely high AC voltage is applied to long distance transmission lines, which carry the voltage to the various cities and towns that the power plant services. At each location where the power is to be used, it passes through power transformers which step it back down to a lower voltage, around 2,300 volts. The AC voltage is then dispersed through wires which are strung

on utility poles through different areas. This relatively high AC voltage may be used in businesses to directly to power high voltage motors and industrial equipment. Before, the AC voltage can be used in the home, it must be reduced even more. This final step-down is accomplished by a transformer which is usually located on a utility pole. This transformer steps the voltage down to 240 and 120 volts, then it's distributed to individual homes.
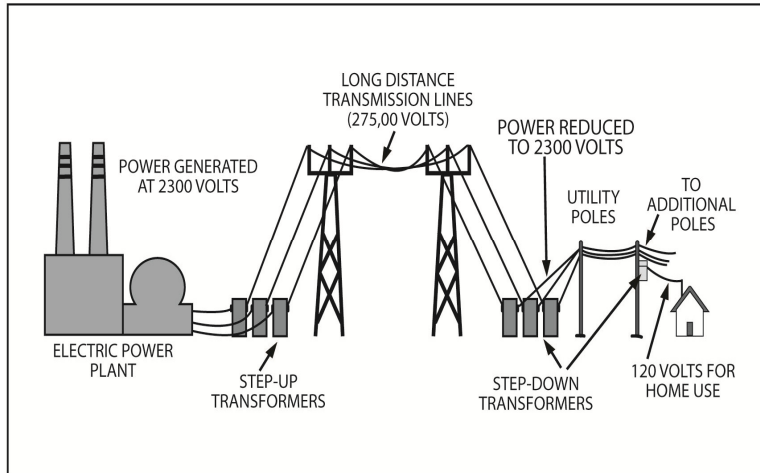

Fig. 10.3

Wall plugs and light fixtures in most homes are 115/120 AC volts at 60 hertz (Hz). Some major appliances like stoves, wall heaters, electrical furnaces, electric dryers, and some air conditioners use the 220/240 AC voltage source. Wall plugs that are rated at something other than 115/120 generally require a special plug. The special plug requirement helps eliminate the possibility of mistakenly plugging an appliance into an improper supply voltage.

AC power is used for heating, cooking, and illumination in the home. All of the large electrical appliances that are used in your home depend upon the 240- or 120-volt AC power provided by the electric power company.

Power cords should be periodically for signs of wear and bare wire. A bare wire can be caused by wearing away a portion of the insulation material that coats the power cord. Keep power cords out of exposed areas. Don't place a power cord or extension cord across a doorway or any place where it might be stepped on or run over by other objects. Most wall receptacles (wall plugs) are rated at 15 amperes. Don't demand more current than a receptacle can supply. Besides blowing fuses, it can start a fire.

If you have an electrical fire, do not pour water on the fire. To put out an electrical fire, use a carbon dioxide fire extinguisher or sand.

Many industries rely on AC power to operate the electric motors that drive their machinery. AC motors are used much more extensively than DC motors because an AC power source is readily available. AC motors are also less expensive, more rugged, efficient, and require less maintenance than comparable DC motors. The few situations that demand use of DC motors, like to operate elevators or certain machine tools; AC power is converted to DC power that's then used to drive the equipment.

AC is used to heat various materials in other industries. In these applications, rapidly varying AC currents are allowed to flow through specially shaped coils of wire. The electromagnetic fields produced by the AC currents, cause heat to be generated within any metal object that is placed within its coils. This process is often used to heat-treat metals. A similar process is also used in the medical profession where AC currents are used to produce heat within body tissue.

Alternating current makes radio or television communication possible. This is because AC carries the sound as well as the picture information that is transmitted from one location to another. In a typical television broadcasting system, the sound and picture information is converted into electrical signals by the microphone and television camera respectively. These signals are applied to the sound and picture transmitters, as shown in Figure 10.4, where they are used to vary characteristics of the high power alternating currents which are produced by the transmitters. The resulting high power AC signals contain the sound and picture information and are applied to the transmitting antenna.
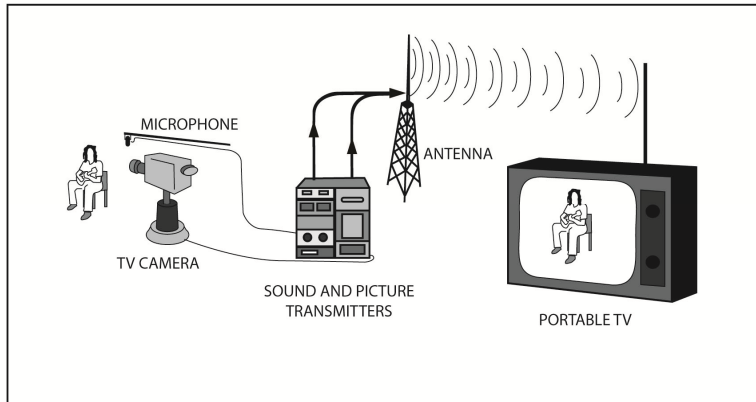

Fig. 10.4

The antenna converts the signals into electromagnetic waves and sends the wave into space. When these waves intercept the antenna on a television set, they produce AC signals within the antenna that are identical to the signals applied to the transmitting antenna. These AC signals are separated and processed by the television set, so that the sound and picture information is extracted and converted into an audible and visual display.

AC signals is pivotal in many applications where information must be transmitted from one location to another. AC signals are utilized in radar equipment, two-way radio communication systems, as well as AM and FM radio broadcast systems. The various telephone systems across the country utilize AC signals, although these signals are carried by wires or transmission lines. Many of the telephone company's transmission lines have been replaced with low-loss fiber optic cables.

Used in many short range applications where the transmitting distance may be only a few feet or a few hundred yard, AC is also crucial. Such applications include the remote control systems that are used to control model airplanes, toys, boats and even cordless telephones. Remote controls for televisions and garage-door openers are also devices that take advantage of short range AC signals.

There are so many uses for AC that it would be impossible to consider all of them. However, this brief overview is meant to help you understand the important role that AC plays in electronics.

Generating AC

Alternating current can be generated in a number of ways, but the most basic means of obtaining AC is with an electromechanical device known as an *AC generator* or *alternator*. An AC generator produces an alternating voltage which in turn develops an alternating current through any load, resistor, lamps, etc., which is connected to the generator's output terminals. AC voltage is produced by a generator by turning a loop of wire within a magnetic field. The relative motion between the wire and the magnetic field causes a voltage to be created into the wire. This voltage changes in magnitude and polarity as the speed and direction of the wire changes in relation to the magnetic field.

Electromagnetic Induction

An AC generator produces an alternating voltage through electromagnetic induction. Electromagnetic induction is the process of inducing a voltage within a wire or conductor by moving it through a magnetic field.

A short wire or conductor has been inserted into the magnetic field that exists between north (N) and south (S) poles of two magnets in Figure 10.5. When you move the conductor up through the magnetic field, it cuts across the magnetic lines of force, flux lines, which are produced by the magnets. As the magnetic flux lines pass through the conductor, the free electrons in the conductor are forced to move. These free electrons move towards one end of the conductor, which leaves a deficiency of electrons in the other end. This excess and deficiency of electrons causes the opposite ends of the conductor to take on negative (-) and positive (+) charges as shown. So, a difference of potential or voltage is developed across the conductor.

The voltage developed across the conductor, shown in Figure 10.5, is due to the relative motion between the conductor and the magnetic lines of force. This relative motion must be present for a voltage to be produced. The conductor may move while the field remains stationary, or the conductor stationary while you moved the field. Either condition produces a voltage. No voltage will be produced when there is no relative motion.
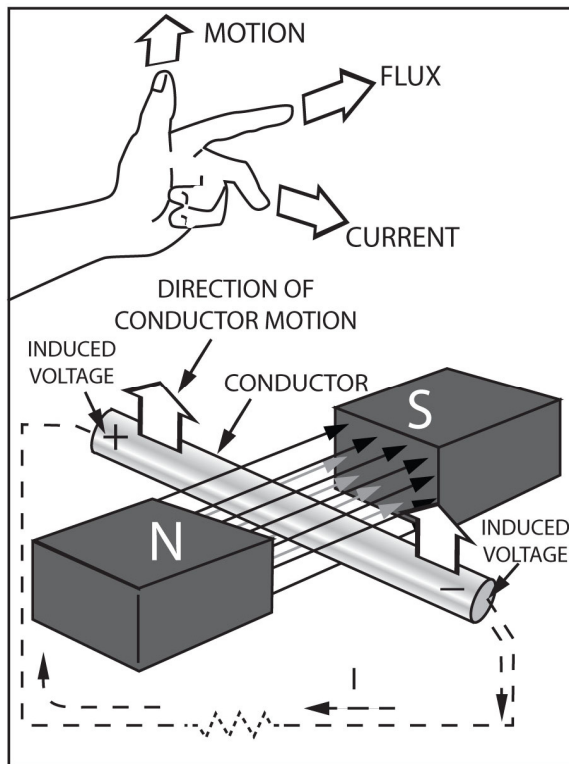
Fig. 10.5

The voltage produced within the conductor is generally called *induced voltage*. This voltage is induced within the conductor regardless of whether there is current flowing through the conductor or not. In fact, a continuous current cannot flow through the conductor unless there is a complete circuit. You might form such a circuit by connecting a load, like a resistor, across the conductor as shown by the dashed line in Figure 10.5. Current could then flow through the load resistance as shown.

The polarity of the voltage induced within the moving conductor is determined by the direction that the conductor is moving. In Figure 10.5, take note of, the direction of the conductor motion and the

direction (north to south) of the magnetic flux. Also, note the polarity of the induced voltage and the direction that current travels when a complete current path is provided. If either the direction of conductor motion or the direction of the magnetic flux is reversed, the polarity of the induced voltage is reversed and current flows in the opposite direction.

You can use the left-hand generator rule, illustrated at the top Figure 1.5, to determine the direction of current flow or the polarity of induced voltage within a conductor. When you position your left hand as shown, your thumb indicates the direction of conductor motion, your index finger points in the direction of magnetic flux, and your middle finger, which is bent out from the palm at a 90 degree angle, points in the direction of the induced voltage.

Several factors determined the amount of voltage that is induced in a conductor. First the induced voltage is affected by the strength of the magnetic field. The stronger magnetic field results in more lines of force per unit area, so there are more lines to cut and the induced voltage increases. When you reduce the field strength, fewer lines of force exist, and the induced voltage decreases.

The speed the conductor moves also impacts the amount of voltage induced by the conductor. The faster the conductor moves, the greater the induced voltage. This occurs because the faster moving conductor cuts more lines of force in a given period of time. When you reduce the speed of the conductor, fewer lines of force are cut per unit of time and the induced voltage decreases.

The length of the conductor with in the magnetic field also affects the induced voltage. The longer the conductor is the greater the induced voltage. The longer conductor cuts more lines of force as it moves through the magnetic field. A shorter conductor intercepts (cuts) fewer lines of force, and induced voltage is decreased.

When a conductor moves at a right angle, 90 degrees, with respect to the magnetic field, maximum voltage is induced. When the angle between the field and the direction of conductor motion decreases, induced voltage decreases. This relationship is true regardless of the direction of the induced voltage.

The relationship between the direction of the field and the direction of conductor motion is shown in Figure 10.6. If the conductor, edgewise, moves straight up from the starting position, direction A, it moves at a right angle, 90 degrees, with respect to the field. Now, the conductor cuts the maximum number of flux lines. The same condition exists when the conductor moves in the opposite direction, direction E. The conductor is still moving at a right angle with respect to the field. The change in direction still induces a maximum current, which develops a maximum voltage. By reversing the direction of conductor motion, the induced current flows into the page, so the direction of current slow reverses.
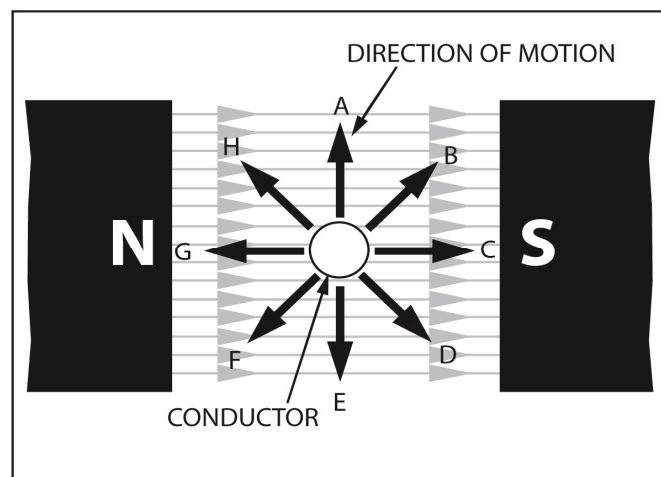
Figure 10.6

If the conductor moves in direction B at the same speed, the cutting angle decreases below 90 degrees. This means that the conductor must travel further between lines of force, so fewer flux lines are cut for the same distance of travel. The induced voltage is less at Point B than it is at points A or E. This is also true when the conductor moves in direction H.

In either direction, B or H, the cutting angle is the same and the induced voltage is the same. In each case, the induced current flows out of the page. The cutting angle is the same when the conductor moves in the direction of D or F. The amount of induced voltage is the same in both examples. However, in direction D or F the induced current flows into the page.

When moving in either direction C or G, the cutting angle is effectively zero. At this time, the conductor is parallel with the lines of force and no lines are cut. Under these conditions, no voltage is induced and no current flows.

Remember, the amount of voltage induced into a conductor is affected by the following four factors:

1. The strength of the magnetic field.
2. The speed the conductor moves.
3. The length of the conductor in the field.
4. The angle at which the conductor cuts the field.

There is one simple rule which takes all these factors into account. This simple rule is, the voltage induced into a conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of force. The word rate in this rule indicates the number of lines of force that are cut per second. The rule indicates that the induced voltage is proportional to the number of lines that are cut per second. When more lines of force are cut per second, the induced voltage increases. When fewer lines are cut per second, the induced voltage decreases. You can increase the number of lines of force that are cut per second, the rate, by increasing the strength of the field, the speed of conductor motion, the length of conductor, or the cutting angle.

A Simple AC Generator

By bending a wire or conductor into the shape of a loop, and then mounting the loop so that it can rotate within a magnetic field, you can basically make a simple AC generator. When the wire loop rotates, an AC voltage is induced into the loop. The only other considerations are to provide a convenient means of extracting the AC voltage generated within the rotating loop and applying this voltage to the load.

Generator Construction

Figure 10.6 shows an AC generator. It consists of a wire loop called an armature, which is mounted so that it rotates within a magnetic field. The magnetic field exists between the north and south poles of a magnet. The magnet that is used for this purpose is commonly referred to as a field magnet. The field magnet is constructed so that it produces a strong, concentrated magnetic field between its poles. It can be either a permanent magnet or an electromagnet. When substantial output power is required, the electromagnet is preferred because it produces high field strength.
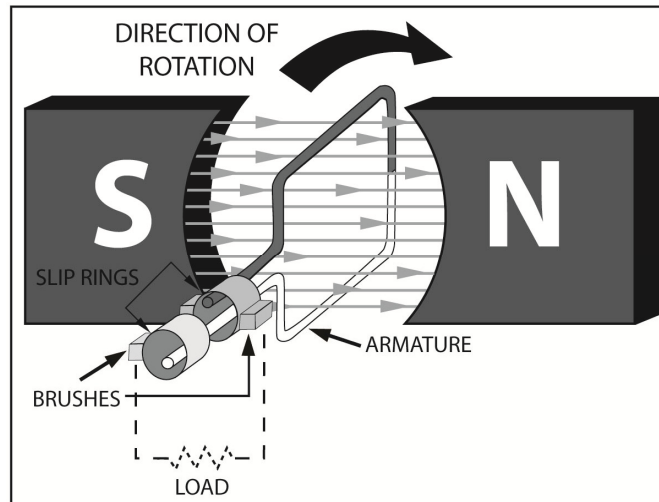
Fig. 10.7

The AC voltage that is induced into the rotating armature must be extracted at the ends of the wire loops which form the armature. But the armature is constantly turning. This makes it impossible to permanently attach any wires or leads directly to the armature. For this reason, it is necessary to use some type of sliding contact at each end of the wire loop. As you can see in Figure 10.7, two cylinders metal rings are attached to the opposite ends of the loop. These metal rings are called slip rings. An external circuit, or load, is connected to these slip rings through contacts which are held against the rings. These contacts are made from a soft but highly conductive material, usually carbon, and are called brushes. The brushes slide against the slip rings as the armature turns. The brushes serve as two stationary contacts to which an external load can be connected. The brushes are the output terminals of the generator. Simply stated, the AC output voltage is applied from the armature, through the brushes, to the load.

Generator Operation

AC generators must operate so that their armature rotates at a constant speed for proper functioning. As the armature rotates in the magnetic field, one side moves down through the magnetic field while the other side moves up. During each complete revolution of the armature, each side must move down and then up through the field. In addition, each side of the armature always remains in contact with its respective brush through a slip ring. Keep these things in mind, while you examine the basic action that takes place during one complete revolution of the armature in the following paragraphs.

An armature shown in four specific positions is illustrated in Figure 10.8. These are intermediate positions which occur during one complete revolution of the armature. Note that one side of the armature and its associated slip ring and brush are black, while the other side is white. These two colors help you keep track of each side of the armature. Also, resistive load is connected to the brushes so that a complete circuit is formed. The complete circuit allows current to flow through the armature to the load, and a voltmeter monitors the output voltage. Note that the voltmeter is connected across the load.
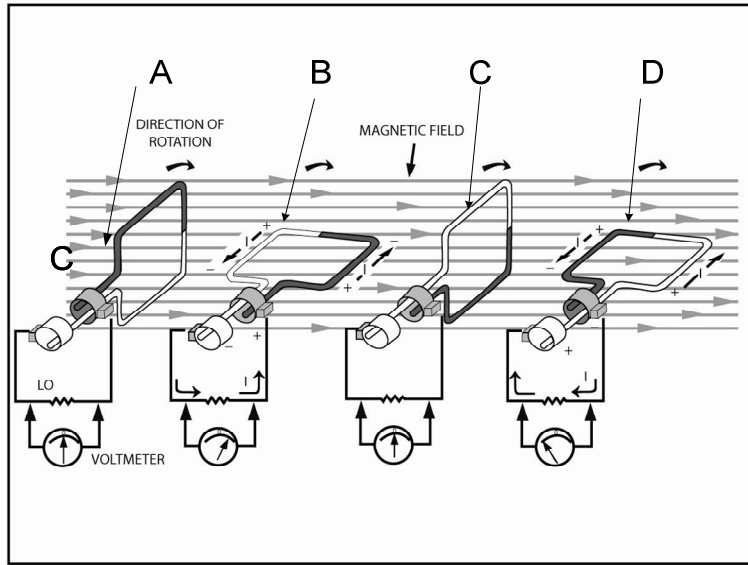
Figure 10.8

When the armature begins to rotate in a clockwise direction from the initial position shown in Figure 10.8, A, notice that initially, the black side of the armature is on top and the white side is on the bottom. As the armature moves from this starting position, the black side moves from left to right. However, both sides move parallel to the lines of force, no lines are cut. When a conductor moves parallel to the field, the induced voltage is zero. Note that the voltmeter, which is connected to the brushes, indicates zero at this time.

As the armature rotates to the position shown in Figure 10.8, B, the black side moves down through the field while the white side moves up. The opposite side of the armature therefore cuts the magnetic lines of force in opposite directions. The polarity of the voltage induced in the black side is opposite the polarity of the voltage induced into the white side. However, the voltages induced in each side are series-aiding and the two sides of the armature form a complete loop. These induced voltages are equal in value. Therefore, the voltage which appears at the brushes is equal to the sum of the voltages induced into each side.

The polarity of these voltages is shown in Figure 10.8, B, along with the resulting currents. Note that series-siding voltages produce a current that circulates through the armature and the load.

In Figure 10.8, B, notice that the armature is horizontal. The black and white sides of the armature cut the magnetic lines of force at right angles (the fastest cutting rate), which results in the maximum induced voltage. At this time, the output voltage that is applied to the load is at its maximum rate as indicated by the voltmeter. It is important to note that the output voltage does not suddenly jump from zero to maximum. The output voltage increases at a specific rate. As the armature rotates from the position shown in, A, to the position shown in, B, it cuts the magnetic lines of force at an ever increasing angle until maximum voltage is obtained. This causes the output voltage to increase smoothly from zero to its maximum value.

When the armature rotates from the position shown in B, to the position shown in C, it cuts the magnetic lines of force at a slower and slower rate. When the armature reaches the position shown in C, the opposite sides of the armature are parallel to the lines of force and no flux lines are cut. This means that the output voltage decreases from maximum to zero as the armature moves to the position shown in C. The corresponding load current also decreases to zero as the output voltage increases.

At this point, the armature has completed one-half of a revolution and produced an output voltage that has increased from zero to maximum value and back to zero. The corresponding load current

also varied in the same manner. It is important to note that up to this point the output voltage changes only in value and not in polarity. This is defined as an alternation. To be more specific, from zero to maximum and back to zero is described as the positive alteration of an AC waveform. Later, this is described as one-half of a sine wave.

As the armature continues its rotation from the position C, to the position shown in 10.8, D, the opposite sides of the armature move across the magnetic lines of force, on opposite directions. However, the black side of the armature now moves up and the white side moves down. This is exactly the opposite of the situation which occurred during the first one-half revolution. Therefore, the voltages that are induced into each side of the armature have polarities which are opposite to those induced earlier. These induced voltages series-aid, as before, to produce and output voltage.

The output voltage now has a polarity that is exactly opposite to the polarity that was produced earlier. As the armature moves to the position shown in D, the new output voltage, with opposite polarity, increases to maximum because the armature cuts the lines of force at the fastest rate in this position. The maximum voltage is indicated on the voltmeter which is connected across the load. The load current is maximum at this time and flows in the direction shown. The amplitude or value is exactly the same as before, but the polarity of the voltage is opposite its initial direction.

A full revolution is completed by the armature by returning to its initial position as shown in Figure 10.8, A. As the armature continues rotating toward its initial position, the armature cuts the lines of force at a decreasing rate, until no lines are cut. This causes the induced voltage within the armature and the resultant output voltage to decrease to zero. The corresponding load current is also zero at this time.

As you can see, one complete revolution of the armature produces a voltage and corresponding load current that changes in both magnitude and direction. Therefore, the output voltage and current are AC values.

Again, consider the generator action that was just described and exactly how an Ac output voltage is generated. Let's rotate the armature one complete revolution, 360 degrees, through the magnetic field. This time, rather than just focusing on the maximum and minimum points, let's consider what's happens at a number of intermediate armature positions.

Since the voltage induced in each side of the armature is series-aiding, it is necessary to observe only the voltage that is induced in one side of the armature. The one-half armature loop rotates through 16 different positions as depicted in Figure 10.9. The conductor rotates through the magnetic field in a clockwise direction.
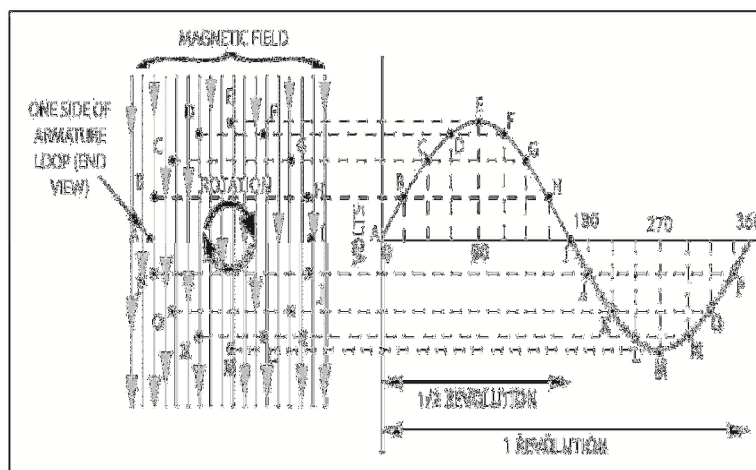
Fig. 10.9

At position A, the wire moves parallel with the lines of force and no voltage is induced. However, as it moves through positions B, C, D, to E, it cuts lines of force at a faster and faster rate. At position E, the wire moves at a right angle (90 degrees) with respect to the field. The voltage induced into the wire is proportional to the rate at which the lines of force are cut. Since the cutting rate increases in a nonlinear manner, the voltage increases in the same way.

This increasing nonlinear voltage is also shown graphically in Figure 10.9; the voltage graph was made by marking off the angular rotation of the wire, in degrees, along a horizontal line. This horizontal line is calibrated for one complete revolution of the wire, 360 degrees. The value of the voltage that is created within the wire is plotted vertically. Notice that there are five voltage values have been plotted that corresponds to wire positions, A through E. Each successive value is higher and corresponds to the rate at which magnetic lines of force are cut. These values are then connected to form a continuous line. The resulting curve shows how the induced voltage varies when the armature rotates one quarter of a revolution, or 90 degrees. Note that the voltage increases rapidly from zero (at zero-degree rotation) and tapers off to a maximum value (at 90 degrees of rotation).

As the wire rotates past position E and moves through positions F, G, H, and I, it cuts lines of force at a slower and slower rate. This causes the value of the induced voltage to decrease from a maximum value, at 90 degrees, to a minimum value, 180 degrees. At position I, the wire is moving parallel to the magnetic flux lines. At this time, no lines are cut and the induced voltage is again back to zero.

The induced voltage values which correspond to wire positions F through I are plotted on the voltage graph as shown. These values are successively lower, with the value at I equal to zero. When you join these voltage values with a continuous line, you can see that the voltage decreases slowly from its maximum value, at a faster and faster rate, until it reaches zero. The voltage curve, between values E and I, shows how the voltage varies when the armature rotates an additional 90 degrees, which is the second quarter of one revolution.

At this point, the armature has rotated one half of one revolution, 180 degree, and has produced a voltage that varies from zero to a maximum value and back to zero again. When the armature moves past position I, it starts cutting flux lines. This time the armature loop moves in the opposite direction through the magnetic field. Therefore, the polarity of the voltage that is induced into the armature during this alternation is opposite to the polarity of the voltage that was produced during the first one-half revolution

As the armature moves from position I through positions J, K, L, and M, it cuts the lines of force at an increasing rate. The amplitude of the induced voltage is the same as it was when the armature moved from position A to position E. The only difference is that the induced voltage now has the opposite polarity. To prove that the polarity is opposite, you can plot the voltage values which occur at positions J, K, L, and M below the horizontal line as shown. This portion of the curve shows that the voltage varies from zero to a maximum value in the opposite direction as the armature wire rotates from the 180 degree position to the 270 degree (position M).

When the armature moves to positions N, O, and P, it cuts the lines of force at a decreasing rate. When it reaches position A, it has completed one revolution, 360 degrees. At this point, the armature again moves parallel to the lines of force and no flux lines are cut.

One complete revolution of the armature produces an AC voltage that varies in both amplitude and direction. During one-half of the revolution, the positive alternation, the voltage increases from

zero to maximum and back to zero. During the next half of a revolution, the negative alternation, the voltage increases from zero to a negative maximum and back to zero again.

The resulting current varies in the same manner when this AC voltage is applied to a load. In other words, the current will increase and decrease in one direction and then increase and decrease in the opposite direction.

One complete revolution equals 360 degrees and is made up of a positive alteration, 0 to 180 degrees, and a negative, 180 to 360 degrees, alternation. These two alternation comprise what is called a cycle of AC. A *cycle of AC* is the combined time that it takes to generate the positive and negative alternation. This is also defined the *period of an AC waveform.*

The armature of an AC generator rotates at a constant speed, therefore, the AC output voltage produced by the device continually changes in value and direction, as shown in Figure 10.9. Each complete revolution of the armature causes the output voltage to vary in the manner shown

The AC generator just described is the simplest device that can be used to generate AC voltages. The AC generators used to produce electrical power for commercial applications are more complex in construction. However, all AC generators operate with the principles just described. Practical AC generators utilize many loops of wire, within their armatures, to increase the induced voltage to a much higher value. These generators may also contain more than one pair of north-south magnetic poles. When more than one pair of poles is used, one revolution of the armature can produce more than one AC voltage variation.

AC generators can also be very small and are designed for low power applications. Alternators that are used on most automobiles are small AC generators that are only six or seven inches in diameter. They can produce a few hundred watts of output power. These alternators, generators, are powered by the car's engine and used to produce an AC voltage that is converted to a DC voltage. The DC voltage is then used to operate the car's electrical system. The newer alternators are used in place of DC generators, which were once widely used, because they are more efficient and require less maintenance. The process of converting AC to DC is relatively easy and inexpensive. The process of converting AC to DC is called rectification and will be explained in detail later in this course.

Other very large AC generators are designed to produce large amounts of electrical power. AC generators used by an electric power company might be too large to fit into the living room of your house. Such a generator might produce as much as 1,000,000 watts of output power. This is enough power for the whole community.

Chapter 11
AC Measurements

Now, that you have a basic understanding of AC and its uses, we will learn about systems for measuring AC.

Basic AC Unit Calculations

To form a basic AC circuit, you can connect a load resistance across an AC voltage source as shown in Figure 11.1 Even though, a resistor is used in this circuit, any resistive component such as a lamp or heating element has the same effect. Such devices are all resistive and have a negligible amount of inductance or capacitance.
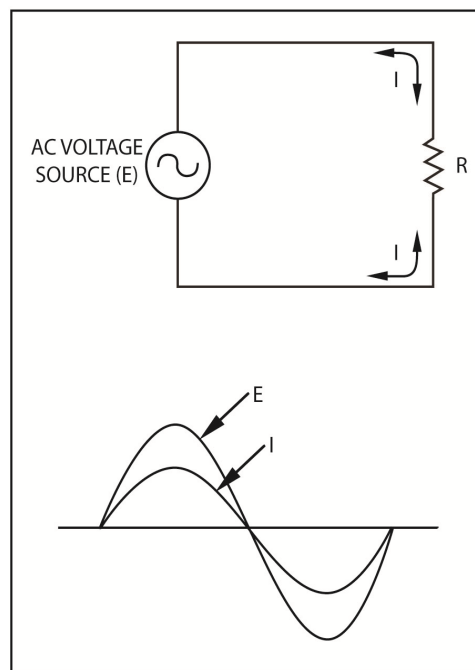

Fig. 11.1

An AC generator or an electronic circuit that produces an AC voltage could be supplying the energy source. When this voltage is applied across the resistor, a corresponding AC current is produced that flows through the resistor. This current varies in amplitude and direction and is *in phase* with the applied AC voltage. Meaning, the current is zero when the voltage is zero and it reaches its maximum when the voltage is at maximum. When the voltage changes polarity, the current also changes direction. The voltage and current in a purely resistive AC circuit are in phase.

This phase relationship, between the voltage and current, is shown graphically in the bottom section of Figure 11.1. The voltage, E waveform and the current, I waveform pass through zero and maximum at the same time. Both E and I also change direction at the same time. The two waveforms do not have exactly the same peak amplitude because they represent different quantities and are measured in different units. They are just drawn together to show that they occur at the exact same time.

The value of current flowing through the resistor in Figure 11.1, at any given instant depends upon the voltage at that instant and the circuit resistance, which remains constant. You can use Ohm's

Law to determine the current at any instant just like you do for a DC circuit. So, when AC circuits are purely resistive, the same rules and laws that apply to DC circuits also apply to AC circuits. Ohm's Law states that the voltage, current, and resistance are mathematically related as follows:

$$E = I \times R$$

This equation states that voltage, which is measured in volts, is equal to current, which is measured in amperes, multiplied by the resistance, which is measured in ohms. As, we've already done, this basic equation can be rearranged to show that current is equal to voltage divided by resistance. This is expressed mathematically as:

$$I = E/R$$

It can also be rearranged to show that resistance is equal to voltage divided by current.

$$R = E/I$$

When you work with AC circuits, you will seldom use instantaneous values of voltage and current in AC calculations. Instead, you will use the effective values of these quantities. The effective value of an AC voltage or current sine wave is equal to 0.707 times its peak or maximum value. Therefore, when you use effective values, you are expressing the AC quantity in terms of its DC equivalent value.

Ohm's Law can be used with effective values just as easily as with instantaneous values. You can quantify the effective value of E if you multiply the effective value of I by R. Likewise, you can determine the effective value of I when you divide the effective value of E by R. Also, R is equal to the effective value of E divided by the effective value of I.

Let's consider a basic circuit that has an AC voltage source and an effective value of 100 volts and a resistance of 100 ohms, see Figure 11.2. Applying Ohm's Law, the effective value of current, I, is equal to:

$$I = E/R = 200 \text{ volts or } 2 \text{ ampere}/200 \text{ ohms}$$

Therefore, an effective voltage or force of 200 volts causes an effective current of 1 ampere to flow through a resistance of 200 ohms.
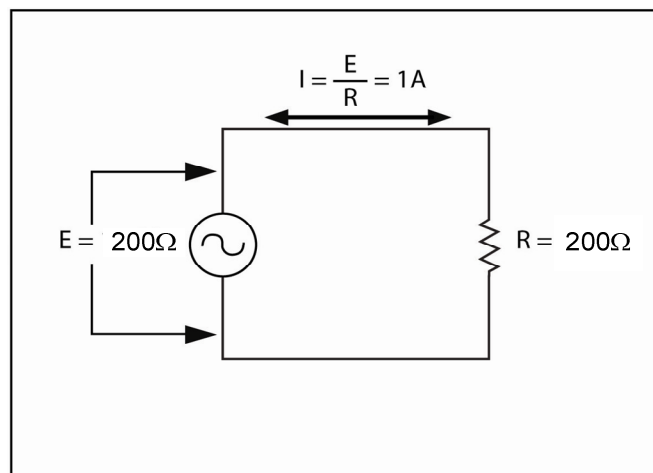

Fig. 11.2

Now, what if we have a circuit where the resistance and current are known and the voltage needs to be figured out. The current has an effective value of 5 amperes and a resistance equal to 100 ohms. According to Ohm's Law, the applied voltage must have an effective value of:

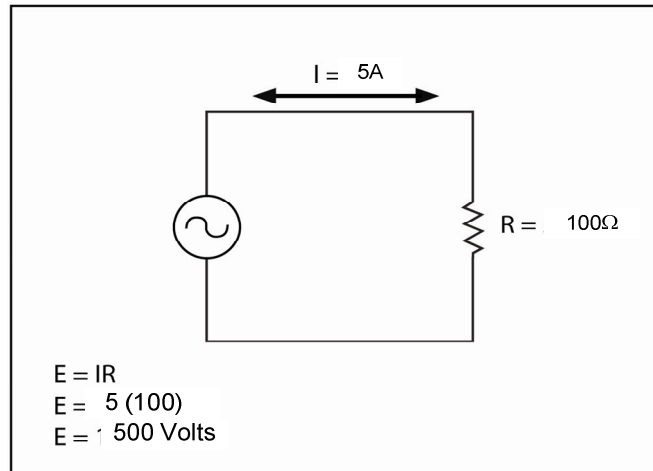$$E = IR = (5 \text{ A}) (100 \text{ ohms}) = 500 \text{ volts}$$

Fig. 11.3

Series AC Circuit Calculations

The current in a purely resistive circuit is always in phase with the applied voltage, even when more than one resistor is used. The single resistor shown in 11.1 could be replaced with two series resistors so that a simple series circuit is formed as shown in 11.4. The current flowing through a circuit is limited by the total resistance of the circuit which is the sum of the two resistances. This current has the same value, at any given instant, at all points in the circuit. Also, this current is in-phase phase with the applied voltage. This in-phase relationship between the applied voltage, EA, and the circuit current is shown in Figure 2-25B.
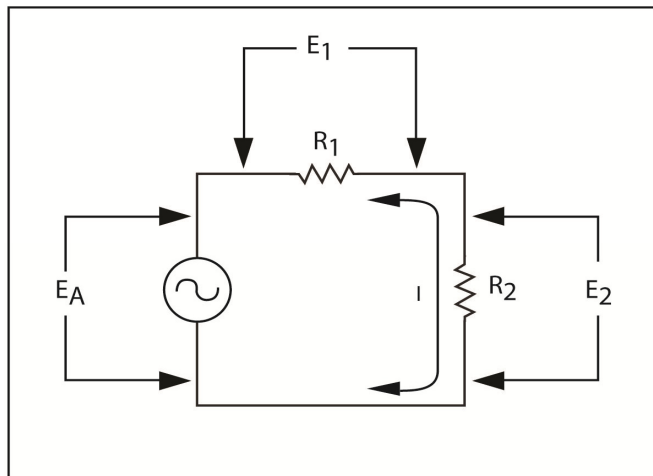
Fig. 11.4

There's a voltage drop across each resistor, because the current flows through both R_1 and R_2, The voltage drop across each resistor at any given instant is equal to the product of the circuit current at that instant and the resistor's value. The two voltages, designated as E_1 and E_2, are in series, and when you add together their instantaneous values, E_1 and E_2 are in phase with E_A, and their combined values, $E_1 + E_2$, is always equal to E_A. This in-phase relationship between E_A, E_1, and E_2 is shown graphically in Figure 11.5. Note that all three of these voltages are in phase with each other and they are also in phase with the circuit current.

Fig. 11.5
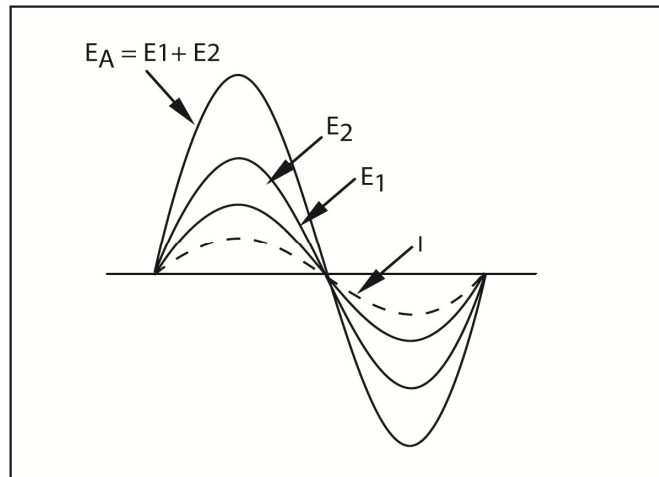
As discussed earlier, it's very common to use effective values of current and voltage when you analyze AC circuits. To illustrate this point, consider a typical series AC circuit. Suppose that the AC voltage source has an effective value of 150 volts and that R_1 and R_2 have values of 50 ohms and 100 ohms, as shown in Figure 11.6. The total resistance of the circuit, R_T, is equal to $R_1 + R_2$. Therefore, R_T equals 50 ohms + 100 ohms or 150 ohms. The circuit contains a single 150 ohm resistor as far as circuit current is concerned. Therefore, the current equals EA divided RT or:

$$I = 150 \text{ volts}/150 \text{ ohms} = 1 \text{ ampere}$$
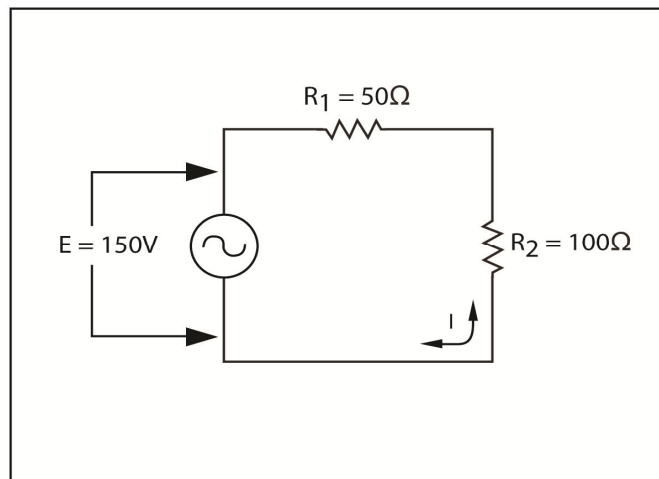
Fig. 11.6

1 ampere is the current value and represents the effective value of circuit current. The current flows through R_1 produces a voltage drop which, according to Ohm's Law, is equal to the circuit times the resistance of R_1 or:

$$E_1 = IR_1 = (1A) \ (50 \text{ ohms}) = 50 \text{ volts}$$

This same current flows through R_2 and produces a voltage across this resistor of:

$$E_2 = IR_2 = (1A) \ (100 \text{ ohms}) = 100 \text{ volts}$$

These voltage drops are proportional to the resistor's values. Also, these voltages are expressed in effective values. The sum of these two effective voltages equals the effective values of the applied voltage. This is expressed mathematically as:

$$E_A = E_1 + E_2 = 50 \text{ V} + 100 \text{ V} = 150 \text{ volts}$$

The above example demonstrates how effective AC values are when used in a simple series AC circuit. As you can see, these effective values are used the same way the DC values are used. The same rules that apply to a series DC circuit that contains only resistance, also apply to a series AC circuit which contains only resistance.

Parallel Circuit Calculations

When two resistors are connected in parallel and an AC voltage is applied to then as shown in Figure 11.7, the total current, I_T, supplied by the voltage source is in phase with the applied voltage, E_A. This in-phase relationship between E_A and I_T is shown in Figure 11.8. However, the total current divides and flows through the two resistors R_1 and R_2. These two currents are designated as I_1 and I_2 in 11.7.

The individual currents are in phase with I_T and their instantaneous values add to produce I_T as shown in 11.8; therefore, at any given instant IT equals the sum of I1 and I_2.

The applied voltage appears across both resistors, and this voltage is in phase with currents I_T, I_1, and I_2 as indicated graphically in Figure 11.8.
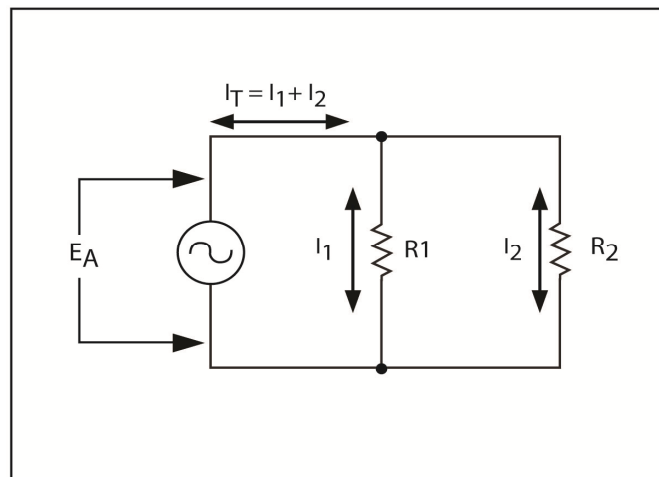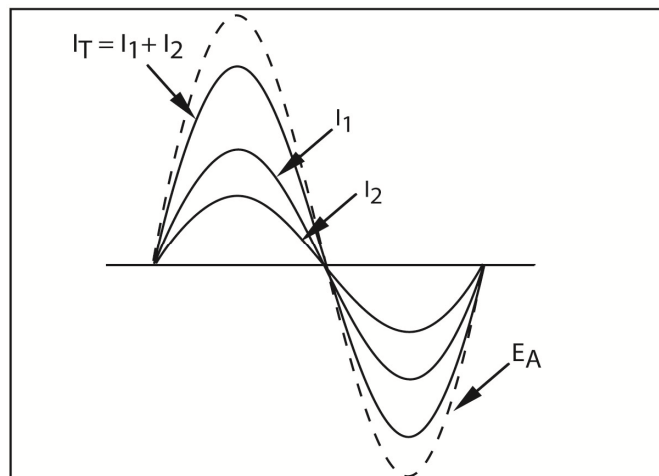

Fig 11.7

Fig 11.8

To demonstrate the use of effective values to analyze a parallel circuit, consider Figure 11.9. Suppose that the applied voltage is 150 volts and R_1 and R_2 have values of 50 ohms and 100 ohms as shown below.
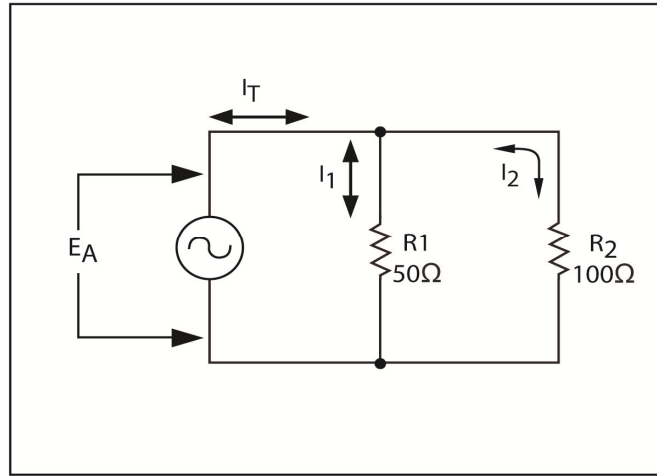

Fig. 11.9

To calculate, the value of branch current I_1, divide the applied voltage by the branch resistance, R_1:

$$I1 = 150 \text{ volts}/50 \text{ ohms} = 3 \text{ amperes}$$

The current through R_2 is equal to the applied voltage divided by R_2:

$$I_2 = 150 \text{ volts}/100 \text{ ohms} = 1.5 \text{ amperes}$$

Total current, I_T, is the sum of the branch currents:

$$I_T = I_1 + I_2 = 3 \text{ A} + 1.5 \text{ A} = 4.5 \text{ amperes}$$

Ohm's Law can be used to determine the equivalent or total resistance of the circuit; because the total current is 4.5 amperes and the applied voltage is 150 volts. In other words, the total resistance is:

$$R_T = \ 150 \text{ volts}/4.5 \text{ amperes} = 33.3 \text{ ohms}$$

The circuit functions as if it contains one resistor that has a value of 33.3 ohms. If you connect a resistor with this value across the voltage source, the total current will be the same.

All of the current and voltage values that were just used are effective values. You use them in exactly the same way as you use DC current and voltage values in DC parallel DC circuit. You can calculate the total resistance of a parallel circuit with the reciprocal formula for resistors connected in parallel. The formula is:

$R_T=$ 1

$$1/R_1+1/R_2+1/R_3$$

This reciprocal formula works for any number of resistors that are connected in parallel. When you have only two resistors connected in parallel, you can use the product over the sum method to calculate the total resistance like this:

$$RT = R1 \text{ x } R2/ \ R1 + R2$$

When all of the resistors that are connected in parallel have the same value, you can simply divide the value of one resistor by the total number of resistors that are connected in parallel:

RT =   The value of one resistor

Number of resistors in parallel

A final method, which can be used to calculate total resistance in a parallel circuit, is called the *assumed voltage method.* In this method, you do not need to know the actual value of the applied voltage or the branch currents. You assume a voltage; use a voltage that you can evenly divide by each of the resistors that are in parallel whenever practical. Next, divide the assumed voltage by each branch resistance to obtain the individual assumed branch currents. Now add the calculated branch to obtain an assumed value for I_T. The last step is to divide the assumed voltage by the assumed total current. This results in the actual total resistance of the parallel resistors.

Power in AC Circuits

Power is consumed by the resistive component in the form of heat in an AC resistive circuit. This is just like it is in a DC resistive circuit. The power in either a DC or AC circuit is measured in units called watts.

In a DC circuit, power in watts is equal to current in amperes times' voltage in volts. The following equation shows this relationship mathematically:

$$P = IE$$

The same relationship applies to AC circuits which contain only resistance. In other words, you can multiply the current at a specific instant by the voltage of that instant to determine the instantaneous power. After you multiply all of the instantaneous values for a complete cycle of voltage and current, you find that the power curve follows the voltage and current changes. In other words, AC power is proportional to the product of voltage and current at any point on their curves.
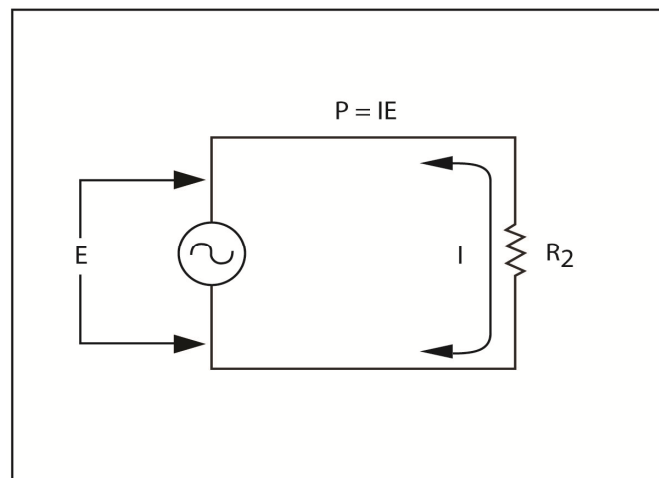
Fig. 11.10

A simple AC circuit is shown in Figure 11.10. The power consumed by the resistor in this circuit varies with the product of the current through the resistor and the voltage dropped by the resistor. The relationship between power, current, and voltage is graphically represented in Figure 11.11. Note that the power curve, or waveform, does not extend below zero axis (horizontal line). This is because the power is effectively dissipated in the form of heat, no matter which direction current flows. So, it's assumed to have a positive value. Also, the power reaches its peak value when both E and I are maximum. Likewise, power drops to zero when both E and I equal zero.
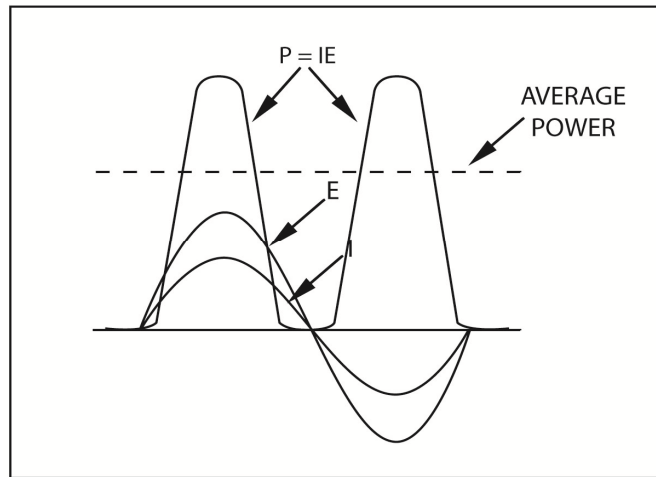
11.11

The power fluctuates between a peak value and zero, the average power that is used by the circuit is midway between these two extremes. So, if you draw a line midway between the peak and zero values, the line will indicate the average power being used. It is average power that is most important in AC circuits. Average power is the power that is actually used in AC circuits.

To calculate the average power dissipated in an AC circuit, multiply the effective value of current times the effective value of voltage. So, you can use the power equation, P = IE, in AC calculations as long as you use the effective values of I and E. Let's say, the resistor in Figure 11.10 has a value of 200 ohms and the applied voltage has an effective value of 200 volts. The current in the circuit is:

$$P = IE = (2\ A)\ (200\ V) = 200\ watts$$

The resistor consumes, dissipate in the form of heat, 200 watts of power.

At times, another form of the power equation that expresses power in terms of voltage and resistance is good to use. This equation states that power is equal to the voltage squared (E2) divided by the resistance and is stated mathematically as:

$$P = E^2/R$$

We could have used this form of the power equation to solve the previous problem. It eliminates the step that calculates the current through the resistor. You can also express the power equation in terms of current and resistance as:

$$P = I^2R$$

The various forms of the power equation provide several means of calculating power. You can use combinations of known values of current, voltage, and resistance to find unknown values. These equations also work for DC circuit calculations.

Chapter 12
Transformers

Transformer Action

Transformers are used to transfer alternating current from one circuit to another. Usually, some characteristics of the AC signal changes during the transformation process. For example, a low-voltage AC may be stepped up to a higher value or a higher voltage may be stepped down to a lower value. Often it is the current which must change. Transformers are used during this process to step up or step down both current and voltage at the same time. In this section, you will take a look at the action which allows the transformer to change voltage and current levels.

Mutual Inductance

Transformer action is based is on a principal called electromagnetic mutual inductance. We discussed this phenomenon earlier when inductors were studied. First, you will briefly review principles of mutual inductance.

When current flows through a conductor, a magnetic field builds up around the conductor. With alternating current, the magnetic current builds, collapses, builds again in the opposite direction, and collapses again for each cycle of the applied current. If you place another conductor in this moving magnetic field, it will have an EMF induced into it.

The transformer is a device that takes advantage of this principle. The two conductors are wound into coils and positioned close together so that the magnetic flux lines of one coil cut the other. Often, the coils are wound one on top of the other. When this is the case, each inductor is coated with a thin insulator material to prevent shorts.

Transformer action is illustrated in Figure 12.1. Coil L_1 is connected to an AC voltage source. As alternating current flows through the coil, a varying magnetic field is set-up. During one half cycle, current flows through L_1 in the direction shown. This establishes a north magnetic pole at the top of L_1. As the current increases, the field expands outward and cuts the turns of wire in L_2. This induces an EMF into L_2. In turn, this causes current to flow up through the load resistor. Thus, the current into L_1 causes current to flow through L_2.

This induces a voltage that is negative at the top and positive at the bottom of L_1. The field induces a current into the secondary, L_2, that develops a voltage that is positive at the top and negative at the bottom. The polarity of the secondary voltage causes electrons to flow up through the load resistor. In this type of transformer, the secondary voltage has inverted polarity, 180° out of phase, from input to output.
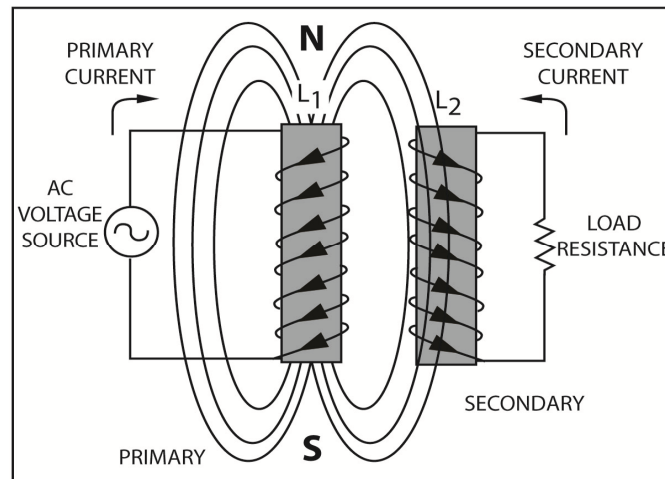
Fig. 12.1

If you have trouble following the description of transformer operation, review the left hand rules for conductors.

At the end of the first half cycle, the current through L_1 drops to 0 for an instant as the sine wave input passes through 180°. As the current decreases, the field collapses back into L_1. When the current in L_1 decreases, the current in L_2 also decreases.

During the next half cycle, the direction of current through L_1 reverses. This causes a magnetic field of the opposite polarity to expand outward from L_1. Once again, the field cuts the turns of L_2 to induce an EMF. However, because polarity of the magnetic field is reversed, the polarity of the voltage that is induced into L_2 is also reversed. Thus, the induced EMF causes current to flow down through the load resistance.

The current in L_2 follows the current in L_1. Each time the current in L_1 reverses direction, the current in L_2 also reverses. Therefore, the alternating current in L_2 has the same frequency as the alternating current in L_1. Energy transfers from one circuit to another even though the two circuits are electrically insulated (physically separated) from each other.

Figure 12.1 shows a simple transformer. The coil to which the AC voltage is applied is called the primary winding. The AC voltage source causes the current in this winding which is called the primary current. The coil into which current is induced is called the secondary winding. The induced current is called the secondary current.

The amount of mutual induction between the two coils is dependent upon the amount of EMF that is induced into the secondary winding. In turn, the amount of mutual induction is determined by the degree of flux linkage between the two coils. You can think of the flux linkage as the percentage of primary flux lines which cut the secondary winding. Another expression which means approximately the same thing is the coefficient of coupling. The *coefficient of coupling* is a number between 0 and 1. When all of the primary flux lines cut the secondary coil, the coefficient of coupling is 1. If two coils are positioned so that some of the primary flux lines do not cut the secondary, the coefficient of coupling is less than one.

The coefficient of coupling and the resistive properties of the coils account for the statement that input (primary) power is always more than the output (secondary) power.

The amount of mutual inductance depends upon the flux linkage or the coefficient of coupling. This is illustrated in Figure 12.2 where the secondary coil, L_2, is wound directly on the primary coil,

L_1.   In this arrangement, nearly all of the flux lines that are produced by the primary cut the secondary windings. So, the coefficient of coupling is close to one.
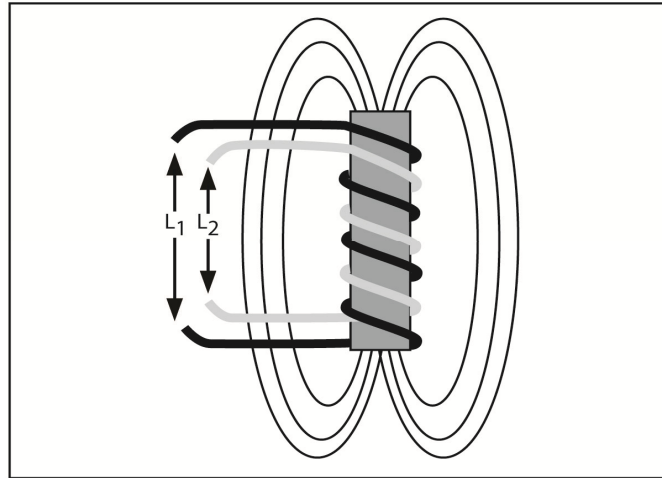
Fig. 12.2

The transformer consists of two coils in Figure 12.3. Here, only a few lines of flux from the primary cut the secondary. Therefore, the coefficient of coupling is low.

Fig. 12.3

Figure 12.4 shows that when you place the two windings far enough apart, no flux linkage between them exists. In this case, there is no mutual inductance and the coefficient coupling is zero. While this arrangement has no practical purpose, it illustrates the importance of the coefficient of coupling. Also, when coils are mounted perpendicular to each other, the coefficient of coupling is zero.
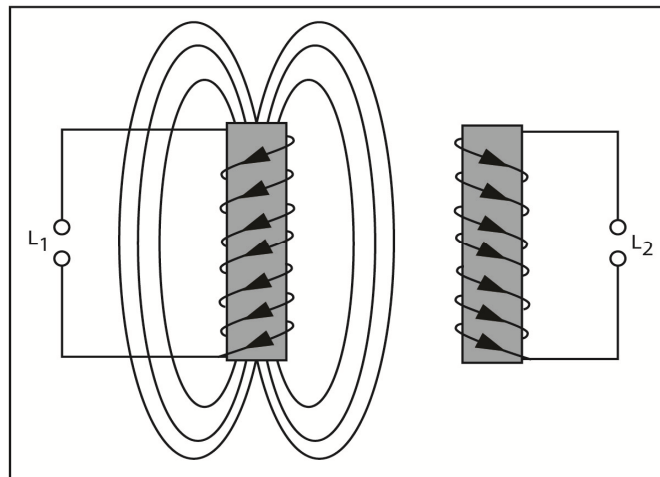
Fig. 12.4

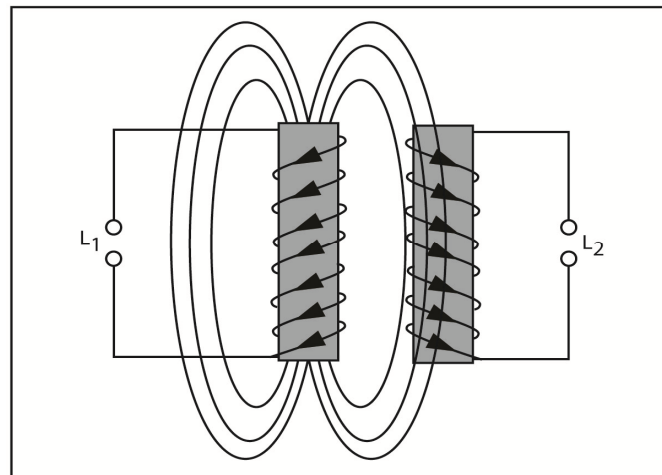The step-by-step sequence of events in transformer action is illustrated in Figure 12.5. When you close the switch, the EMF of the generator is applied across the primary. This causes current to flow through the primary. The current produces magnetic flux lines which expands outward and cut the secondary. This induces an EMF into the secondary winding. When a path for current flow exists, the EMF causes a secondary current to flow. A load is connected across the secondary. Energy transfers from the generator to the load even though the two circuits are not physically connected.
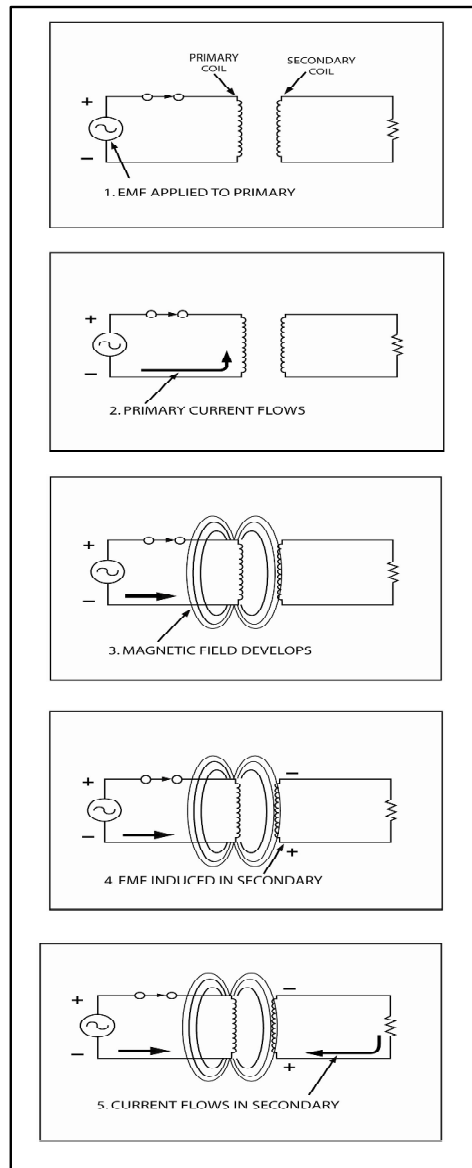
Fig. 12.5

Except for the initial turn on and turn off of the source voltage, transformers are not used in DC circuits, because there is no movement of flux lines. When there is no relative motion (expanding and collapsing) of the magnetic field, there is no induced voltage. Therefore, the transformer is considered to be an AC component only.

Transformer Construction

Construction techniques for transformers vary depending upon the type of transformer and the particular application. All transformers can't be used for the same application. A substation transformer in a power distribution system may approach the size of a small house. On the other hand, a transformer in a transistor radio may be no larger than a pencil eraser. In spite of the vast size difference, the two transformers operate on the same basic principle. Both have primary and secondary coils. In both, energy is coupled from the primary to the secondary by mutual inductance.

The frequency a transformer must pass, the voltage and current involved, and several other factors dictate the design of a transformer. Transformers are bulky, heavy, and expensive when they are compared to other electronic components. Therefore, they are used only in limited applications.
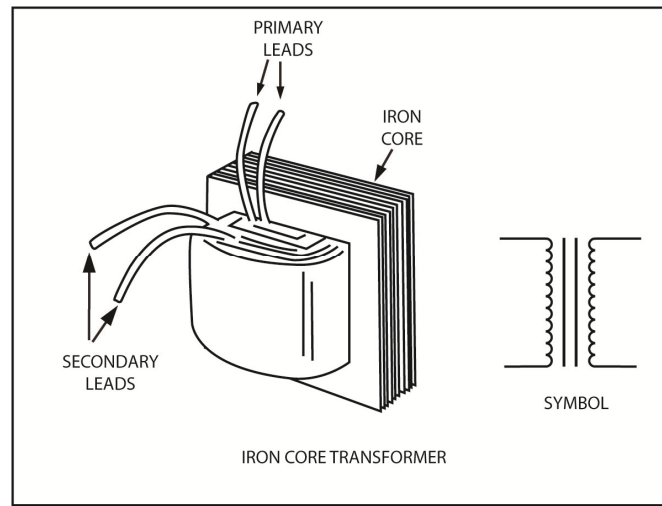
Fig. 12.6
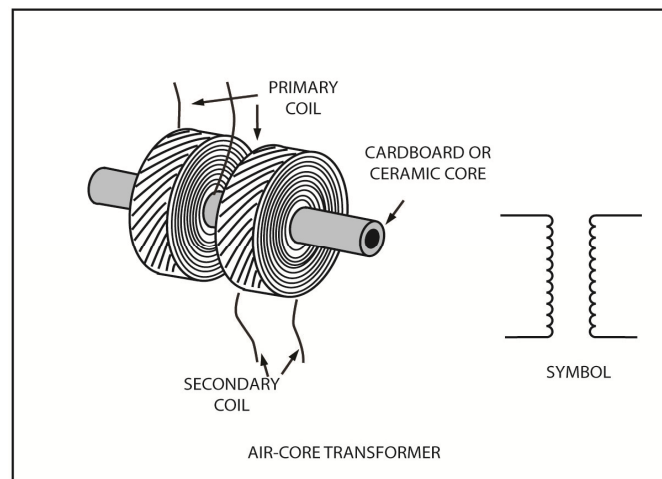
Fig. 12.7

In Figure 12.6, the construction of an iron-core transformer is shown. This is compared to Figure 12.7, which shows an air core transformer. The iron-core transformer is much larger and heavier. The primary winding is wound on one arm of the core. The secondary is wound directly on top of the primary. Note that the symbol for the transformer shows the two coils. The two lines between the coils represent the iron core. The iron core concentrates the lines of force into a small area. Recall from your study of inductance that iron has a high permeability which means it is easy to magnetize.

The make-up of the air-core transformer is different. It is designed to be used at much higher frequencies. Iron core losses increases as frequency increases. Transformers which are designed to operate at high frequencies use little or no iron at the core. Instead, a non-conductive material that has the same permeability as air used. High-frequency cores are usually either ceramic or simply cardboard tubes.

Transformer Theory

Previously, we saw how transformer action can be used to couple an AC signal from one circuit to another. In this section, you will explore this action further.

Transformer No Load

Figure 12.8 shows a transformer being operated without a load, which means the secondary of the transformer, is open. Therefore, there is no secondary current. Even so, there is primary current because the primary is connected across an AC voltage source.

EXCITING CURRENT
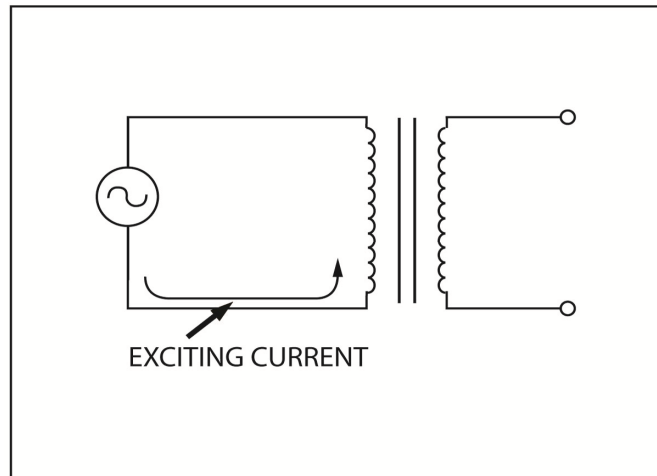
Fig. 12.8

In this situation, the impedance of the transformer's primary and the applied voltage determine the amount primary current. Since no power is being used in the secondary, the primary acts like an inductor. The primary of a typical iron-core transformer can have an inductance of several henrys. This tends to keep the primary current very low.

In addition to the inductance, the primary winding has a certain value of AC resistance which limits the current even further. The small amount of primary current that flows with no load is called the *excitation current*. Figure 12.9 shows two functions that the exciting current must perform. First, it overcomes the AC resistance of the primary. In Figure 12.9, the resistance of the inductor is shown as a separate resistor. The resistance dissipates power in the form of heat. Secondarily, the exciting current supports the magnetic field in the core.

The XL of the primary is normally much larger than its AC resistance. Thus, the exciting current lags behind the applied voltage by almost 90°. As a result, when no current flows in the secondary, the primary of the transformer acts like an inductor.

EXCITING CURRENT OVERCOMES
THE AC RESISTANCE OF PRIMARY
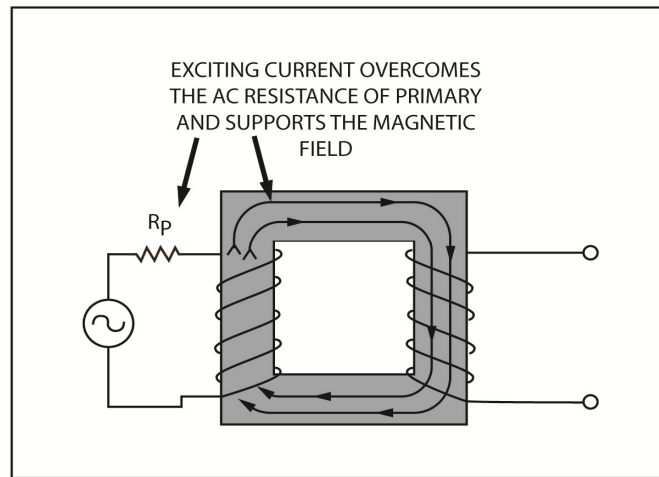AND SUPPORTS THE MAGNETIC
FIELD

Fig. 12.9

We've already learned with inductors that the current lags the applied voltage due to the counter EMF that is produced by the coil. The following is a brief review of this topic.

The applied EMF causes current to flow in the primary winding in Figure 12.9. In turn, this current establishes the magnetic field. However, as the magnetic field expands outward, it cuts the primary winding and induces a counter EMF. This counter EMF opposes the applied EMF. Thus, the primary current lags behind the applied current.

This is what happens when there is no secondary current. However, when secondary current flows, these conditions change and the transformer operates differently. Since the transformer is normally operated with the secondary load, you must understand why it operates differently when secondary current flows.

Transformer with Load

A simple transformer with a load resistor connected across the secondary winding is illustrated in Figure 12.10. When AC current flows in the primary; it induces a current into the secondary.

The polarity of the applied voltage is negative at the top of the primary and positive at the bottom in Figure 12.10. This forces current to flow down through the primary winding. When you use the left-hand rule that was developed earlier, you find that the current develops a magnetic field in the direction shown.

As the magnetic field expands outward, it induces a counter EMF into the primary winding. This counter EMF opposes the applied EMF. Although, the applied EMF forces current to flow down through the primary, the counter EMF tries to force current up through the primary. The result is a small current which flows down through the primary.
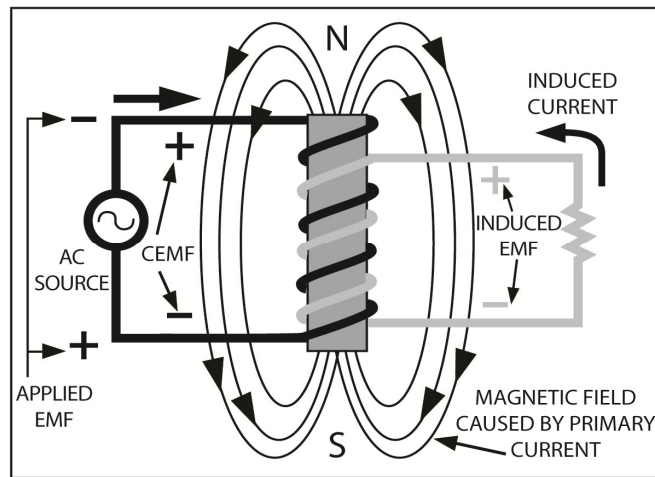
Fig. 12.10

Notice here the secondary is wound directly on top of the primary. So, the primary current's expanding magnetic field also cuts the secondary winding. Since the secondary is wound in the same direction as the primary, the EMF induced into the secondary has the same polarity as the counter EMF in the primary. Thus, the induced current in the secondary flows in the direction shown. In this configuration, there is no polarity inversion between the primary and secondary windings.

As shown in Figure 12.11, the current flow in the secondary establishes a magnetic field of its own. With the left-hand rule, you can verify that the magnetic field has the polarity shown. As the magnetic field expands, it cuts the secondary winding and induces a counter EMF. This counter EMF tries to force current to flow down through the secondary in opposition to the induced current.

This expanding flux in the secondary also cuts the primary turns and induces yet another EMF back into the primary winding. This induced EMF is in the same direction as the counter EMF of the secondary. Thus, this EMF tends to force current to flow down through the primary. Or stated another way, the current that is induced into the primary, from the secondary, aids the original primary current. This causes the primary current to increase.
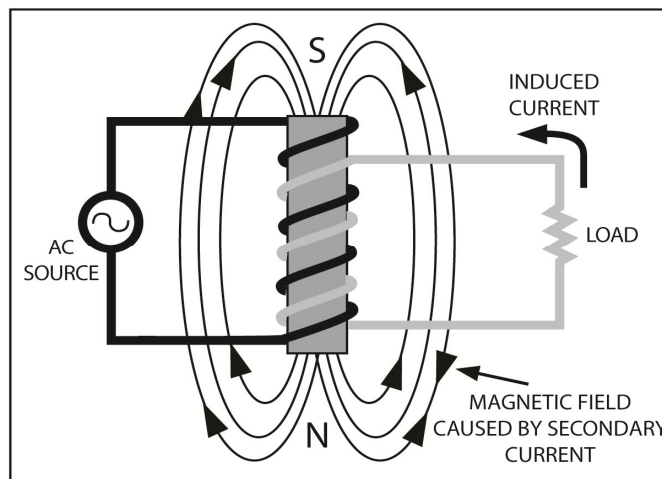

Fig. 12.11

The expanding magnetic field of the secondary causes an increase in primary current. The more current that flows in the secondary, the stronger the secondary magnetic field becomes. This

process increases the primary current. As a result, an increase in secondary current causes an increase in primary current. The exact amount of increase in each depends upon the turn's ratio.

The sum of the effects that were just described is called *mutual inductance*. The inductance is mutual because the primary induces a voltage into the secondary and, simultaneously, the secondary induces a voltage back into the primary.

This entire process is described in the step by step process below:

1. AC in the primary establishes a fluctuation magnetic field.

2. The varying flux induces a counter EMF into the primary and an EMF into the secondary.

3. The induced EMF causes current to flow in the secondary.

4. The current in the secondary establishes a magnetic field which is opposite to the field caused by the primary current.

5. The secondary flux induces an EMF back into the primary winding which opposes the counter EMF of step 2. This decreases the primary counter EMF.

6. Primary current increases because the counter EMF decreases.

Transformer Ratios

Transformers have many applications. You can use them to step-up or step-down voltage, step-up or step-down current, or make one value of impedance appear to be another value. In all these applications ratios are critical. In the first application, the ratio is that of an input voltage to an output voltage. In the second case, the ratio is that of a primary current to a secondary current. In the third case, the ratio is that of input impedance to output impedance. The number of turns in the primary winding compared to the number of turns in the secondary determines each of the ratios.

Voltage Ratio

Transformers are frequently used to step-up or step-down voltages. Many electronic devices are powered by 115 VAC at 60 Hz. A transformer can be used transform the 115 VAC to whatever value you require.
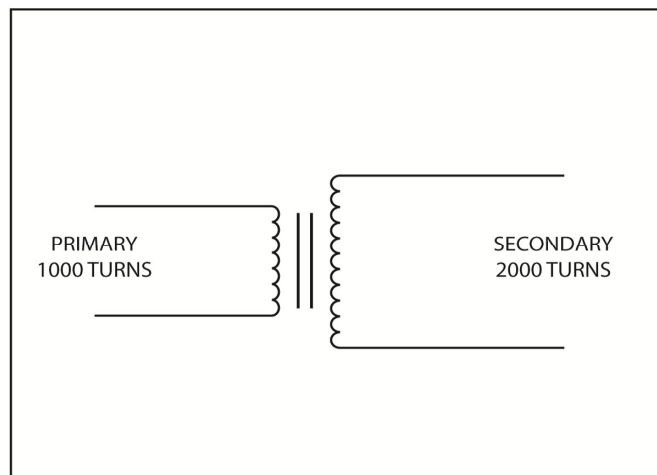

Figure 12.12

When the output, secondary voltage, is higher than the input, primary voltage, the transformer is a step-up transformer. The amount of step-up is determined by the turn's ratio of the transformer.

Figure 12.12 illustrates the turn's ration of a typical transformer. The primary consists of 1,000 turns of wire while the secondary has 2,000 turns. The turn's ratio is defined as the ratio of the number of turns in the secondary, N_S, to the number of turns in the primary, N_P. Mathematically speaking, it looks like:

$$\text{Turns ratio} = N_S/N_P$$

The turn's ratio for Figure 12.12 is:

$$\text{Turns ratio} = N_S / N_P = 2000/1000 = 2$$

This is expressed as a turn's ratio of 2 to 1 or 2:1. When the secondary has more turns than the primary, the voltage is, stepped-up. For example, when the turn's ratio is 2:1, the secondary voltage will be twice as high as the primary voltage. Therefore, the voltage ratio is equal to the turn's ratio. The voltage ratio is directly proportional to the turn's ratio and is expressed by the equation:

$$E_{S/}\ E_P = N_P\ /N_S$$

It may be more convenient to think of the turns ration as N_P/N_S

When you do this, the voltage ratio equation is:

$$E_{P/}\ E_S = N_P/N_S$$

Either of these equations can be used to find the secondary voltage when you know the turns ratio and the primary voltage. Figure 12.13 shows the 115 VAC applied to the primary. To find the secondary voltage, rearrange the formula like this:

$$E_S\ /E_P = N_s\ /N_p$$

$$E_S = N_S/N_P\ \text{x}\ E_P$$

$$E_S = 2000/1000\ \text{x}\ 115\ \text{V}$$

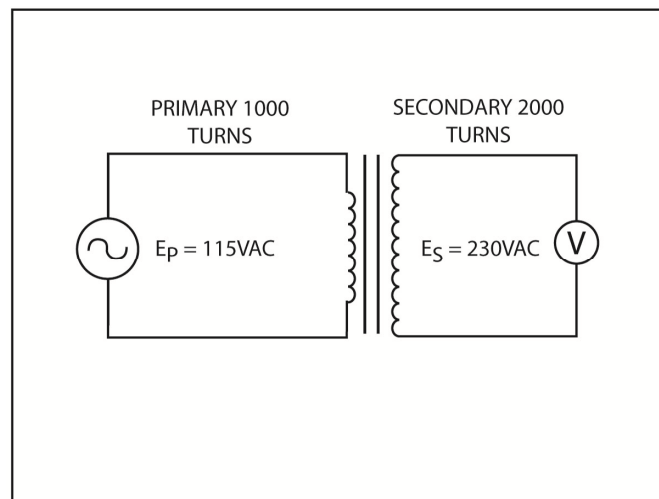$$E_S = 2\ \text{X}\ 115\ \text{V}$$

$$E_S = 230\ \text{V}$$

Fig. 12.13

With the proper turn's ratio, you can step-up the input voltage to any value you require.

Remember that AC voltages are understood to be RMS or effective values, unless otherwise specified. You should also recognize the 115 voltage value as the effective voltage that is available in most homes or industry. On many pieces of equipment, you may have noticed a power function switch that is labeled 115/230. This switch selects the desired turn's ratio, either 1:1 or 2:1.

Transformers can also be used to step-down a voltage. To accomplish this, the secondary should have fewer turns than the primary. In Figure 12.14 below, the primary has 1,000 turns while the secondary has 250 turns. The primary voltage is given as 100 VAC. Here's how you find the secondary voltage:

$$E_S / E_P = N_S / N_P$$

$$E_S = N_S / N_P \text{ x } E_P$$

$$E_S = 250/1000 \text{ X } 100V$$

$$E_S = \frac{1}{4} \text{ X } 100V$$

$$E_S = 25V$$
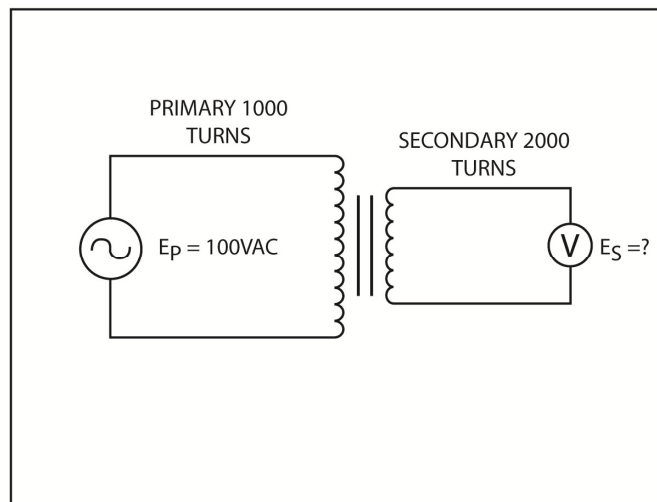
Fig. 12.14

As long as the coefficient of coupling is high and the transformer losses are low, the above equations will work correctly. To be completely accurate, the transformer must have a coupling coefficient of 1 and an efficiency of 100%. While these conditions are impossible to achieve in practice, some transformers come very close. In this section, we are assuming that we have an ideal transformer. But in the real world, transformers fall far short of the ideal transformer. General purpose transformers have efficiency ratings between 60 and 80%.

Power Ratio

When you ignore the losses in the transformer, the power in the secondary is the same as the power in the primary. So, in the ideal transformer the power is 1. Although the transformer can step-up voltage, it can't step-up power. You can never take more power from the secondary than you put in at the primary. Therefore, when a transformer steps-up a voltage, current goes down. Therefore, you can assume the output power to be the same as the input power. This is expressed by the equation:

$$P_P = P_S$$

P_P is the power in the primary, and P_S is the power in the secondary.

Current Radio

When a transformer steps-up voltage, it must at the same time step-down current. Otherwise, it would deliver more power in the secondary than is supplied by the primary. You can derive an equation for the current ratio to prove. Remember that when you ignore losses:

$$P_P = P_S$$

The formula for power is P = EI. Thus the power equals E_P x IP, while the power in the secondary equals E_S x I_S Based on this, if $P_P = P_S$:

$$E_P \text{ x } I_P = E_S \text{ x } I_S$$

The voltage ratio equation is:

$$E_S/E_P = N_S/N_P$$

Transposing:

$$E_S = N_S/N_P \text{ x } E_P$$

Next, substitute this expression for E_S in the previous equation:

$$E_P \text{ x } I_P = N_S /N_P \text{ x } E_P \text{ x } I_S$$

Now, divide both sides by E_P:

$$\cancel{E_P} \text{ x } I_P /\cancel{E_P} = N_S /N_P \text{ x } \cancel{E_P} \text{ x } I_S /E_P$$

You're left with:

$$I_P=N_S/N_P \text{ x } I_S$$

Finally, dividing by IS, bring us to:

$$I_P/I_S = N_S/N_P$$

This states that the current ratio is inversely proportional to the turn's ratio. Voltage is directly proportional to turns ratio. This makes sense, because the more turns means more wire and more wire means more resistance. Anytime resistance increases current will decrease.
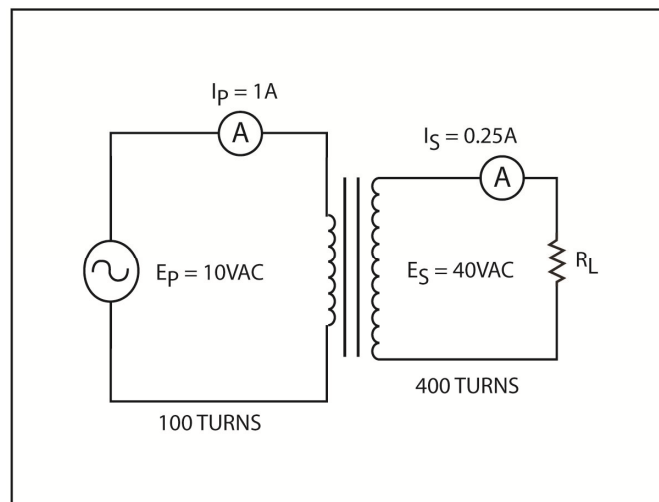

Fig. 12.15

A transformer with a turns ratio of 4:1 is shown in Figure 12.15. This means that the secondary has 4 times as many turns as the primary. Therefore, the voltage is stepped-up by a factor of four, from 10 V to 40 V. However, the current is stepped-down from 1 ampere in the primary to only 0.25 amperes in the secondary. The current ratio formula can be reworked to prove this:

$$I_P/I_S = N_S/N_P$$

If you cross multiply, you get:

$$I_S (N_S) = I_P(N_P)$$

Now divide by N_S:

$$I_S = I_P(N_P)/N_S$$

$$I_S = N_P /N_S \text{ x } I_P$$

$$I_S = 100/400 \text{ x } 1A$$

$$I_S = ¼ \text{ x } 1A$$

$$I_S = 0.25A$$

Transformers can also step-up current. But in this process, voltage must be stepped-down. To step-up current, the primary must have more turns than the secondary as shown in Figure 12.16. The secondary current is:

$$I_S = N_P/N_S \text{ x } I_P$$

$$I_S = 3000/300 \text{ x } 1A$$
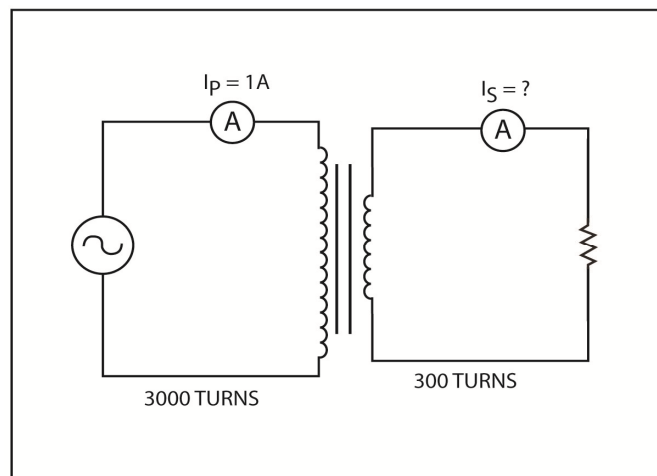
$$I_S = 10 \text{ X } 1A$$

$$I_S = 10A$$

Fig. 12.16

Solving Transformer Problems

Now, the uses of the voltage and current ratio formulas are understood, you can solve a wide variety of transformer equations. The circuit in Figure 12.17 has the number of turns, I_S, and the value of R provided. Now, we need to find the values for E_P and I_P.
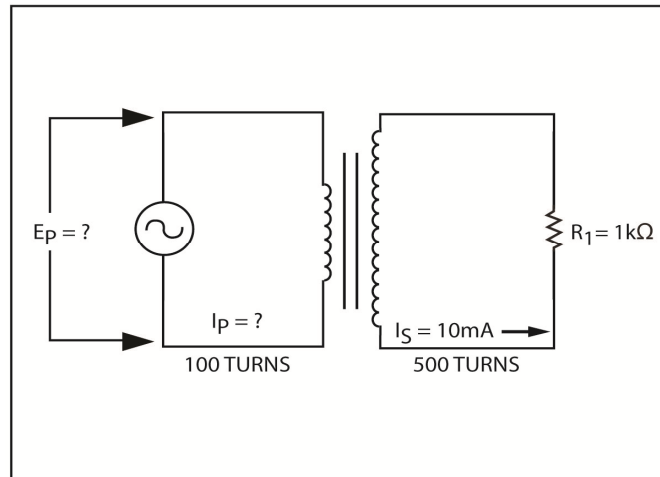
Fig. 12.17

I_P can be determined immediately, since I_P and the turn's ratio are given:

$$I_P / I_S = N_S / N_P$$

$$I_P = N_S / N_P \text{ x } I_S$$

$$I_P = 500/100 \text{ x } 10 \text{ mA}$$

$$I_P = 5 \text{ X } 10 \text{ mA}$$

$$I_P = 50 \text{ mA}$$

The turn's ratio is known, so you can find E_P if you know E_S:

$$E_S = I_S(R_1)$$

$$E_S = 10 \text{ mA x } 1\Omega$$

$$E_S = 10 \text{ V}$$

Now find E_P:

$$E_S/E_P = N_S/N_P$$

Cross multiply:

$$E_S (N_P) = E_P (N_S)$$

Dividing by NS provides:

$$E_S (N_P)/N_S = E_P$$

Rearranging the equation provides:

$$E_P = N_P /N_S \text{ x } E_S$$

$$E_P = 100/500 \text{ x } 10V$$

$$E_P = 1/5 \text{ x } 10V$$

$$E_P = 2V$$

Another problem is illustrated in Figure 12.18. Here, turns ratio, the primary voltage, and the power dissipated in the secondary circuit are given. You want to find the secondary voltage, the secondary current, and primary current, and the value of R_1.
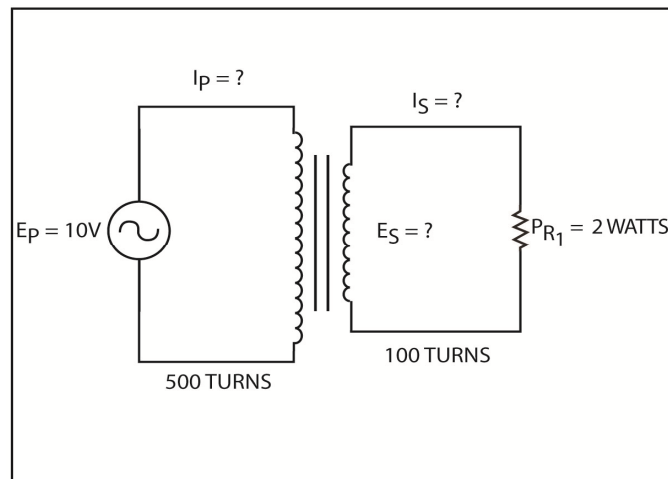
Fig. 12.18

Because the turns ratio and E_P are given, you can compute the value of E_S:

$$E_S/E_P = N_S/N_P$$

$$E_S = N_S/N_P \text{ x } E_P$$

$$E_S = 100/500 \text{ x } 10V$$

$$E_S = 1/5 \text{ x } 10V$$

$$E_S = 2V$$

E_S is known, you can compute I_S:

$$P_S = E_S \text{ X } I_S$$

$$I_S = P_S / E_S$$

$$I_S = 2W/2V$$

$$I_S = 1A$$

Now the I_S and the turn's ratio is computed, you can equate I_P:

$$I_P /I_S = N_S/N_P$$

$$I_P = N_S / N_P \text{ x } I_S$$

$$I_P = 100/500 \text{ x } 1A$$

$$I_P = 1/5 \text{ X } 1A$$

$$I_P = 0.2A$$

Ohm's Law is used compute the value of R_1:

$$R_1 = E_S/I_S$$

$$R_1 = 2V/1A$$

$$R_1 = 2\Omega$$

You can also rearrange the power formula to find the same value:

Impedance Ratio

One of the most important applications of a transformer is impedance matching. Maximum power is transferred from a generator to a load, when the impedance of the generator matches the impedance of the load. When impedances do not match, power is wasted.

There are many cases in electronics in which the impedance of the signal source or generator does not match the load which it must drive. For example, a transistor amplifier stage might be most efficient when it drives a 100-ohm load. Nevertheless, the amplifier may be required to drive a 4-ohm speaker. This is a mismatch that results in wasted power and inefficient operation.

A transformer can correct this mismatched impedance. The transformer can make one value of impedance appear to be another value. In the above example, a transformer is placed between the transistor amplifier and the speaker. When you choose the proper turn's ratio, the transformer can make the 4-ohm speaker appear to be a 100-ohm load to the transistor amplifier.

You have seen that the voltage or current step-up of a transformer depends upon the turn's ratio. The impedance matching capability of a transformer also depends upon the turn's ratio. However, the impedance ratio is equal to the turns ratio squared. That is:

$$Z_P/Z_S = (N_P/N_S)^2$$

Z_P is the impedance of the primary circuit, Z_S is the impedance of the secondary circuit, and N_P/N_S is the primary to secondary turns ratio.

Rearrange the formula to make it easier to understand:

$$N_P/N_S = \sqrt{Z_P/Z_S}$$

You can use this equation to solve impedance-matching problems. The problem is to find a turn's ratio that matches a 100-ohm generator (such as the transistor amplifier) to a 4-ohm load (such as a speaker). You can solve this type of problem with the formula:

$$N_P/N_S = \sqrt{Z_P/Z_S}$$
$$N_P/N_S = \sqrt{100/4\,\Omega}$$
$$N_P/N_S = \sqrt{25}$$
$$N_P/N_S = 5$$

The turn's ratio must be 5:1. The primary must have 5 times as many turns as the secondary.

Impedance matching is one of the most important applications of a transformer. With the proper turn's ratio, transformers can match a wide range of impedances.

Transformer Losses

Transformers which are used in electronic circuits are very efficient devices. Efficiency of ninety percent or better are normal in transformers. All transformers have some losses. In many cases, these losses dictate transformer design. Power transformers in particular are designed to minimize losses. The losses are separated into several categories.

Core Losses

In power transformers, the largest loss occurs in the transformer's core. Special construction techniques help eliminate much of this. Core losses can be divided into two separate parts.

Eddy Current Losses

The cores of power transformers are generally made of soft iron or steel. Because iron and steel are good conductors, and are ferromagnetic, a current can be induced into the core. This occurs when the core is subjected to a moving magnetic field. As you saw, a moving magnetic field is a requirement in all transformers. Unless manufacturers take special precautions, large circulating currents are induced into the core of a transformer. These induced circulating currents are called eddy currents.

The eddy currents induced into the core are illustrated below in Figure 12.19. When alternating current flows through the winding, a changing magnetic field develops around the core. As this field expands and contracts, it induces a voltage into the core. The induced EMF causes eddy currents to slow as shown. These eddy currents are sometimes referred to as skin effect because they flow along the conductor's surface core by changing magnetic field.
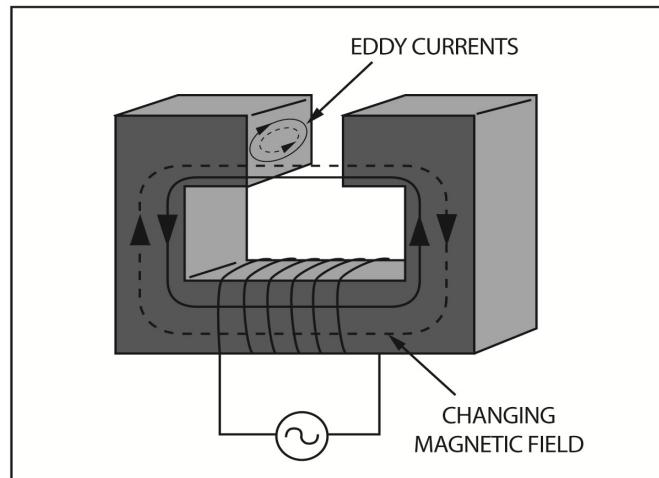

Fig. 12.19

Manufacturers can change the construction of the core to reduce eddy currents. The core is a solid block of metal in the figure above. Because the cross sectional areas of the core is large, it has very little resistance and large eddy currents flow.

The eddy currents produce a power loss that is proportional to the current squared (P = I2R). When you reduce the eddy currents, the power loss is less.

If the core is made of many thin sheets of metal rather than a solid block of metal, eddy currents can be further reduced. Figure 12.20 illustrates how this reduces the eddy currents. The top of Figure 12.20 shows large eddy currents flowing through the low-resistance solid core. However, you can use several thin sheets to form a core that has the same magnetic characteristics as shown in the bottom section of Figure 12.20.

The individual sheets are coated with an insulating varnish so that no current can flow between the sheets. Thus, any eddy currents that are produced are restricted to a single sheet of metal. Because the cross section area of a sheet is quite small, the resistance of each sheet is relatively high. This high resistance keeps the magnitude of the eddy currents low. Consequently, the power loss is much lower when the core is made of thin laminated (insulated) sheets.
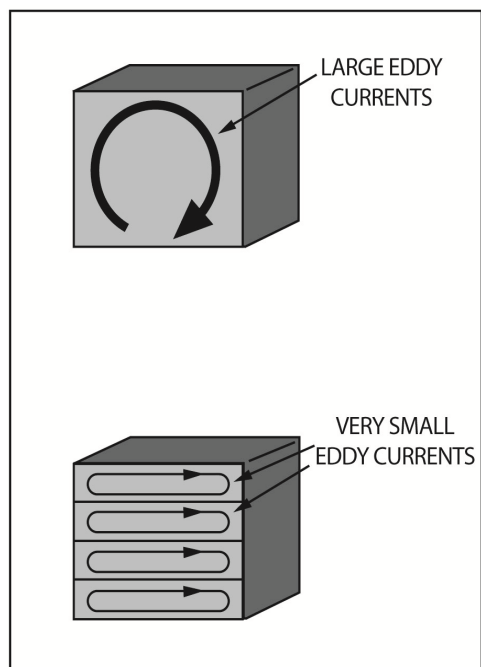
Fig. 12.20

In Figure 12.21, the thin sheets that make up the core are called laminations are shown. The lamination gets its name from its shape. Frequently, an iron core is made up of a combination of E and I shaped laminations. Remember, the purpose of laminating a core is to reduce the power loss that is caused by eddy currents.
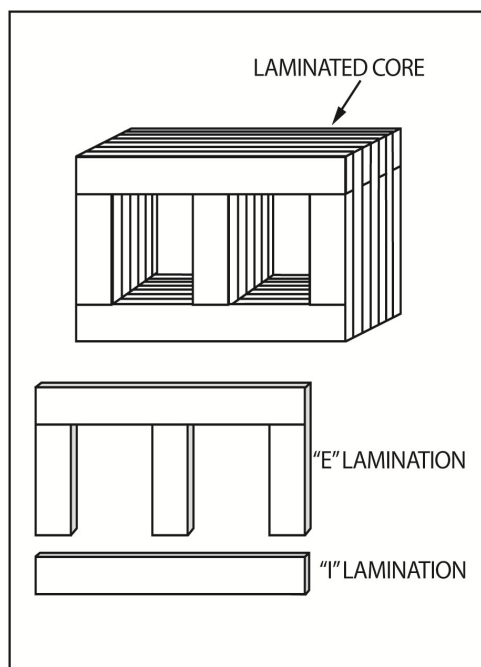
Fig. 12.21

Hysteresis

Another type of loss that occurs in the core of a transformer is called hysteresis. When iron is not magnetized, its magnetic domains are arranged in a random pattern. However, when a magnetizing

force is applied, the domains are lined up by the magnetic field. When the magnetic field reverses, the domains must also reverse their alignment. In a transformer, the magnetic field reverses direction many times each second. The frequency of the applied AC source determines the number of reversals per second. For example, with a 60-Hz source, the magnetic field reverses 120 times per second. Remember, the magnetic field reverses twice each cycle. When it reverses direction, the domains must overcome friction and inertia. While it does this, a certain amount of power is dissipated in the form of heat. This power loss is referred to as the hysteresis loss.

The terms friction and inertia refer to the basic laws of physics that state, a body at rest tends to stay at rest, and a body in motion tends to stay in motion. So, anytime you have relative motion there is friction and inertia. They are a form of resistance to motion and they do cause power to be dissipated.

Soft iron, under normal circumstances has a high hysteresis loss. The hysteresis loss in steel is lower than soft iron. Some large power transformers use a special type of metal called silicon steel because it has a low hysteresis loss.

Losses through hysteresis increase as frequency increases. An iron-core transformer that has a small hysteresis loss at low frequencies may have a large hysteresis loss at higher frequencies. Hysteresis loss is directly proportional to frequency.

Copper Loss

The resistance of the copper wire in the primary and secondary windings causes this loss. A transformer winding can consist of hundreds of turns of fine copper wire.

The amount of copper loss is proportional to the current squared. When the current through a transformer doubles, the copper loss increases by a factor of 4. The formula $P=I^2R$

Copper loss by be reduced by increasing the size of the copper wire you use for the windings. The larger the diameter of the wire, the smaller its resistance. Dissipated power and resistance are directly proportional to each other. When you decrease the resistance, you decrease the I^2R loss. Another method you can use to reduce copper loss or I^2R loss is to keep the current in the transformer as low as possible.

External Induction Loss

Often, external conductors are cut as the magnetic field expands and contracts around the transformer. When a current is induced into an external conductor, some power is taken from the transformer circuit. In most cases, the power that is lost by external induction is so small that you can ignore it. However, the voltage that is induced into outside circuits can be bothersome. For example, in a sensitive amplifier circuit, the unwanted induced voltage from a transformer may interfere with the signal you are trying to amplify.

Shielding can reduce interference that is caused by magnetic induction. Often, sensitive circuits are placed inside a metal shield which prevents stray magnetic fields from reaching the circuits. Also, transformers themselves are often placed in thin metal housings to prevent magnetic fields from escaping.

Earlier, you used a high-permeability material, soft iron to form a core to concentrate the magnetic force lines into a magnetic field close to the inductor. In this case, the flux lines are prevented from cutting the external conductor. These shields are called permeability shields. Remember, magnetic flux lines cannot be blocked, but they can be rerouted.

Transformer Efficiency

Due to transformer losses, more power is applied to the primary of the transformer than is available for use in the secondary. All transformers have power losses. Hence, the efficiency of a transformer is always less than 100%.

The ratio of output power to input power is the transformer's efficiency. So, when a transformer has an input power of 120 watts and an output power of 100 watts, its efficiency is:

$$\text{Efficiency} = \text{power output} / \text{Power input}$$

$$= 100 \text{ W} / 120 \text{ W} = 0.83333$$

Efficiency is normally stated in terms of a percentage. Therefore, you must multiply the decimal fraction by 100 to convert it to a percentage. The input power is the primary power. The output power is the secondary power. The formula for a transformer's percent of efficiency is:

$$\% \text{ efficiency} = P_S/P_P \times 100$$

P_P is the power in the primary, or input power. P_S is the power in the secondary, or the output power. Therefore, in the above example,

$$\% \text{ efficiency} = P_S/P_P \times 100$$

$$\% \text{efficiency} = 100W/120W \times 100$$

$$\% \text{efficiency} = .8333 \times 100$$

$$\% \text{efficiency} = 83.33\%$$

Transformer Applications

Transformers are versatile devices. They are used to step-up voltage, step-down voltage step-up current, step-down current, and match impedance. Also, they can produce 180° phase shift, provide two signals which are 180° out of phase, and isolate one circuit from another. They can pass AC while they block DC. They can also provide several signals at various voltage levels. You will now look at some of these applications in more detail.

Power Distribution

One of the most important applications of transformers is to transmit power over long distances. Often, the power generating stations are located near coal fields or dams which are usually far from the cities where the electrical power is needed. Therefore, the electrical energy must be transported over great distances by way of transmission lines. The transformer plays a major role in transmitting this energy efficiently.

Long distances transmission lines are generally made of aluminum. Copper lines have better electrical characteristics but are too expensive, too heavy, and lack structural strength. You will recall that aluminum has a higher resistivity than copper. Consequently, power losses in aluminum lines are high, unless special precautions have been taken.

Most transmission line power loss is caused by the resistance of the line. Recall that $P = I^2R$. Therefore, the amount of power loss is proportional to the resistance of the line and to the square of the current. Obviously then, the easiest way to reduce the power losses in the line is to keep the current as low as possible.

Let's assume a generating station produces 12,000 volts at 10 amperes. Assume that these 120,000 watts of power are transmitted over a transmission line that has a resistance of 100 ohms. When transmitted as 12,000V at 10A, the power loss in the line is:

$$P = I^2R$$

$$P = (10A)^2 \text{ x } 100 \text{ ohms}$$

$$P = 100 \text{ x } 100$$

$$P = 10,000 \text{ watts}$$

A transformer allows you to transmit the 120,000 watts as 120,000V at 1A. In this case, the power loss is:

$$P = I^2R$$

$$P = (1A)^2 \text{ x } 100 \text{ ohms}$$

$$P = 1 \text{ x } 100$$

$$P = 100 \text{ watts}$$

When you step the current down by a factor of 10, the power loss reduces by a factor of 100. For this reason, power is transmitted over great distances at a very high voltage levels. Upon reaching its destinations, the electrical power is stepped-down in voltage to the values required in homes and by industry.

Electronic Applications

In electronic devices, transformers are used to step-up or step-down voltage. Many electronic devices require 115 VAC for power. Most of the devices have a power transformer which steps the voltage up or down, as required. In transistorized and integrated circuit equipment, the AC line voltage is usually stepped-down then changed to DC by a process called rectification. In older vacuum-tube equipment, the line voltage is usually stepped-up then rectified. Vacuum tubes require higher DC voltages than transistors and integrated circuits. As you can see, you can use transformers to make the line voltage compatible with both types of equipment.

Transformers are also used as impedance-matching devices. They can match the impedance of one circuit to that of another. The impedances must be matched for maximum power to be transferred from one circuit to another circuit.

Phase Shifting

Depending on how the transformer is wound, it provides either a 180° phase shift or no phase shift. This means that the voltage in the secondary is either in phase or 180° out of phase with the voltage in the primary. In some applications, the phase shift is unimportant while in other applications it is extremely important. Figure 12.22 shows a transformer in which the input signal is in phase with the output signal.
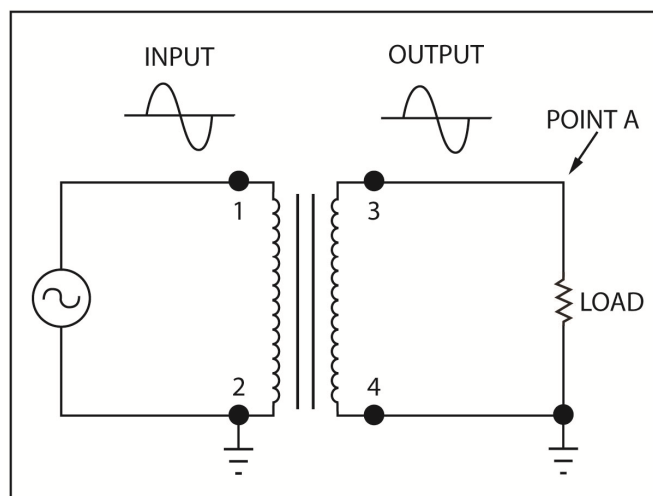
Fig. 12.22

The phase relationship between the windings of the transformer is sometimes indicated on schematic diagrams by dots as shown in Figure 12.23. The ends of the windings which are marked by dots are in-phase. Therefore, the voltage at pin 3 is in phase with the voltage at pin 1. Figure 12.24 shows a transformer that is wound differently. Here, the voltage at pin 4 is in phase with the voltage at pin 1. Stated another way, the voltage at pin 3 is 180° out of phase with the voltage at pin 1.

Fig. 12.23

Fig. 12.24

An in-phase output or 180° out-of- phase output from either type of transformer can be obtained as illustrated in Figure 12.25. Note that you can reverse the phase simply by interchanging the leads to the load.
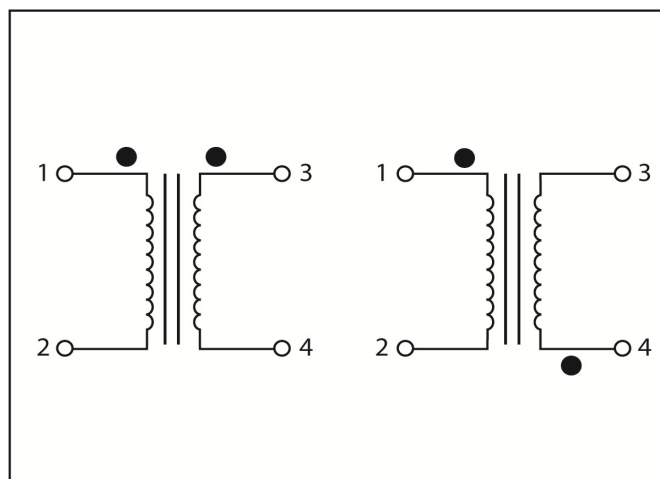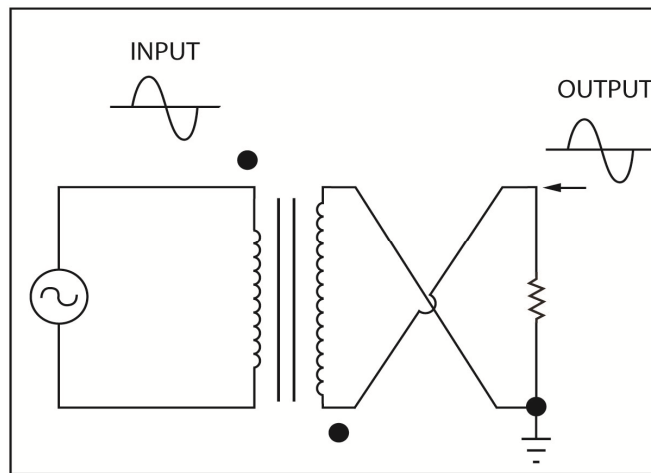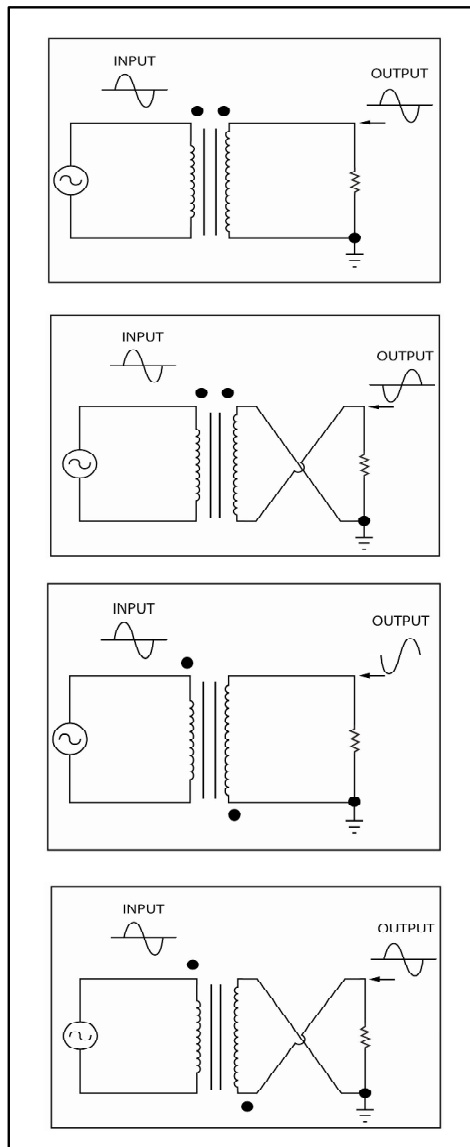
Fig. 12.25

Phase Splitting

Some circuits require two AC signals of equal amplitude, but 180° out of phase. A transformer can be used to provide the two out-of-phase signals. Figure 6-15 shows a transformer with the center-tapped secondary. This simply means that the center of the secondary is brought out to a terminal which is labeled pin 4. In this Figure, the terminal is grounded. The dots indicate that the voltage at pin 3 is in phase with the voltage at pin 1. If you ignore the center tap, the voltage at pin 5 must be 180° out of phase with the voltages at pins 1 and 3. When the center tap is grounded, two signals which are equal in amplitude and 180° out of phase exist at opposite ends of the secondary winding. Transformers are often used to produce two equal amplitude signals that are 180° out of phase.

Isolation

Transformers are also used to isolate one circuit from another. An AC device that does not use a power transformer often has a metal chassis that connects to one side of the AC power line. Anyone who touches this chassis and ground at the same time can receive an electrical shock.

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However, a power transformer isolates the chassis from the input AC line. When you separate the circuit from the input power, you greatly reduce the possibility of accidental shock.

Frequently, technicians repair equipment without transformers. When the hot chassis is removed from its plastic or wooden cabinet, the possibility of accidental shock increases. To safeguard himself, the technician places an isolation transformer between the AC line and the chassis. The isolation transformer has a turn's ration of 1 to 1. That is, it takes 115 VAC from the line and delivers 115 VAC to the equipment. This isolates the chassis from the AC line and provides additional protection from accidental shock.

Autotransformer

This is a special type of transformers with only one winding. The winding has at least three electrical connection points called taps Part of this coil is used as the primary, while another part is used as the secondary. Generally, part of the coil is used as both primary and secondary.

Figure 12.26 shows an autotransformer being used to step-down the applied voltage. Here, the entire winding serves as the primary. The lower half of the coil is used as the secondary winding. Because there are fewer turns in the secondary than in the primary, the voltage is stepped-down and the current is stepped-up.
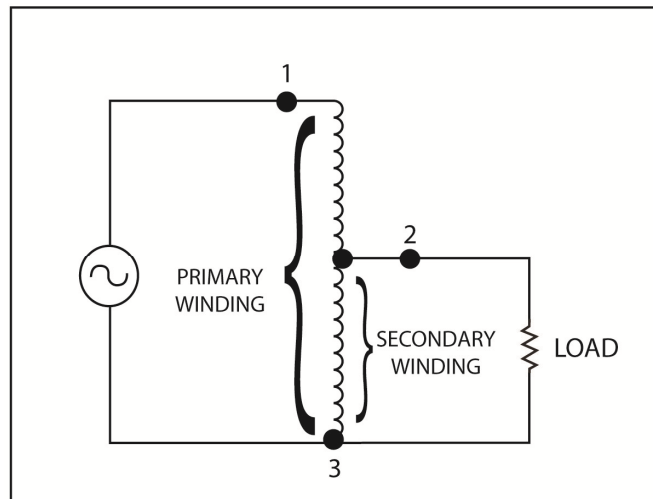

Fig. 12.26

These transformers can be turned around to step-up voltage as illustrated in Figure 12.27 below. Here, the lower half of the coil is used as the primary, while the entire coil is used as the secondary. Since the secondary has more turns, the transformer steps-up voltage and steps-down current.
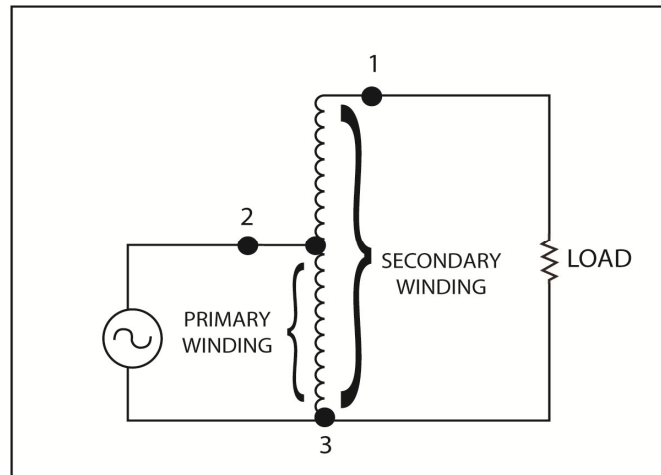
Fig. 12.27

In Figure 12.28, the autotransformer is compared with a conventional transformer. The conventional transformer in figure 6-17A steps the applied voltage down from 120 VAC to 20 VAC. This requires a turn ratio of 6:1. If you ignore losses, the current steps-up from 1A to 6A.
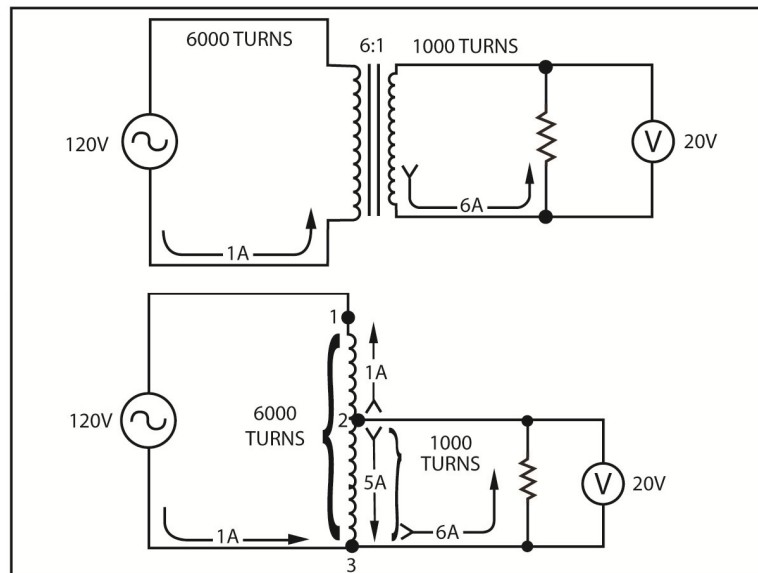
Fig. 12.28

The bottom section of Figure 12.28 shows how you can accomplish the same job with an autotransformer. The tap at pin 2 is placed at 1,000 turns. Thus, the primary, in this case the entire coil, has 6,000 turns. Only 1,000 of the turns are used for the secondary. Note that 6 amperes flows in the load, but only 5 amperes flows through the secondary winding. The reason for this is that the current in the secondary winding flows in the opposite direction to the current flowing in the primary. Thus, the 1 ampere primary current subtracts from the 6 amperes of secondary current.

This example illustrates the advantages of an autotransformer. Notice, fewer turns of wire are required in an autotransformer. Also, since the current in the secondary winding is lower, the I^2R loss is lower. In many cases, the autotransformer is also easier to construct and therefore less expensive. Its main disadvantage is that the secondary is not isolated from the primary. It is usually used in electronic circuits that have low-current and high-frequency requirements.

A special type of autotransformer is shown if Figure 12.27 The load is connected between the movable arm and the bottom of the coil. You can move the arm up or down to change the turn's ratio. This causes a corresponding change in voltage across the load. You can vary the output voltage from about 0 VAC to over 130 VAC. This device is called a *variable autotransformer.*
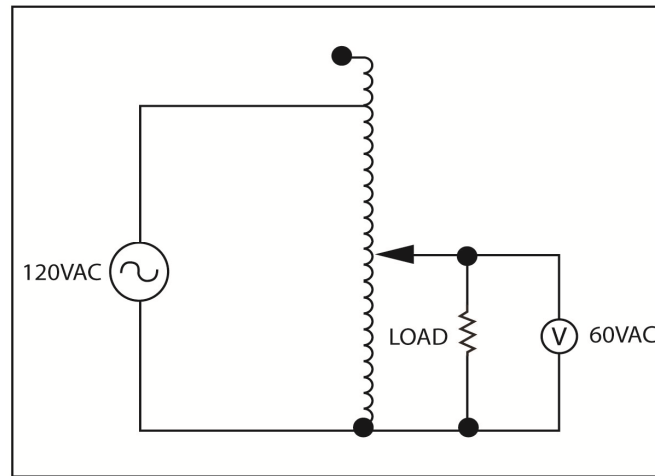
Fig. 12.27

The autotransformer gets its name because it is usually used in the audio frequency range. The audio frequency range is considered to extend from approximately 10 hertz to 25,000 hertz. Due to their inductive reactance, transformers have limited uses in high-frequency circuits. The exception is the special tuned tanks in IF and RF applications. These special signal-coupling transformers are used in extremely low-current applications. This coupling requirement is usually in the microampere range.

Appendix A
Scientific Notation

In electronics it is common to deal with both very large and very small numbers. An example of a very large number is the speed at which electricity travels. It travels at the speed of light which is approximately 1,000,000,000 feet per second or about 300,000,000 meters per second. As for very small numbers, consider the size and weight of an electron. Scientists believe that an electron has a diameter of approximately 0.000,000,000,0022 inch and a weight of about 0.000,000,000,000,000,000,000,000,0009 gram. Sometimes, you perform arithmetic with numbers such as these. To simplify such arithmetic, a shorthand method called scientific notation has been developed to express numbers. The following programmed instruction sequence serves as an introduction to scientific notation.

---

1. As you learned above, scientific notation is a shorthand method that makes it easier to express numbers. While you can use scientific notation to express any number, this technique is particularly helpful in when you need to express very large numbers and very _____ numbers.

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2. (small) Scientific notation is based upon a concept called powers of ten. Thus, in order to understand a scientific notation you should first learn what powers of _____ means.

---

3. (ten) In mathematics, you multiply the numbers times itself one or more times to raise a number to a power. Thus, to raise 5 to the second power, you multiply 5 times itself. That is, 5^2 is 5 x 5 = _____.

---

4. (25) Also, 5 to the third power is the same as 5 x5 x 5 = _____.

---

6. (fourth) The above examples use the powers of five. However, you can raise any number to a power by the techniques of multiplying it times itself the required number of times. Thus, the powers of two looks like this:

    2 to the second power equals 2 x 2 = 4

    2 to the third power equals 2 x 2 x 2 = 8

---

2 to the fourth power equals 2 x 2 x 2 x 2 = 16

2 to the fifth power equals 2 x 2 x 2 x 2 x 2 = 32

2 to the sixth power equals 2x2x2x2x2x2 =_____

7. (64) In mathematics, the number which is raised to a power is called the base. If 5 is raised to the third power, you consider the 5 the _____.

8. (base) The power to which the number is raised is called the exponent. If 5 is raised to the third power, the exponent is 3. In the same way, if 2 is raised to the sixth power, 2 is the base while 6 is the _____.

9. (exponent) There is a shorthand method for writing "2 raised to the sixth power." It is:

$$2^6$$

Note that you write the exponent as a small number at the top right of the base.

Therefore, in the example 3^4, 3 is the _____ while 4 is the _____.

10. (base, exponent) You read the number 3^4 as 3 "raised to the fourth power." It is equal to:

$$3 \text{ x } 3 \text{ x } 3 \text{ x } 3 = 81$$

you read the number 4^6 as _____.

11. (4 raised to the sixth power) Scientific notation uses powers of ten. Several powers of 10 are listed below:

$10^2 = 10 \text{ x } 10 = 100$

$10^3 = 10 \text{ x } 10 \text{ x } 10 = 1000$

$10^4 = 10 \text{ x } 10 \text{ x } 10 \text{ x } 10 = 10,000$

$10^5 = 10 \text{ x } 10 \text{ x } 10 \text{ x } 10 \text{ x } 10 = 100,000$

$10^6 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 =$ _____.

12. (1,000,000) Multiplication by 10 is extremely easy since all you have to do is add one zero for each multiplication. Another way to look at it is that multiplication by ten is the same as moving the decimal point one place to the right. Thus, you can find the equivalent of 10^2 by multiplying $10 \times 10 = 100$; or simply add a 0 after 10 to form 100; or by moving the decimal point on place to the right to form 10.0. = 100. In any event 10^2 is equal to _____.

13. (100) There is a simple procedure for converting a number expressed as a power of ten to its equivalent number. You simply write down a 1 and after it write the number of zeros that are indicated by the exponent. For example, 10^6 is equal to 1 with 6 zeros after it. In the same way 10^{11} is equal to 1 with _____ zeros after it.

14. (11) This illustrates one of the advantages of power of ten. It is easier to write and remember 10^{21} than its equivalent number: 1,000,000,000,000,000,000,000. Try it yourself and see if it isn't easier to write 10^{35} than to write its equivalent number of :

_____.

15. (100,000,000,000,000,000,000,000,000,000,000,000) In the above examples, you converted a number that is expressed in powers of ten to its equivalent number. You will now convert these numbers in the opposite direction. Remember that you must express the number with 10 as the base with the appropriate exponent. You determine the exponent simply by counting the number of zeros which fall on the right side of the 1. thus, 1,000,000 becomes 10^6 because there are 6 zeros in the number. In the same way, 10,000,000,000 is expressed as _____.

16. (10^{10}) To be sure you have the right idea, study each of the groups below. Which group contains an error? _____

| Group A | Group B | Group C |

$10^6 = 1,000,000$	$1000 = 10^3$	$10^7 = 10,000,000$
$10^2 = 100$	$10,000 = 10^4$	$10^9 = 1,000,000,000$
$10^9 = 1,000,000,000$	$100 = 10^2$	$10^{10} = 10,000,000,000$

17. (Group C) there are two special cases of powers of ten which require some additional explanation. The first is 10^1. Here the exponent of 10 is 1. If you follow the procedure in Frame 13 you find that $10^1 = 10$. That is, you put down a 1 and add the number of zeros indicated by the exponent. Thus $10^1 =$ _____.

18. (10) The other special case is 10^0. Here, the exponent is 0. One again you follow the procedure in Frame 13. Here again, you write down a 1 and add the number of zeros indicated by the exponent. However, since the exponent is 0, you add no zeros. Thus, the equivalent number of 10^0 is 1. That is $10^0 =$ _____.

19.)1) Any base number with an exponent of 1 is equal to the base number. Any base number with an exponent of 0 is equal to 1. Thus, $X^1 =$ _____ and $X^0 =$ _____.

20. (X,1)   In the above examples, the exponents were positive number. For simplicity, the plus sign was omitted, Therefore, 10^2 is the same as 10^{+2}. Also, 10^6 is the same as _____.

21. (10^{+6}) Positive exponents represent numbers larger than 1. Thus, numbers like 10^2, 10^7, and 10^{15} are greater than one and require _____ exponents.

22. (positive) Numbers smaller than one are indicated by negative exponents. Thus, numbers like 0.01, 0.0001, and 0.00001 are expressed as negative powers of ten because these numbers are less than _____.

23. (1) Some of the negative powers of ten are listed below:

    $10^{-1} = 0.1$

    $10^{-2} = 0.01$

    $10^{-3} = 0.001$

    $10^{-4} = 0.0001$

$10^{-5} =$ _____

---

24. (0.00001)   A brief study of this list shows that this is simply a continuation of the list shown earlier in frame 11. If you combine the two lists in a descending order, the result looks like this:

$10^{6} = 1{,}000{,}000$

$10^{5} = 100{,}000$

$10^{4} = 10{,}000$

$10^{3} = 1{,}000$

$10^{2} = 100$

$10^{1} = 10$

$10^{0} = 1$

$10^{-1} = .01$

$10^{-2} = 0.01$

$10^{-3} = 0.001$

$10^{-4} = 0.0001$

$10^{-5} =$ _____

---

25. (0.00001) You can think of the negative exponent as an indication of how far the decimal point must be moved to the left to obtain the equivalent number. Thus, you can develop the procedure for converting a negative power of ten to its equivalent number. The procedure is to write down the number 1 and move the decimal point to the left the number of places that are indicated by the negative exponent. For example, 10^{-4} becomes:

0.0001. or 0.0001

Notice that the -4 exponent indicates that the decimal point must be moved _____ places to the _____.

26. (4, left) Up to now you used powers of ten to express only those number which are exact multiples of ten such as 100, 1000, 10,000 etc. obviously, if these were the only numbers which could be expressed as powers of ten, this method of writing numbers would be of little use.   Actually, any _____ can be expressed in powers-of-ten notation.

27. (number) The technique is shown by an example. If you can represent 1,000,000 as 10^6, then you can represent 2,000,000 as 2 x 10^6. That is, you express the quantity as a number multiplied by the appropriate power of ten. As another example, 2,500,000 = 2.5 x 10^6. Also 3,000,000 = _____

28. (3 x 106) In the same way you can write 5,000 as 5 x 10^3. Some other examples are:

$$200 = 2 \times 10^2$$

$$1500 = 15 \times 10^2$$

$$22,000 = 22 \times 10^3$$

$$120,000 = 12 \times 10^4$$

$$1,700,000 = 17 \times 10^5$$

$$9,000,000 = \underline{\hspace{2cm}}$$

29. (9 x 10^6) By the same token, you can convert in the opposite direction. Thus, 2 x 10^5 becomes 2 x 100,000 or 200,000. Also 2.2 x 10^3 = 2.2 x 1000 = 2.200. And, 66 x 10^4 = _____.

30. (660,000) You may have noticed that when you use powers of ten there are several different ways to write a number. For example, you can write 25,000 as 25 x 103 because 25 x 1000 equals 25,000. However, you can also write it as 2.5 x 104 because 25 x 10,000 equals 25,000. You can even write it as 250 x 100 since 250 x 100 = 25,000. In the same way, 4.7 x 104, 47 x 103,

and 470 x 102 are three different way of writing the number _____.

31. (47,000) Numbers smaller than one are expressed as negative powers of ten in much the same way. Thus, you can express .0039 as 3.9×10^{-3}, 39×10^{-4}, or $.39 \times 10^{-2}$. Also, 6.8×10^{-5}, 8×10^{-6}, and $.68 \times 10^{-4}$ are three different ways of expressing the number _____

32. (.000068) As you can see, there are several different ways in which you can write a number as a power of ten. Scientific notation is a way of using powers of ten so that all umbers can be expressed in a uniform way. To see exactly what scientific notation is, consider the following examples of numbers that are written in scientific notation:

$$6.25 \times 1018$$

$$3.7 \times 106$$

$$4.0 \times 102$$

$$6.8 \times 10\text{-}4$$

$$3.9 \times 10\text{-}6$$

$$2.2 \times 10\text{-}12$$

Note that the numbers range from a very large number to an extremely small number. And yet, all of these numbers are written in a uniform way. This method of writing numbers is called scientific _____

33. (notation) The rules for writing a number in scientific notation are quite simple. First, you always place the decimal point after the first digit on the left which is not a zero. Therefore, the final number appears in this form: 6.25. 7.3, 9.65, 8.31, 2.0 and so forth. It must never appear in a form such as: .625, 73, 96.5, .831 or 20. Thus, there is always one and only one digit on the _____ side of the decimal point.

34. (left) The second rule involves the sign of the exponent. If the original number is greater than 1, the

exponent number must be positive. If the number is less than 1, the exponent must be negative. Thus, 67,000 requires a positive exponent but 0.00327 requires a _____ exponent.

35. (negative) Finally, you determine the magnitude of the exponent by the number of places that the decimal places is moved. For example, 39,000.0 is expressed as 3.9×10^{-4} because the decimal point must be moved 4 places in order to have only one digit to the left of it. With this rule, 6,700,000,000 is expressed as 6.7 x _____.

36. (109) The number 0.00327 is expressed as 3.27 x 10-3. Here, the decimal point is moved 3 places in order to have one digit to the left of it. Likewise, 0.00027 is expressed as 2.7 x _____.

37. (10-4) to be sure you have the idea, look at the groups of numbers below. Which of the following groups contains a number that is not expressed properly in scientific notation? _____

Group A	Group B	Group C
6.25×10^{18}	1.11×10^{11}	69×10^{10}
3.75×10^{-9}	-3.1×10^{7}	3.4×10^{7}
4.20×10^{1}	-3.1×10^{-2}	39.5×10^{2}
7.93×10^{0}	2.00×10^{2}	6.0×10^{4}

38. (Group C) The number 39.5 x 102 is not written in scientific notation because there are two digits on the left side of the decimal point. The minus signs in Group B may have confused you. Although, it has not been mentioned, negative numbers can also be expressed in scientific notation. Thus, a number like -6,200,000 becomes -6.2 x 106.   All of the rules previously stated hold true except that now you place a _____ sign before the number.

39. (minus)   Small negative numbers are handled in the same way. Thus, -0.0092 becomes -9.2 x 10-3. The minus sign before the number indicates that this is a negative number. The minus sign before the exponent

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indicates that this number is less than _____.

40. (1) Listed below are numbers which are converted to scientific notation. Which one of these groups contains an error? _____.

Group A	Group B	Group C
$2,200 = 2.2 \times 10^3$	$119,000 = 1.19 \times 10^5$	$119 = 1.19 \times 10^2$
$32,000 = 3.2 \times 10^4$	$1,633,000 = 1.633 \times 10^6$	$93 = 9.3 \times 10^1$
$963,000 = 9.63 \times 10^5$	$937,000 = 9.37 \times 10^4$	$7.7 = 7.7 \times 10^0$
$660 = 10^2$	$6,800 = 6.8 \times 10^3$	$131.2 = 1.312 \times 10^2$

41. (Group B 937,000 converts to 9.37×10^5 and not to 9.37×10^4.) Which of the groups below contain an error? _____

Group A	Group B	Group C
$0.00037 = 3.7 \times 10^{-4}$	$0.44 = 4.4 \times 10^{-1}$	$.37 = 3.7 \times 10^{-1}$
$0.312 = 3.12 \times 10^{-1}$	$0.0002 = 2.0 \times 10^{-4}$	$.0098 = 9.8 \times 10^{-3}$
$0.068 = 6.8 \times 10^{-2}$	$0.0798 = 7.98 \times 10^{-2}$	$.00001 = 1.0 \times 10^{-5}$
$0.0092 = 9.2 \times 10^3$	$0.644 = 6.44 \times 10^{-1}$	$0.00075 = 7.5 \times 10^{-3}$

42. (Group A) The final number in Group A requires a negative exponent.   Which of the groups below contains an error? _____

Group A	Group B	Group C
$3,700,000 = 3.7 \times 10^6$	$9440 = 9.44 \times 10^3$	$20 = 2.0 \times 10^1$
$-5,500 = 5.5 \times 10^3$	$-110 = -1.1 \times 10^2$	$0.02 = 2.0 \times 10^{-2}$
$0.058 = 5.8 \times 10^{-2}$	$0.0062 = 6.2 \times 10^{-4}$	$-200,000 = -2.0 \times 10^5$
$-0.0034 = 3.4 \times 10^{-3}$	$-0.0123 = 1.23 \times 10^{-2}$	$0.000200 = 2.0 \times 10^{-4}$

43. (Group B) 0.0062 is equal to 6.2 x 10-3.   Match the following:

1. 16   a. 1.6×10^{-3}
2. .0016   b. 1.6×10^4
3. 160,000   c. 1.6×10^{-0}
4. 1.6   d. 1.6×10^1
5. .016   e. 1.6×10^{-2}
6. 16,000   f. 1.6×10^5

44. (1-d, 2-a, 3-f, 4-c, 5-e, 6-b) Another concept that goes hand in hand with powers of ten and scientific notation

is metric prefixes. These are prefixes such as *mega* and *kilo* which when they are placed before a word change the meaning of the word. For example, the prefix *kilo* means *thousand.* When kilo and meter are combined, the word kilometer is formed. This word means 1000 meters. In the same way, the word kilograms mean _____ grams.

45. (1000) Since, kilo means 1,000 you can think of it as multiplying any quantity times 1000 or 10^3. Another popular metric prefix is *mega. Mega* means *million.* Thus, megaton is one million tons or 10^6 tons. In the same way one million volts is referred to as a _____ volt.

46. (mega) One thousand watts can be called a kilowatt. Also, one million watts can be called a _____.

47. (mega) One million watts can be called a mega watt. Mega is _____.

48. (10^6) Often it is convenient to convert from one prefix to another. For example, sine a megaton is 10^6 tons and a kiloton is 10^6 tons, a megaton equals 1000 kilotons. And, since a megaton is one thousand times greater that a kiloton, the kiloton is equal to .001 megatons. Now consider the quantity 100,000 tons. This is equal to 100 kilotons or _____ megatons.

49. (106) Often, it is convenient to convert from one prefix to another. For example, since a megaton is 106 tons, a megaton equals 1000 kilotons. And, since a megaton is one thousand times greater than a kiloton, the kiloton is equal to .001 megaton. Now consider the quantity 100,000 tons. This is equal to 100 kilotons or _____ megatons.

50. (0.1) Kilo is often abbreviated k. Thus, 100 kilowatts may be expressed as 100 k watts. Mega is abbreviated M. Therefore, 10 megawatts may be expressed as _____ watts.

51. (10M) the quantity 5k volts is 5 kilovolts or 5000 volts. Also, 5 M volts is 5 megavolts or _____ volts.

52. (5,000,000) There are also prefixes which have values less than one. The most used are:

   milli   which means thousandth (.001) or 10^{-3}, and

   micro   which means millionth (.000,001) or 10^{-6}

One thousandths of an ampere is called a milliamp ere. Also, one thousandths of a volt is called a _____.

---

53. (millivolt) If a second is divided into one million equal parts, each part is called a microsecond. Also, the millionth part of a volt is called a _____.

---

54. (microvolt) One volt is equal to 1000 millivolts or 1,000,000 microvolts. Or, 1 volt equals 10^3 millivolts and 10^6 microvolts. Expressed another way, 1 millivolt equals .001 volt while 1 microvolt equals .000001 volt. Thus, 1 millivolt equals 10^{-3} volts while 1 microvolt equals _____ volt.

---

55. (10^{-6}) Powers of ten allow you to express a quantity using whichever metric prefix you prefer. For example, you can express 50 millivolts as 50 x 10^{-3} volts simply by replacing the prefix milli with its equivalent power of ten. In the same way 50 microvolts is equal to 50 x _____ volts.

---

56. (10-6) When writing abbreviation for the prefix milli the letter small *m* is used. A small *m* is used to distinguish it from mega which used a capital M. Obviously, the abbreviation for micro cannot also be *m*. To represent micro the Greek letter μ (pronounced mu) is used. Thus, 10 millivolts abbreviated 10 m volts while 10 microvolts is abbreviated 10 μ volts. Remember, m means 10^{-3} while μ means _____.

---

57. (10^{-6}) Match the following:

   1. M watt   a. 10^{-3} watts

   2. k watt   b. 10^{-6} watts

3. m watt   c. 500 x 10^{-3} watts

4. μ watt   d. 10^6 watts

5. .5 watt   e. .5k watts

6. 500 watts   f. 10^3 watts

7. 500,000 watts   g. .5 M watts

8. .00005 watts   h. .05 k watts

9. 50 watts   i. 5 m watts

10. .005 watts   j. 50 μ watts

57. (1-d, 2-f, 3-a, 4-b, 5-c, 6-e, 7-g, 8-j, 9-h, 10-i) Additional aspects of powers of ten, scientific notation, and metric prefixes will be described later.

Appendix B

Coach Technician Formula Reference Sheet

Metric Prefix	Symbol	Powers of 10 Value	Conversion
Giga	G	Billion 1,000,000,000	$\times 10^9$
Mega	M	Million 1,000,000	$\times 10^6$
Kilo	k	Thousand 1,000	$\times 10^3$
milli	m	Thousandth .001	$\times 10^{-3}$
micro	μ	Millionth .000001	$\times 10^{-6}$
nano	n	Billionth .000000001	$\times 10^{-9}$
pico	p	Millionth of a Millionth .000000000001	$\times 10^{-12}$

$10^9 \quad 10^6 \quad 10^3 \qquad 10^{-3} \quad 10^{-6} \quad 10^{-9} \quad 10^{-12}$

10^0

G   M   k   m   μ   n   p

Peak Value
Effective Value = 0.707 x peak
Average Value = 0.636 x peak

Voltage or Current

0 _____ Time

1/2 Cycle

Peak Value = 1.414 x effective Value

Peak Value = $\dfrac{\text{Average Value}}{0.636}$

Peak-to-Peak Value = 2 x Peak Value

Average Value = 0.636 x Peak Value

Effective Value (0.707 x Peak Value)
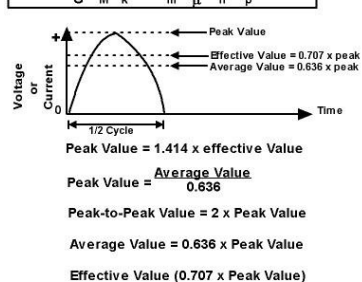
In. lbs = Ft. lbs x 12

Ft. lbs = $\dfrac{\text{In. lbs}}{12}$

E / I R
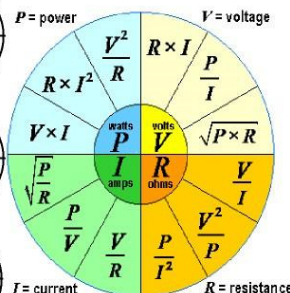
E / I_C X_C

E_L / I X_L

E / I Z

$= \dfrac{N_S}{N_P}$

$\dfrac{E_S}{E_P} = \dfrac{N_S}{N_P}$ $\qquad$ $\dfrac{I_P}{I_S} = \dfrac{N_S}{N_P}$

$\dfrac{Z_P}{Z_S} = \left(\dfrac{N_P}{N_S}\right)^2$ $\qquad$ $\dfrac{N_P}{N_S} = \sqrt{\dfrac{Z_P}{Z_S}}$

$P_P = P_S$

%efficiency $= \dfrac{P_S}{P_P} \times 100$

P = power $\qquad$ V = voltage

$\dfrac{V^2}{R}$ $\quad$ $R \times I$

$R \times I^2$ $\quad$ $\dfrac{P}{I}$

$V \times I$ $\quad$ $\sqrt{P \times R}$

watts P $\quad$ volts V

amps I $\quad$ ohms R

$\sqrt{\dfrac{P}{R}}$ $\quad$ $\dfrac{V}{I}$

$\dfrac{P}{V}$ $\quad$ $\dfrac{V}{R}$ $\qquad$ $\dfrac{P}{I^2}$ $\quad$ $\dfrac{V^2}{P}$

I = current $\qquad$ R = resistance

$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$ $\qquad$ $R_t = R_1 + R_2 + R_3 + R_4 + \dots R_n$

$T = \dfrac{L}{R}$ $\qquad$ $T = RC$ $\qquad$ $f = \dfrac{1}{T}$

$L = \dfrac{1}{4\pi^2 f^2 c}$ $\qquad$ $2\pi fL = \dfrac{1}{2\pi fC}$ $\qquad$ $C = \dfrac{1}{4\pi^2 f^2 L}$ $\qquad$ $R_T = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_4} + \dots \dfrac{1}{R_N}}$

$L_T = L_1 + L_2 + L_3 + L_4 + \dots L_N$ $\qquad$ $C_T = \dfrac{1}{\dfrac{1}{C_1} + \dfrac{1}{C_2} + \dfrac{1}{C_3} + \dfrac{1}{C_4} + \dots \dfrac{1}{C_N}}$ $\qquad$ mho's $= \dfrac{1}{\text{ohm's}}$

$L_T = \dfrac{1}{\dfrac{1}{L_1} + \dfrac{1}{L_2} + \dfrac{1}{L_3} + \dfrac{1}{L_4} + \dots \dfrac{1}{L_N}}$ $\qquad$ $C_T = C_1 + C_2 + C_3 + C_4 + \dots C_N$

$X_L = 2\pi fL$ $\qquad$ $X_C = \dfrac{1}{2\pi fC}$ $\qquad$ $Z = \sqrt{R^2 + (X_C - X_L)^2}$

Appendix C
Resistor Color Bands

Four-band identification is the most commonly used color coding scheme on all resistors. It consists of four colored bands that are painted around the body of the resistor. The scheme is simple: The first two numbers are the first two significant digits of the resistance value, the third is a multiplier, and the fourth is the tolerance of the value. Each color corresponds to a certain number, shown in the chart below. The tolerance for a 4-band resistor will be 2%, 5%, or 10%.

The Standard EIA Color Code Table per EIA-RS-279 is as follows:

Color	1st band	2nd band	3rd band (multiplier)	4th band (tolerance)	Temp. Coefficient
Black	0	0	$\times 10^0$		
Brown	1	1	$\times 10^1$	±1% (F)	100 ppm
Red	2	2	$\times 10^2$	±2% (G)	50 ppm
Orange	3	3	$\times 10^3$		15 ppm
Yellow	4	4	$\times 10^4$		25 ppm
Green	5	5	$\times 10^5$	±0.5% (D)	
Blue	6	6	$\times 10^6$	±0.25% (C)	
Violet	7	7	$\times 10^7$	±0.1% (B)	
Grey	8	8	$\times 10^8$	±0.05% (A)	
White	9	9	$\times 10^9$		
Gold			×0.1	±5% (J)	
Silver			×0.01	±10% (K)	
None				±20% (M)	

Appendix D
Weights and Measures

Fraction	Inches	Millimeters		Fractions	Inches	Millimeters
1/64	.016	.40				
1/32	.031	.079				
3/64	.047	1.19				
1/16	.062	1.59				

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