

## OVERVIEW

A question asked by many people not educated in electrical theory is: What is electricity? You cannot see electricity but can witness its effects on electrical apparatuses around the world. You cannot hear electricity but can hear electric discharges in the form of thunder, or the production of sound in speakers. You cannot smell or taste electricity, but it is a real force in getting work done. Electricity lights lamps, heats and cools buildings, makes motors turn, and drives electronic devices.

Once you learn the basics of electrical theory, you gain a new understanding of many of the devices you see around you each day. The key to using electricity is to be able to predict what will happen as you connect electrical power to electrical and electronic circuits and apparatuses and use the phenomenon of electricity. However, you must take precautions to use it carefully. It is a very versatile form of energy, but it can be lethal if not used correctly. As an electrician or electrical worker, it is your job to apply the benefits of electrical power while keeping yourself and the general public free of dangerous situations.

Very early in the 20th century, a sleeping student was awakened by his teacher's question, "James, what is electricity?" Sleepy and confused, the student tried vainly to recover. "Er-r-r, well, um-m-m, I *did* know, sir. But I forgot." "What?" cried the smiling professor. "You are the only person in history to know what electricity is, and you forgot!"

Intensive research and investigation in the 18th and 19th centuries had shown much about the behavior of electricity but little about its roots. Consequently, the unfortunate student's statement that "I *did* know" predated anyone knowing the true nature of electricity. The real understanding of electrical fundamentals began with J. J. Thompson's 1897 discovery of the electron. However, a comprehensive knowledge of electricity was slow in developing, requiring many subsequent 20th-century revelations about the fundamental structure of the atom.

In this chapter you will learn the basic measurements used in the study of electricity. We start with direct current (DC) first because it is easier to understand. To get you started, we begin with electrical terms that allow you to understand the basic features of any electrical circuit. In Chapter 2 you will learn the molecular theory of electricity. Each chapter in this book adds to your knowledge of electricity.

## OBJECTIVES

After completing this chapter, you will be able to:

- Describe the units of measurement of current, voltage, resistance, and power
- Demonstrate your knowledge of the units ampere, volt, ohm, and watt by giving examples of their usage
- Explain the electron theory of current flow versus conventional current flow
- Solve electrical problems using Ohm's law and Watt's law
- Describe some safety procedures and equipment used for electrical safety requirements

## INTRODUCTION

Electricity is an invisible force that can produce heat, motion, light, and many other physical effects. This invisible force provides power for lighting, radios, motors, heating and cooling, and many other applications. The common link among these applications is the electrical charge.

**Electricity**, *electron*, and *electronics* are English words that come from a word with a Greek background, *elektron*. The literal English translation of this word is “to be like amber.” More than 2,500 years ago, the Greeks found that by rubbing amber with other materials it became charged with this invisible force and could attract bird feathers, hair, cloth, and other materials. In the 1600s, William Gilbert found that along with amber, other materials could be charged with this invisible force. He categorized those materials that could be charged as “electriks” and those materials that could not be charged as “non-electriks.”

About a hundred years later, in 1733, Charles DuFay discovered that some charged materials would attract other objects and that other charged objects would repel different objects. Benjamin Franklin suggested the convention that two types of charges existed, positive (+) and negative (–), and that “like” charges repel (positive from positive and negative from negative) and “unlike” charges attract (positive to negative). An example of how these charged materials were classified and how they react to each other is shown in Figure 1–1.

To use electricity, you must be able to measure its effects and be able to control how the electricity is manipulated. In this chapter you will learn how to apply Ohm’s law in your day-to-day electrical responsibilities. As you work through the chapter, remember that although the examples are for DC circuits, Ohm’s law will find application in AC as well. In fact, Ohm’s law will probably be the formula you use most often as an electrician.

### Positive and Negative Charges

<b>POSITIVE</b>
Glass Rubbed on Cotton or Wool

<b>NEGATIVE</b>
Amber Rubbed on Cloth

*Opposite Charges ATTRACT*

<b>POSITIVE(+)</b>
Glass Rubbed on Cotton or Wool (or)
<b>NEGATIVE(–)</b>
Amber Rubbed on Cloth

<b>POSITIVE(+)</b>
Glass Rubbed on Cotton or Wool (or)
<b>NEGATIVE(–)</b>
Amber Rubbed on Cloth

*Similar Charges REPEL*

**Figure 1–1.** Positive and negative charges are caused by various material interactions.

Remember that when Ohm was doing his greatest work there were no computers, no calculators, and no electric lights! He could use only earlier published manuscripts on physics, a slide rule, and his mind. Without the aid of modern technology, he published Ohm's law, which describes in detail the relationship among voltage, current, and resistance in a simplified form. In Ohm's nomenclature,  $I$  is the current of the circuit,  $E$  is the voltage applied to the circuit, and  $R$  is the total resistance of the circuit. The following sections discuss specific definitions relating to each term.

The variable letters are representations of electrical quantities (explained in detail later in the chapter). For now, the letter  $I$  represents electrical flow or current. The letter  $I$  evolved from the notion that it was representative of the intensity of flow, measured in amperes (amps). The letter  $E$  represents the electrical pressure of the power supply, known as the voltage. The letter  $E$  evolved from the abbreviation of electromotive force, measured in volts ( $V$ ). The letter  $V$  is sometimes used in formulas to indicate the voltage within the circuit. You will find that the letters  $E$  and  $V$  are used interchangeably from one reference to another, and in some cases both methods are used in one reference. The important concept to remember is that both  $E$  and  $V$  refer to electromotive force or voltage in the circuit. The letter  $R$  represents the opposition to the current flow in the circuit (the resistance), measured in ohms. Ohm's law is used for calculating circuit quantities with the following formula:

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

## ELECTRICAL TERMS

In your study of electricity, there are many key terms you should learn. The first of these key terms are *current*, *voltage*, and *resistance*. In this chapter these and other terms are described in



## FieldNote!

In 1827, a German named Georg Simon Ohm published a formula that expresses the single most important relationship in all of electricity. This formula, named Ohm's law in honor of its discoverer, finds application in virtually all aspects of the electrical and electronic industries.

Georg Simon Ohm was born on March 16, 1789 in Erlangen, Germany, and was educated at the University of Erlangen (Figure 1-2). From 1833 to 1849, he was director of the Polytechnic Institute of Nurnberg, and from 1852 until his death in 1854 he was professor of experimental physics at the University of Munich. Between 1825 and 1827, he developed a mathematical description of electrical current in circuits. What is now known as Ohm's law appeared in print in 1827. This work strongly influenced the electrical theory development of his day but was not well received by his peers.

detail, along with an explanation of how they are used and how they relate mathematically to one another. This mathematical relationship among current, voltage, and resistance is known as **Ohm's law**. Many of you have probably heard of Ohm's law in high school, in technical school, or from some on-the-job experience.

## CURRENT

Your first challenge is to study the effects of DC (direct current) circuits and be able to predict what will happen on the basis of meter reading and observation of results of electricity. We will build the individual measurements and tie the individual definitions together through Ohm's law. We will make some assumptions at this point and then return to explain further as we delve deeper into the theory and verify the physical measurement. In other words, we will start with empirical evidence and go back to the theoretical concepts.

We will start with the basic premise of electricity. Electricity is the movement of electrons that have been activated or energized by an external energy. The external energy is imparted to the electrons, which "flow in a conductor."

### Ohm



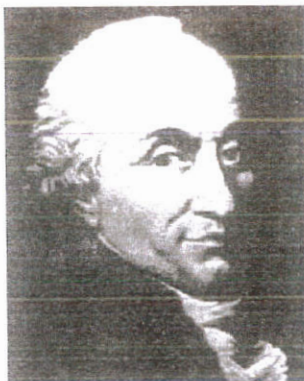
**Figure 1-2** Georg Simon Ohm lived 1789-1854.



## FieldNote!

The French physicist Charles A. de Coulomb (Figure 1–3) first studied the movement of electrons through materials. We call this flow of electrons through a material the current. Coulomb proved that like (positive to positive) charges repel and that unlike charges (positive to negative) attract. He also proved that this repelling force changes value as you change the distance between the charged materials. Coulomb studied the amount of charge on an electron and the amount of force between electrons, and on the basis of his research he defined the coulomb as equal to the total charge exhibited by  $6.25 \times 10^{18}$  electrons.

### Coulomb



**Figure 1–3** Charles de Coulomb, 1736–1806, is shown above.

### Ampère



**Figure 1–4** André Ampère, 1775–1836, is depicted above.

The electrons give up their energy at an electrical load as they produce heat, light, motion, and so on. As these electrons are moving in the conductor (wire), we have a way to measure the flow. The number of electrons is measured by the number of **coulombs** per second that move past a fixed point in the circuit. A coulomb is a fixed quantity of electrons.

If we could see electrons with the naked eye and we counted  $6.25 \times 10^{18}$  electrons moving past a point in 1 second, we would record the *flow* of electron **current** as 1 **ampere**. The flow of electron current is similar to the flow of water in a pipe. If we use the analogy of water flow, we could count the number of drops of water (electrons) and make a quantity of drops equal to 1 gallon (1 coulomb). If we measure 1 gallon of water moving past a point in 1 second, we would have the current of 1 gallon per second (i.e., 1 coulomb per second, or 1 ampere).

## THE AMPERE

Now that we know what a coulomb is, how do we use the definition of the coulomb? Another French scientist, André M. Ampère (Figure 1–4), used the coulomb in his definition of the ampere. In the early 1800s, Ampère studied the effects

of electrons flowing through wires. He defined an ampere as 1 coulomb of electrons flowing past a specific point in a wire in 1 second.

Although this definition remains accurate in the international system (SI) of weights and measurements, another definition is used in the meter-kilogram-second (MKS) measurement system adopted by the world in the 20th century. The newer definition in the MKS system defines *ampere* on the basis of the amount of force, in newtons per meter of length, created between two wires carrying equal amounts of current.

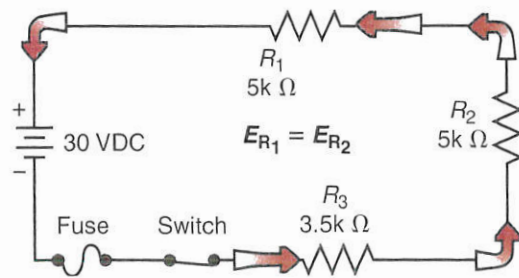
You will learn later that current flow creates a magnetic field. You also know through experience that two magnetic fields will either attract or repel each other, depending on their polarity. The new definition of an ampere is based on these facts and is stated as follows: When two long parallel wires, 1 meter apart, carry equal currents and the magnetic force between the two wires is  $.0000002$  ( $2 \times 10^{-7}$ ) newtons per meter, the current flow in each wire is equal to 1 ampere.

## DIRECTION OF CURRENT FLOW AND METERS

Current flow has a specific direction in a series DC circuit. In Figure 1–5, note that the battery has a positive and a negative side. The negative terminal is labeled negative because that is where there is a buildup or excess of electrons in the battery. Because electrons have a negative charge, this terminal is labeled negative.

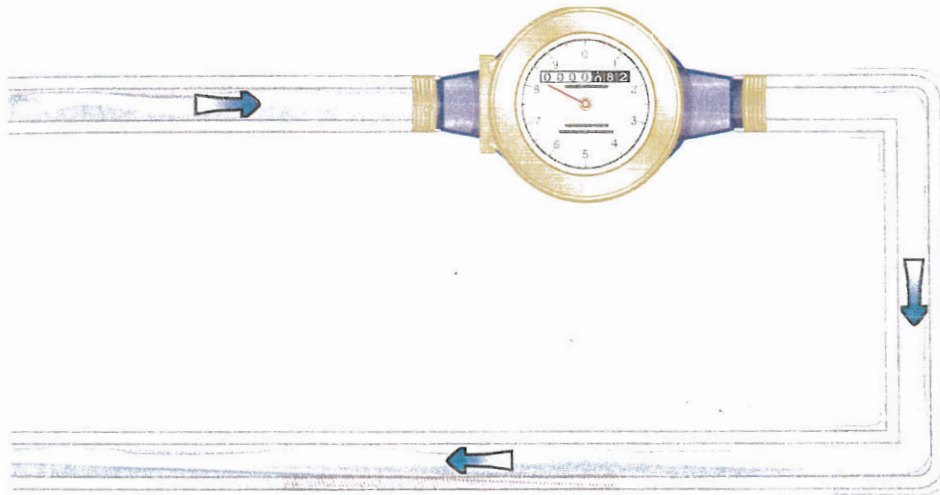
The excess electrons leave the negative terminal and travel through each circuit component and back to the positive terminal. Thus, *outside* the battery the current flows from negative to positive. *Inside* the battery, the electrons move from the positive terminal toward the negative terminal.

### DC Circuit Current Flow



**Figure 1-5** This DC circuit with a battery and three resistors shows current flow and electrical polarities.

### Water Flow Meter



**Figure 1-6** A water analogy equates water flow meters and current flow meters.

This concept is important in understanding circuits that are internal versus external to a power source.

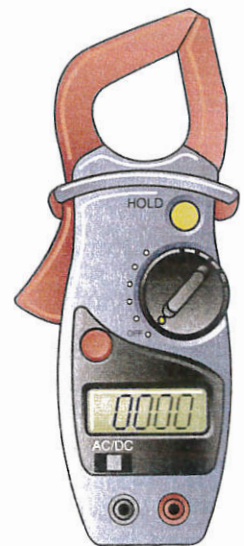
## MEASUREMENT OF CURRENT

We can measure the amount of current flow in a circuit by using a meter called an ammeter (not amp-meter). The ammeter uses various means for measuring current flow. Generally we need to measure the flow by inserting an ammeter into the flow, much like we would with a flow meter for water (Figure 1-6). As the current flows through the circuit it

will also flow through the meter movement. The movement responds to the magnetic field created by the current flow and reacts by driving the meter pointer to the right, or upscale.

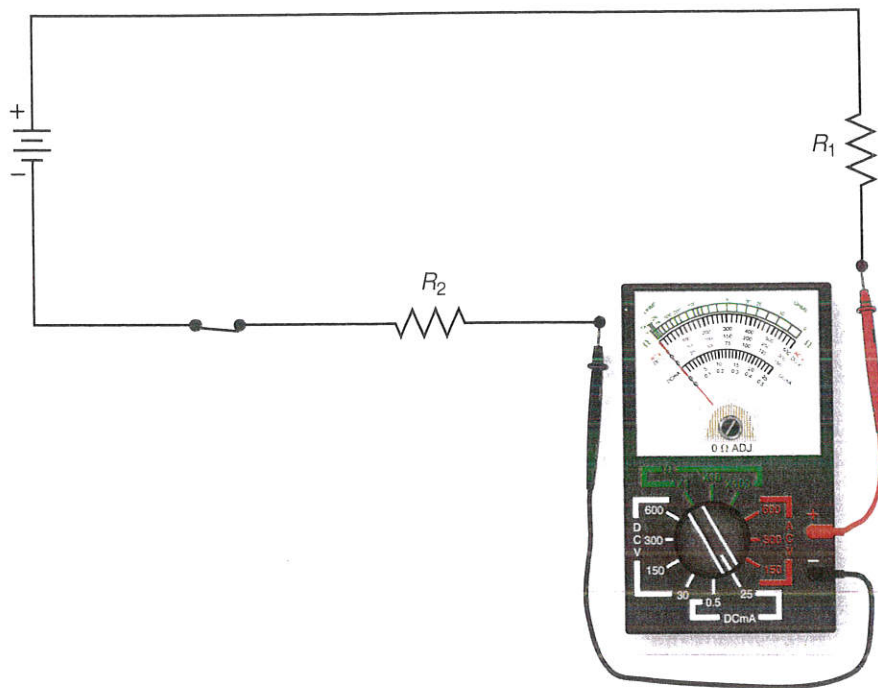
This type of meter is referred to as an analog meter, with a face marked as a scale and a pointer to point to the exact reading. Another popular meter is a digital meter, which automatically produces a digital readout of the current. Most of these meters are clamp-on meters that actually measure the magnetic field produced by the current and convert that quantity using electronics and a programmed chip to read in amperes (Figure 1-7).

### Clamp-On Meter



**Figure 1-7** A clamp-on-style meter can be used to measure current.

### Analog Meter in Circuit

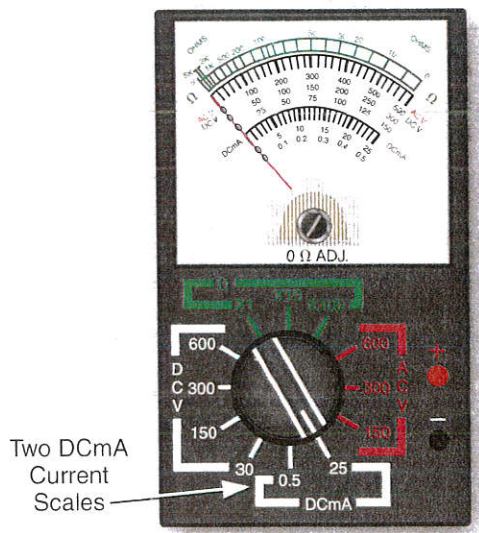


**Figure 1-8** An analog meter can be inserted into the circuit, as above.

To measure current, the standard meter is inserted in the circuit current path and becomes part of the circuit (Figure 1-8). Although each

type of meter may have its own internal power source, the operation of the meter is such that the actual current supplied by the circuit is used to drive the sensing element in the meter when the meter is used to measure current.

### DC Current Scales



**Figure 1-9** The analog meter shown above has two different amperage scales for current measurement.

Because of the large variations available in both voltages and resistances in a circuit, current can vary over a large range of values, from a few microamps (one millionth of an amp) to thousands of amps. Ammeters and multimeters are not capable of measuring currents much above a few amps. For larger currents, it is impractical to build a series ammeter that can carry the full circuit current. This chapter is limited to a discussion of ammeters used for small DC currents.

Most multimeters also have multiple scales for use in current readings. Figure 1-9 shows an analog ammeter that has two DC current scales. The full-scale readings for these two scales are 0.5 DCmA and 25 DCmA.

The maximum current that can be directly read using this meter is 25 mA. Currents greater than 25 mA can overdrive the meter element and damage it.

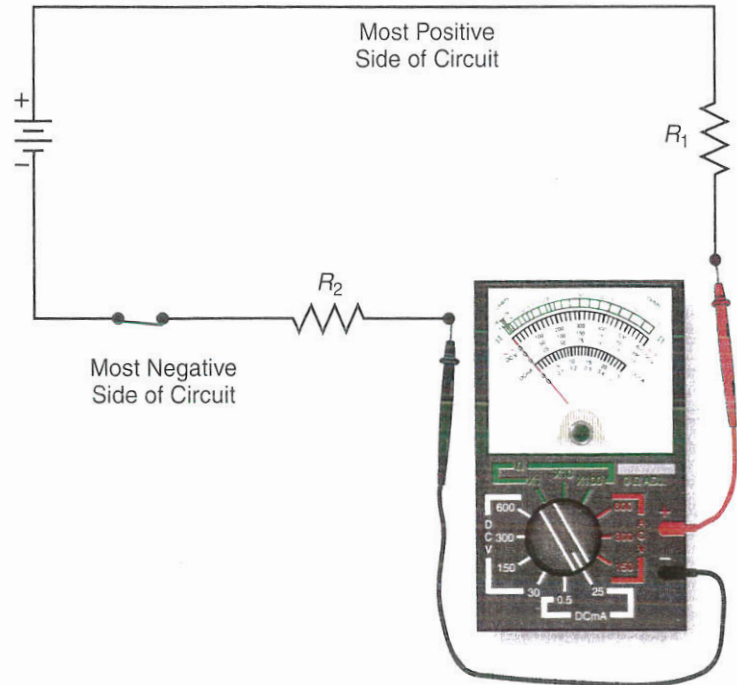
The scales for current on the analog meter are located on the meter face. The scale nearest the bottom corresponds to the 0 DCmA to 0.5 DCmA scale and is calibrated in 0.01 DCmA increments. The scales used for current measurements are much more linear than the scale used for resistance measurements. For this reason, it is much easier to read close to the ends of the scale. Maximum accuracy is still obtained, however, when the meter is read with the indicator near the center of the selected current scale.

When measuring current, you should always begin with the highest scale on the meter and then decrease the scale to obtain the proper reading if the first selected scale was too high. Most modern electronic multimeters also have fuse protection on current scales to prevent internal damage to the meter. The presence or absence of such a meter protection fuse must be verified for each meter used.

When using an analog meter to measure DC current, the polarity of the current is indicated by the direction of the meter needle's deflection. Normally, the meter is connected so that the red test lead (+) is connected to the more positive point in the circuit as the current is flowing toward the positive power supply terminal, and the black test lead is connected to the more negative point in the circuit that is supplied by the current source (Figure 1-10).

If the analog meter is connected incorrectly for more than a fraction of a second, the meter may be damaged because the current will try to drive the needle downscale and may in fact bend the delicate pointer. Damage to the meter movement (the part that moves the needle) may also affect the accuracy of future meter readings.

### Correct DC Circuit Connection

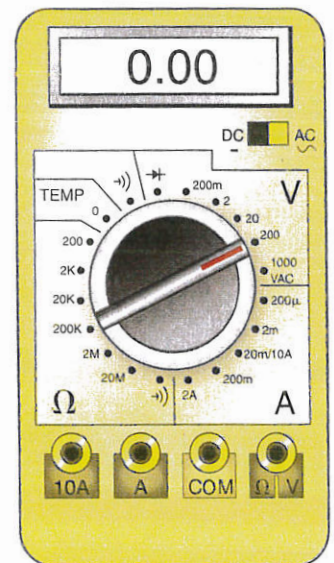


**Figure 1-10** Analog meters need to have the DC circuit connected with the proper polarity.

**CAUTION:** When using any type of meter to measure electrical values in an energized circuit, be sure to follow the safety precautions recommended by the meter manufacturer. Do not attempt to use test equipment for purposes for which the meter was not designed. To do so will damage or destroy the meter and might injure the individual performing the test.

Figure 1-11 shows a digital meter, which can be used to measure current. The digital meter includes five different current scales, including 200  $\mu$ A (microamp), 2 mA (milliamp), 20 mA, 200 mA, and 2 A. In addition, one position of the selector (20 m/10 A) serves a dual purpose. For all normal scales of the meter, the test leads are inserted into the COM and A jacks of the meter. However, when the selector switch is set to the 20 m/10 A position and the test leads are inserted into the COM and 10 A jacks, the meter will read 10 amps full scale.

### Digital Multimeter



**Figure 1-11** Above is an example of a digital multimeter used for current and other measurements.



## FieldNote!

For voltage sources up to 1,000 V, American National Standards Institute (ANSI), Canadian Standards Association (CSA), and International Electrotechnical Commission (IEC) have established four electrical work environment categories. They range from CAT I (least hazardous), to CAT IV (most hazardous). The category designation depends on potential surges, as well as circuit impedance. Multimeters selected for use must be certified by their manufacturer to meet CAT I, CAT II, CAT III, or CAT IV, as appropriate. Work should be performed only with appropriate personal protective equipment (PPE) as described in National Fire Protection Association's NFPA 70E. PPE ranges from natural cotton clothing for CAT I, to specialized face mask, gloves, and clothing furnished by the employer for CAT IV.

This is useful when measuring higher currents in a circuit. However, one additional precaution must be followed when using the 10 amp scale on the particular meter shown in Figure 1-11. All current scales for this particular digital multimeter are fuse protected, with the exception of the 10 amp scale. If the current exceeds 2 amps for any of the current scales except the 10 amp scale, the internal (replaceable) fuse will blow, creating an "open" to protect the circuit, multimeter, and possibly the user. If the current exceeds 10 amps when the meter is set up to read current on the 10 amp scale, the meter will be damaged or destroyed and the user could possibly be injured. It is important that you know if, and how, the particular meter you are using is protected against such occurrences.

When the digital meter is used to measure current, the scale is selected using the meter's selector switch. The position of the decimal point on the digital display will indicate the range of readings for the current scale selected. Table 1-1 outlines the scales for this meter. An additional switch, one that must be set for the digital meter shown, is the DC/AC switch. This switch is used to tell the meter if

the current being measured is DC (direct current) or AC (alternating current). In this chapter, it is assumed that all currents are DC.

On some multimeters, an overcurrent (current larger than the selected scale) would be displayed with a single digit 1. Care must be taken not to confuse this type of overcurrent indication with a legitimate, in-scale reading such as 1.000, 10.00, or 100.0. Some digital multimeters indicate such an overload condition by displaying the letters OL. Read the manual supplied with any meter you might use to find out how that meter indicates overcurrent or overload conditions.

When the current reading on a digital meter is underscale, the reading will be shown as a series of zeros with the decimal point correctly located for the scale being used. In the 200 mA scale position, for example, when there is no current flowing through the meter or the current through the meter is less than 100  $\mu\text{A}$ , the meter display will be 00.0. If you see this reading and you suspect there should be some current present in the circuit, adjust the selector switch to the next lower range and try to measure the current. Repeat this procedure until the selected scale allows the circuit current to be measured or until you get to the lowest scale. Currents below 0.1  $\mu\text{A}$  are not detectable by this meter.

**Table 1-1**

The typical scales of the digital meter and what the display may indicate are listed.

Scale	Display at Maximum
200 $\mu\text{A}$	199.9
2 mA	1.999
20 mA	19.99
200 mA	199.9
2 A	1.999
10 A	10.00

Digital meters can measure current of either polarity. When the red test lead is connected to the more positive point in the circuit and the black test lead is connected to the more negative point, the digital meter will indicate the polarity by showing a plus sign (+) in front of the numerical reading or by not indicating a sign for the circuit current. When the red test lead is connected in the circuit to a point that is more negative than the black test lead, however, this reverse polarity will be indicated by a minus sign (–) in front of the numerical reading of the digital display. The meter’s accuracy is not affected by the polarity of the applied signal.

**TIP:** It is a good practice to always identify lead polarity and connect accordingly. This helps prevent misconnections when using an analog meter.

When measuring current with either type of meter (analog or digital), the procedure to obtain accurate measurement of the current value is the same. Digital meters are often more precise and easier to read for steady-state currents or currents that are not changing rapidly, whereas analog meters often work better when currents are changing or varying and will not settle down to a precise value.

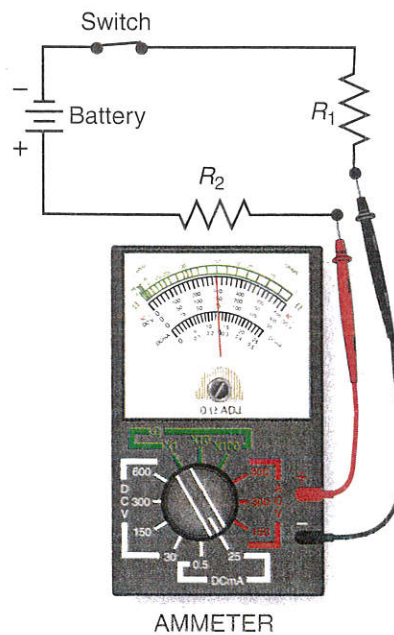
The normal power or voltage supply for the circuit must be applied in order to take current readings. However, the circuit must be turned off in order to safely connect the ammeter before taking the current readings. Caution must be used to ensure that the meter polarity is correct (even if using a digital meter) and that the scale selected for the reading is as great or greater than the highest anticipated circuit current. Generally, the meter’s selector switch can be set to the highest scale and then adjusted downward if the scale is too high.

In the case of the digital meter, if the current is within the limits of the 10 amp range but greater than the

2 amp range, the 10 A test lead jack and 20 m/10 A switch selector position must be used. If later you wish to lower the range setting, power must again be removed from the circuit because removing the test lead will involve breaking the current path in the circuit.

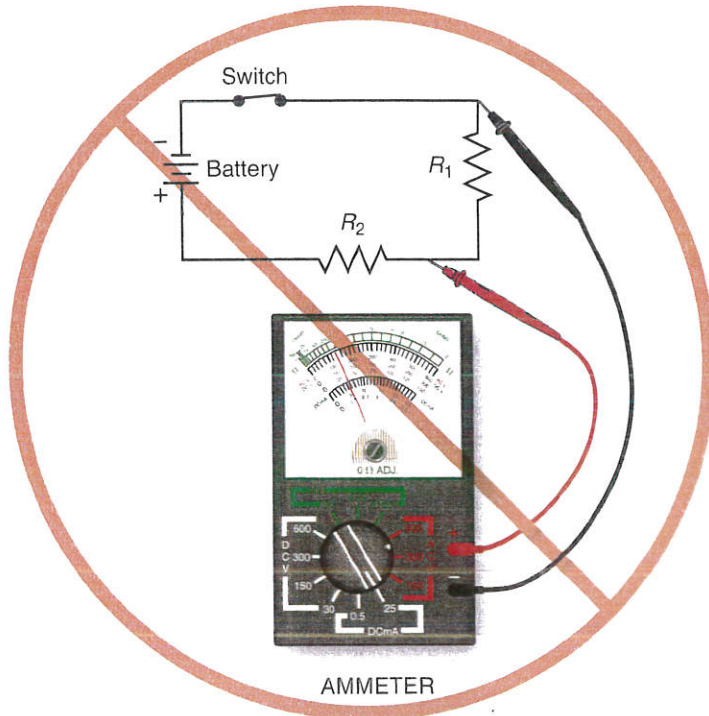
Because there is a single current path through a series circuit, the circuit can be broken and the meter inserted at any place in the circuit. The current reading will be the same wherever the meter is inserted into the circuit. The following material explores circuits for which it is necessary to measure the current. Figure 1–12 shows the proper way to measure the current in this circuit. The circuit has been broken between resistors  $R_1$  and  $R_2$  and the meter inserted with the positive test lead toward the positive power supply lead. The meter could have been inserted at any place in the circuit by breaking the conductor at that location.

#### Ammeter: Proper Connection



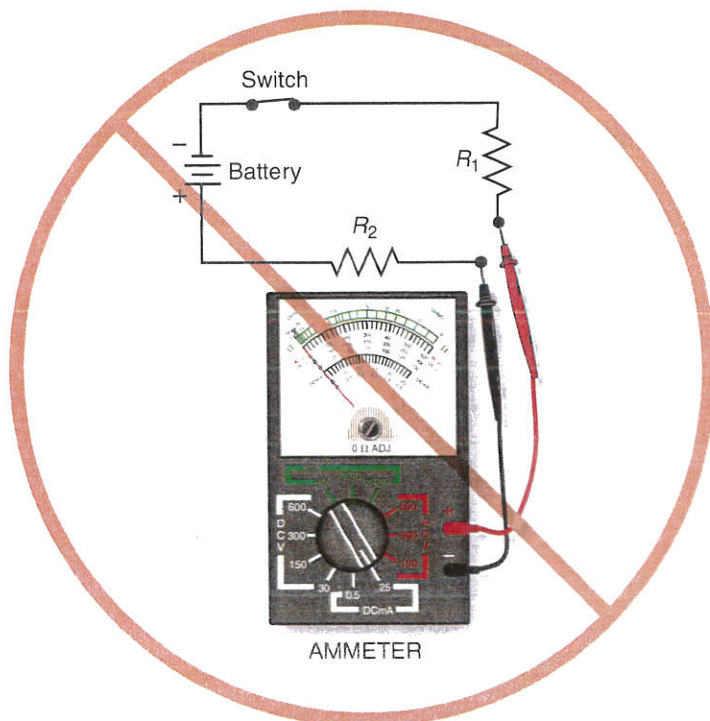
**Figure 1–12** This in-line ammeter is connected correctly.

### Ammeter: Improper Connection



**Figure 1-13** This in-line analog ammeter is connected incorrectly across a component.

### Ammeter: Improper Connection



**Figure 1-14** An ammeter connected backwards in a circuit can cause damage.

Figure 1-13 shows a circuit in which the current measurement would be in error because the meter is improperly installed. The meter must be placed in series with other circuit components not in parallel, as shown. If the meter were connected as shown, the internal resistance of the meter would be in parallel with resistor  $R_1$ , creating an additional current path and changing the parameters for the circuit (thus giving an erroneous reading for circuit current).

Figure 1-14 shows a circuit in which an analog meter is incorrectly connected. The negative meter lead is connected to the more positive circuit point and the positive meter lead to the more negative circuit point. This could damage the analog meter's movement. This connection would not be a problem, however, if a digital meter were used for this measurement.

There are clamp-on ammeters that are used to measure circuit current without breaking the circuit. These work by sensing the magnetic field surrounding a conductor as a result of current flowing through that conductor. These meters are generally used on AC circuits but are also available for DC circuits.

### CONVENTIONAL CURRENT FLOW

In the early days of electricity, before the development and understanding of electron theory, electricians did not know which way current flowed. They believed that *something* was flowing, and they needed to know which way it was flowing. On the basis of the magnetic field created and how it interacted with the earth's magnetic field, early experimenters decided that current flowed from the positive pole to the negative pole of a DC source. This concept is named **conventional current flow**, also known as hole flow or positive current flow.

In modern times, an explanation must be given for the concept of conventional current flow. When an electron leaves an atom, it creates a gap called a hole in the atom it left. The atom with a missing electron is now a positive ion and will want to attract another free electron. However, the new electron has to come from somewhere. This means it makes a hole somewhere else.

If you look at the holes' movements (hole flow), it looks as if they are moving in a direction opposite that of the electrons. Thus, we have a modern explanation for the concept of conventional current flow. Conventional current flow is still used in many engineering applications and in electrical engineering and physics classes in engineering colleges. Figure 1-15 illustrates the concept of conventional current flow. Thus, many people in the electrical industry learn by explanations involving conventional current flow.

### ELECTRON CURRENT FLOW

Now, of course, we know that the electrons are actually moving through the conductor (wire). Since the mid 1900s, electrician and technician training has used the more correct term **electron current flow** in all training and day-to-day applications. This book and others you will use as electricians use *electron current flow*. Figure 1-16 shows both conventions and their relative directions.

The maximum possible speed of the electrons is the speed of light in free space, which is equal to 299,792,458 meters per second (186,282 miles per second). You will learn that some materials allow electrons to move more freely than others. We will conclude that electrons will move more slowly in a conductor than through the vacuum of space. There are many factors to take into account, including material, voltage, and frequency of the current flow. (You will learn about frequency when you study AC theory.)

### Conventional Current Flow

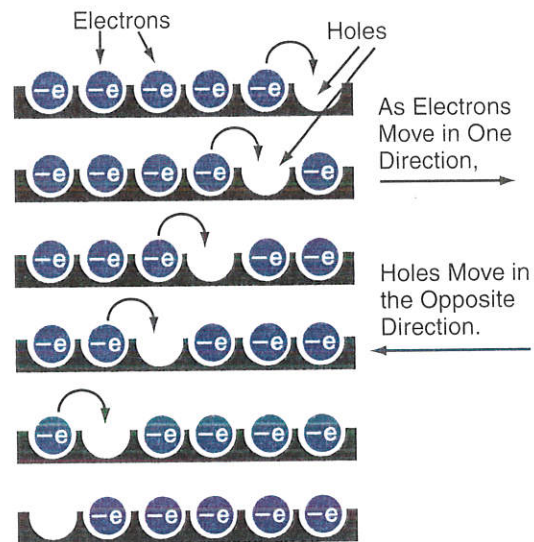


Figure 1-15 Electrons flow opposite to “hole” flow.

### Current Flow

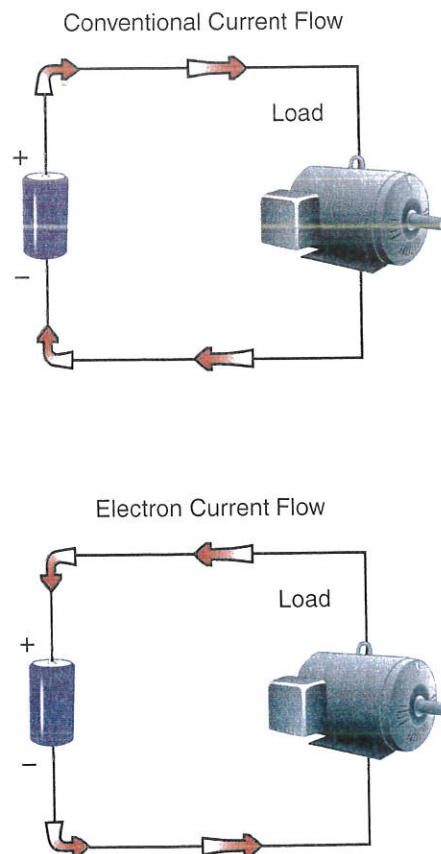


Figure 1-16 Conventional current flow is opposite to electron current flow.

Generally, the current in a conductor (wire) will flow at something less than the speed of light, often 80% of light speed or less.

## THE VOLT

Using the definition of the coulomb, we can now define the volt. Voltage is the **electromotive force (EMF)**, a potential difference in electron charges. A potential difference exists when one object has a greater or fewer number of electrons than another object. Because each electron has a fixed amount of charge, there is potential energy available because of the two different electrical charges. This potential difference causes electrons to be repelled or attracted from one material to another (see Figure 1–17). In a circuit, this is from the negative side to the positive side of a battery. The volt is defined in terms of the coulomb and joule. (A joule is the amount of energy equal to 0.737 foot-pounds.)

The volt is defined as the amount of potential that will cause 1 coulomb to do 1 joule of work. Keep in mind that it is the current doing the work, not the voltage. Voltage does not flow; it causes current flow, somewhat like a pump that causes water flow in a fluid

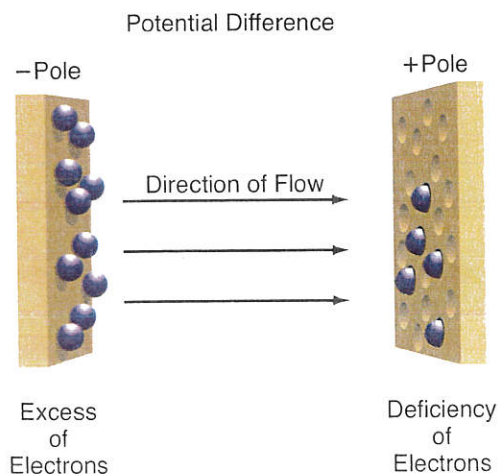
system. The potential difference (EMF) shown in Figure 1–17 acts as a pump to force electrons to flow in the direction indicated. The analogy of the pump refers to the tendency of the electrons to move and to try to balance out. Refer to Figure 1–18 for an analogous situation with a water system.

A potential difference between the two points creates a pressure difference, and the water will move from where there is more water (excess of electrons) to a point where there is a shortage of water (not enough electrons). The EMF is the difference in potential energy between two points or difference in pressure. The positive polarity point has too few electrons, which creates a net positive charge. The negative polarity point has an excess of electrons, and therefore has a negative charge. The difference is measured in voltage, also known as a difference in potential. The “potential” of the circuit is referred to as the EMF or voltage.

## VOLTMETER

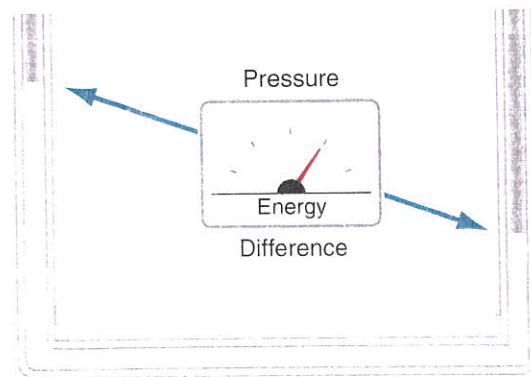
The means of measuring the potential difference, or difference in pressure, is a voltmeter. The meter actually provides a path for electrons to flow from negative to positive through the meter.

### Potential Difference



**Figure 1–17** Potential difference is caused by an imbalance of electrical charges.

### Pressure Difference



**Figure 1–18** The difference in the amount of water creates a potential difference of energy.

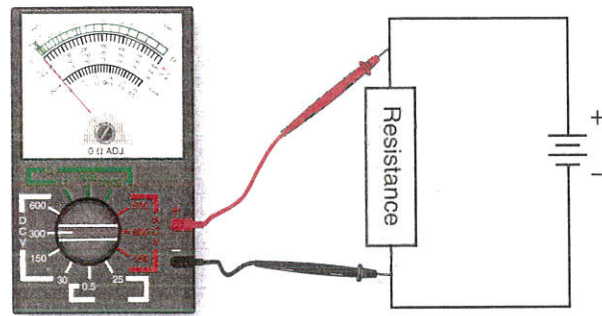
With a greater pressure difference, more current flows and the meter shows a higher reading. Conversely, with less potential difference in pressure there is less current flow and a smaller reading is obtained. The amount of current is very small and does not usually affect the circuit characteristics. See Figure 1–19 for connection of a voltmeter. We can connect the meter right across the positive and negative terminals of the power supply to see the amount of potential pressure of the source.

This is not to say that the internal resistance of the meter does not affect the circuit's operation, only that the voltmeter is not supposed to alter the operation of the circuit. The amount of current flowing through a good high-impedance (high resistance) meter is negligible and does not affect the operation of the circuit. Actually, a very small current does flow through the voltmeter. However, it is small enough that no significant change occurs in the circuit.

The voltmeter can be used to measure the voltage across any device in a circuit. Voltage is the driving force that produces movement of electrons in a circuit. Ohm's law relates all voltage, current, and resistance in a circuit. The amount of current in a circuit with a fixed resistance or load will be directly proportional to the amount of voltage present. Voltage may exist, however, even though no current is flowing in the circuit. A voltmeter can be used, for example, to measure the potential in a battery even though the battery is not connected in a circuit and no current is flowing from the battery. Voltage potential can exist either in or out of a circuit. Current is present only when both a voltage source and a current path are present.

As with current, voltages can vary from very small values (millivolts and microvolts) to very large values (mega-volts). The meters described in this chapter can measure voltages as low as a few millivolts or (depending on the type of meter and the type of voltage

### Voltmeter Connection

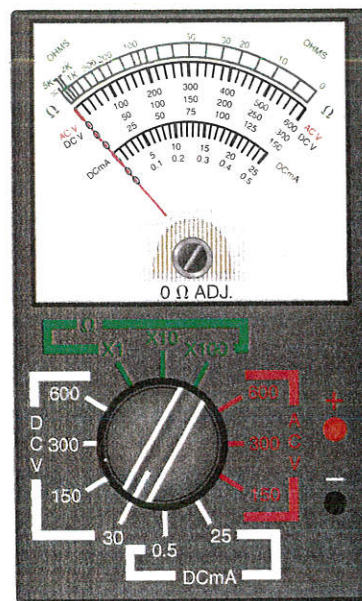


**Figure 1–19** The correct connection of a voltmeter is across the component.

being measured) as high as 1 kilovolt (1,000 V). For safety purposes, it is important to check the maximum voltage rating of a multimeter before using it. Many multimeters have a maximum rating of 600 V. To accommodate this range of voltages, different voltage scales are included with each meter.

Figure 1–20 shows the analog meter discussed previously. The DC voltage scales are located between the resistance and current scales on this meter.

### Analog Meter



**Figure 1–20** A typical analog meter with four switchable DC voltage selections is shown above.

Three different numerical scales are provided for the voltage ranges on the analog meter to provide four different DC voltage (DCV) ranges. The DCV ranges included on the analog meter include 30, 150, 300, and 600, indicating voltage ranges of 0 V to 30 V, 0 V to 150 V, 0 V to 300 V, and 0 V to 600 V. The same faceplate scales are used for both the DC and the AC measurements. However, different selector switch positions are used. The markings for the various scales are broken into 1 V, 5 V, 10 V, and 20 V increments, depending on the scale being used.

When measuring voltage, you should always begin with the highest scale. You can then reduce the scale, using the selector, to obtain the most accurate reading. Generally, voltmeters are temporarily connected to a circuit by means of test probes, but voltmeters of a nonmultimeter type can be installed where continuous monitoring of a circuit voltage is required.

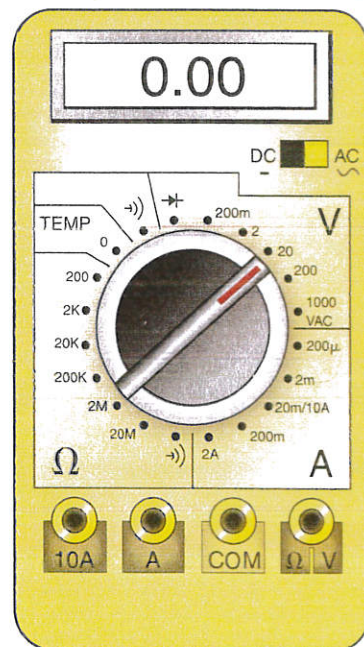
Voltages are polarized just like currents. When using the analog meter,

you must connect the meter to the correct polarity. The red test lead is inserted into the positive (+) test-lead jack and is connected to the more positive point in the circuit. The black test lead is inserted into the negative (–) test-lead jack and is connected to the more negative point in the circuit. As in performing current tests, the meter may be damaged if left connected to the wrong polarity for more than a fraction of a second.

Figure 1–21 shows the digital meter discussed previously. The digital meter has five different voltage ranges, as well as a special voltage scale indicated by the diode symbol ( $\rightarrow$ ). Voltage ranges on the digital meter include 200 m, 2, 20, 200, and 1,000, indicating DC voltage ranges of 0 V to 200 millivolts, 0 V to 2 V, 0 V to 200 V, and 0 V to 1,000 V. The scale designated by the diode symbol is a special voltage scale used for testing semiconductor devices and is slightly different from a normal voltage scale. This special scale is common but is not important to the discussion at this time.

To measure voltage with the digital meter, the test leads are inserted in the test-lead jacks marked COM and  $\Omega/V$ . When used to measure voltage, the scale selected on the meter's selector switch will determine the position of the decimal point on the display. Scales for this meter are outlined in Table 1–2. As in current measurements, the DC/AC switch must be set to select DC or AC voltage measurements.

### Digital Multimeter



**Figure 1–21** A digital multimeter with multiple voltage ranges is shown above.

**Table 1–2**

Voltage scales on a digital meter are indicated here, with maximum readings on each scale.

Scale	Display at Maximum
200 mV	199.9
2 V	1.999
20 V	19.99
200 V	199.9
1,000 V	1.000

Overvoltages would be displayed as a 1 and should not be confused with voltage displays in which all digits would be shown. Some meters display the symbol OL (overload) to show voltage values beyond the range of the meter. Be sure to read the manual supplied with the meter you might use to find out how it indicates overvoltage or overload conditions.

When the voltage reading on a digital meter is underscale, the display will show a series of zeros with a decimal point correctly located for the scale being used. In the 200 mV, position, for example, when there is no voltage present at the test leads or the voltage is less than 0.1 mV, the meter display will be 00.0. If you get such a display on any scale other than the 200 mV scale (already the lowest scale available) and you suspect there should be some voltage present at the test leads, adjust the selector switch to the next lowest range to attempt to measure the voltage. Repeat this procedure until the selected scale allows the voltage to be measured or until you reach the lowest scale. Voltages below 0.1 mV cannot be measured with this multimeter.

Digital meters can measure voltage of either polarity. When the red test lead is inserted into the  $\Omega/V$  test-lead jack and connected to the more positive point and the black test lead is inserted in the COM test-lead jack and connected to the more negative point, the meter will indicate a positive voltage by displaying a plus sign (+) or by displaying no sign in front of the numerical value. If the polarity of the test leads is reversed, the numeric display will be preceded by a minus sign (-). The digital meter's accuracy is not affected by the polarity of the applied voltage.

## MEASURING VOLTAGE

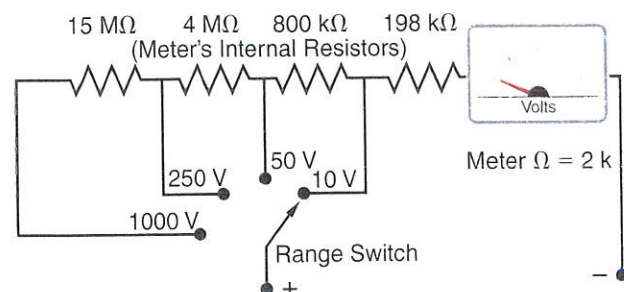
With either type of meter, the procedures for measuring voltage are the same. As with resistance and current,

voltage values are more easily read with digital meters when the voltages are steady-state (unchanging). Generally, analog meters work better for voltage values that fluctuate rapidly or that will not settle down to a precise value.

Most voltmeters measure voltage by drawing a very small amount of current from the circuit being tested. The voltage to be measured is used to produce a small current through a known resistance. The meter is then calibrated to show the voltage rather than the current. All voltmeters produce some error when connected to a circuit, but some designs produce less error than others. Generally, the higher the input impedance or load (resistance) provided by the meter, the more accurate the voltage reading will be. Meters with very high input impedances (greater than 10 million ohms) generally do not affect the circuit to which they are connected because the current through the meter is extremely small (Figure 1-22). Each range creates a preset voltage drop across the meter movement to read the voltage being measured.

Analog meters are polarity-sensitive and may be damaged if connected incorrectly. Be sure the scale selected for the voltage measurement is equal to or greater than the highest anticipated circuit voltage. Generally, the meter's switch should be set to the highest voltage scale and then adjusted downward if the scale is too high.

### Voltmeter Internal Resistance



**Figure 1-22** A voltmeter has internal resistance to adjust for each voltage range.

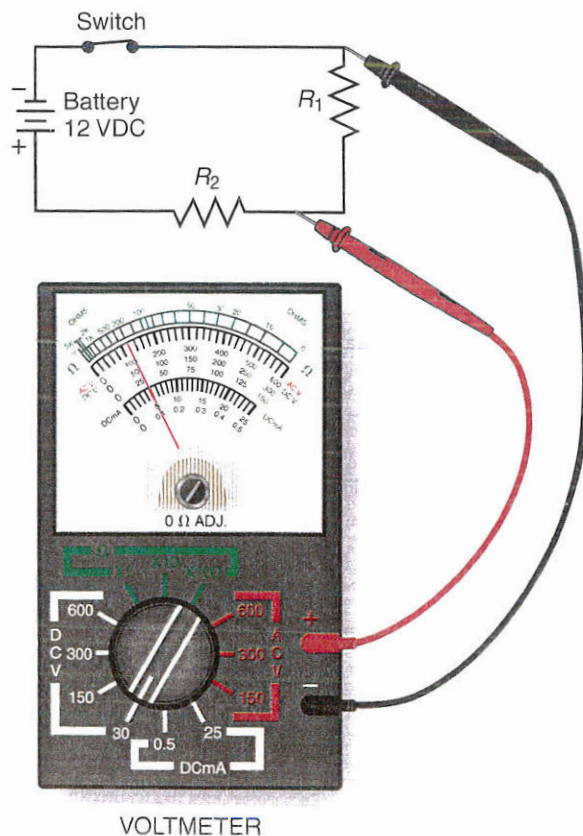
In electrical and electronic circuits, voltages are developed or are present across each component in the circuit. Each of these voltages can be measured independently, or the voltage across two or more components can be measured at the same time. Voltage measurements are measurements of the difference in potential between any two points in a circuit.

Figure 1-23 shows the proper way to measure the voltage across resistor  $R_1$ . The voltmeter is connected across the resistor and will show only the voltage developed as current flows through that resistor. The positive meter lead is connected to the more positive end of the resistor (the end closest to the positive terminal of the power supply or battery), and the negative test lead is connected to the more negative end of the resistor (the end closest to the negative terminal of the power supply or battery). Figure 1-24 shows a voltmeter

connected across resistors  $R_1$  and  $R_2$ . The voltage indicated would be the total voltage developed across both of these resistors, which would be equal to the power supply voltage.

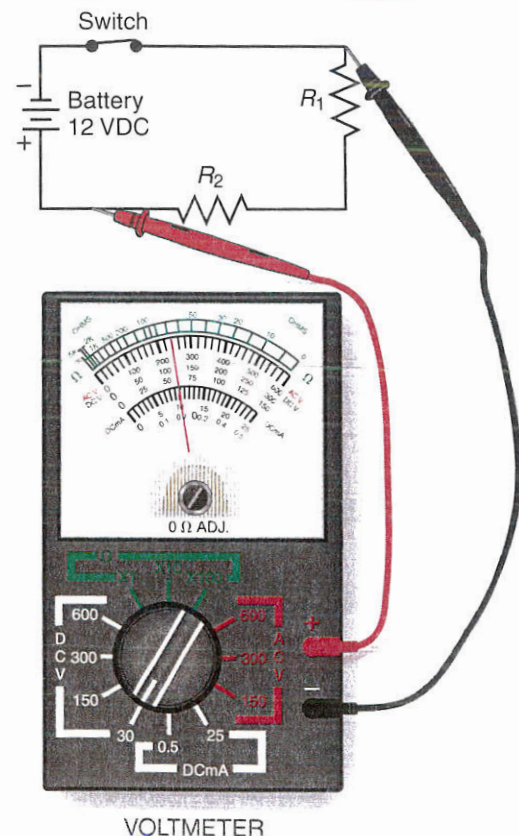
Figure 1-25 shows a voltmeter inserted in series, with the circuit between resistors  $R_1$  and  $R_2$  as it might be connected to measure current. Ammeters have a very low internal resistance and do not significantly affect the circuit when installed in series. Voltmeters, as discussed previously, have a very large internal resistance. As a result, the current path would be greatly altered if the voltmeter were installed in this manner. The voltmeter reading would not reflect the voltage across  $R_1$  or  $R_2$  but would indicate a voltage very close to the power supply potential, because the very small current flowing through the meter would not produce a significant voltage drop across resistors  $R_1$  and  $R_2$ .

### Voltmeter: Proper Connection



**Figure 1-23** This analog meter is correctly connected across a component.

### Voltmeter: Proper Connection



**Figure 1-24** This voltmeter is correctly connected across two components.

## THE OHM

Now that we have defined the ampere and the volt, let's look at the **ohm**. The ohm is a measurement of the amount of opposition to current flow that exists in a circuit object. We can go to the water analogy again and see the effects of opposition. As the water pipe is restricted, it takes more pressure to force the same amount of water flow through the pipe. If we constrict the pipe too much or add a great deal of resistance to the flow, the water flow will diminish until it stops with maximum restriction. The resistance to electron flow in a conductor has the same effect. More resistance means less flow if the pressure stays the same.

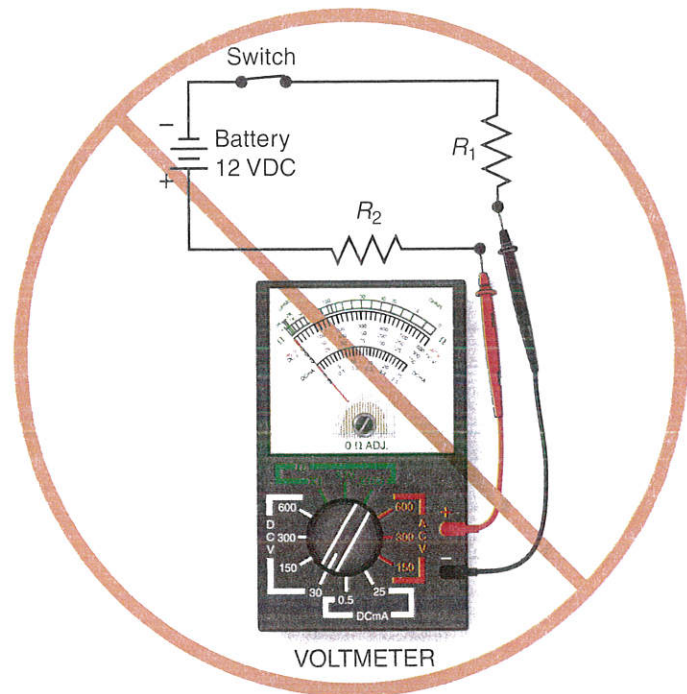
By definition, 1 ohm is the amount of **resistance** in a circuit that allows 1 ampere of current to flow when a potential of 1 volt is applied. This is a statement of Ohm's law. The unit of measure of resistance is the ohm, and the symbol used for the ohm is the Greek symbol omega ( $\Omega$ ). Resistance is a property of all materials through which current can flow. Some materials allow current to flow more easily than others. A material that has many free electrons is a conductor. Likewise, a material with few free electrons is an insulator. A conductor, therefore, has a low resistance and an insulator has a high resistance.

### MEASURING RESISTANCE

The way to measure the resistance that a circuit or component has to the flow of electrons is to use an ohmmeter. This meter typically has its own source of current, such as a battery. As you use the test leads (Figure 1-26), the battery supplies a small current to the test situation and measures how much current flows with a specified amount of voltage or pressure. The meter is set to convert this small current to a scale marked in ohms.

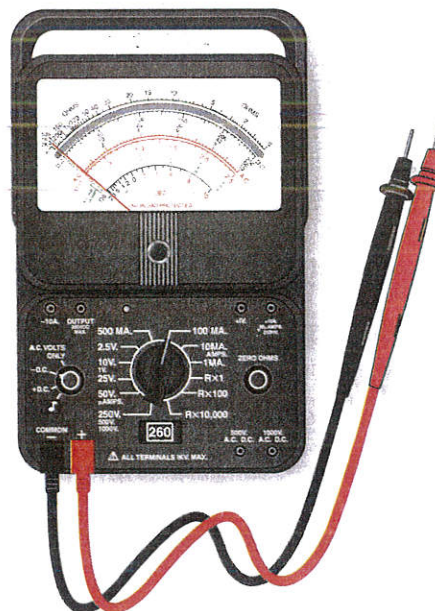
If the test situation has a small resistance, more current will flow and the meter reads upscale and therefore indi-

### Voltmeter: Improper Connection



**Figure 1-25** This voltmeter is incorrectly connected in series with the components.

### Ohmmeter



**Figure 1-26** The ohmmeter has its own power supply that provides a source of current.

cates a low ohm reading. Conversely, a high-resistance component will not allow much current to flow and the meter reads low on the scale (high in ohms).

In Figure 1–27, note that the scale is reversed, compared to normal scales, with low resistance at the far right and high resistance at the far left of this analog meter. A digital meter uses the same scenario but converts the small current flow through the test item directly to ohms on the readout.

**CAUTION:** Never read ohms of a circuit with the power on. The only power must be that supplied from the meter.

## USING AN OHMMETER

A meter designed to measure resistance is called an ohmmeter. Meters designed to measure several circuit characteristics are called multimeters. A multimeter generally contains an ohm scale for reading resistance. Resistance is a physical characteristic of a conductor or anything conductive. Ohmmeters and multimeters that measure resistance do so by applying a known voltage across the resistor and measuring the resultant current or by supplying a known current to a resistor and then measuring the resultant voltage.

These are both applications of Ohm's law. Scales on ohmmeters are calibrated to read resistance rather than voltage or current. Multimeters

have multiple scales, each having a maximum resistance value (calibrated in ohms) used for resistance measurements. Resistances in circuit components vary from very small to very large values. For different applications, it is sometimes necessary to measure resistance values that vary from micro-ohms (0.000001) to megohms (1,000,000). It is not practical to design a meter that could read such a large range of resistance values on a single scale. Most ohmmeters available today have a range selector switch that allows the user to select the appropriate range for reading the resistance values being measured.

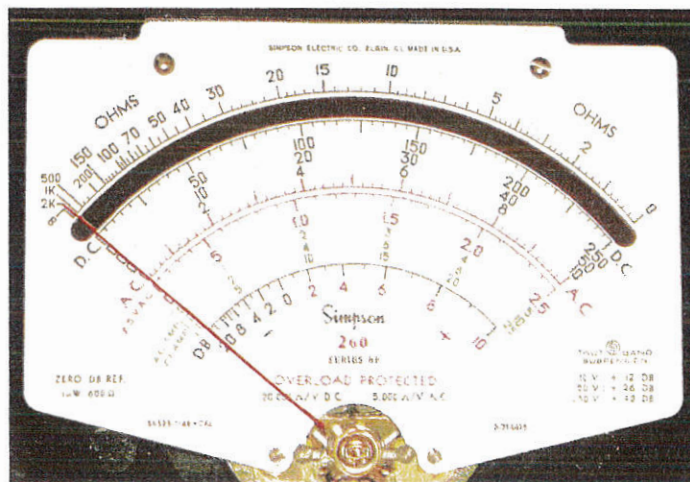
## ANALOG METERS

Figure 1–28 shows an analog multimeter. The analog multimeter uses a moving indicator and a fixed set of graduated scales. As the value being measured changes, the meter needle or pointer will move to some location between the meter scale limits. The value being measured can then be read from the scale being used. Multimeters are capable of measuring voltage, current, and resistance. The top scale on the meter shown in Figure 1–28 is the ohms scale used for resistance measurements. A selector switch allows the user to select three different ohm-scale ranges.

All ohm ranges use the same (top) scale. Multiple resistance scales are necessary because of the nonlinearity of the ohm scale. Even though the scale goes from 0 ohms to  $\infty$  (infinity, or an open circuit), the scale is very difficult to read accurately at the upper end. Note that the numbers are closer together at the left, or high end, of the scale.

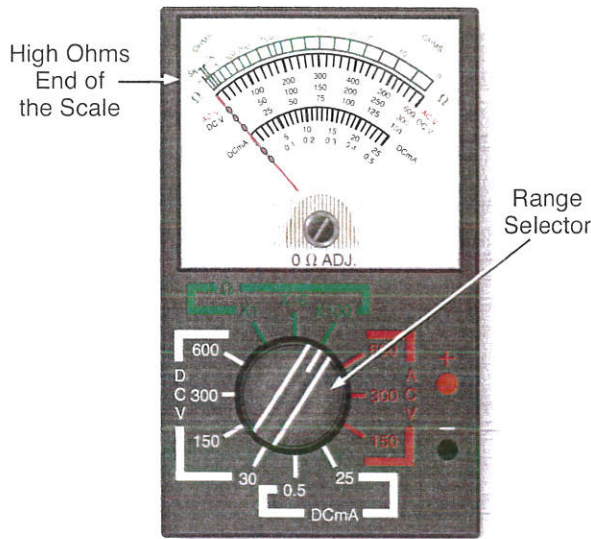
The analog meter includes a selector switch that can be used to select scales X1, X10, and X100 (Figure 1–29). This makes reading the correct value much easier because a scale can be selected to match the value of the resistance to be measured. If the pointer reads close to either end of the scale, selecting a different scale may allow the user to move the needle toward the center of the meter's scale.

### Ohmmeter Scale



**Figure 1–27** The ohmmeter scale on an analog multimeter is reversed, compared to the other scales.

## Analog Multimeter



**Figure 1-28** A typical analog multimeter with multiple scales is shown above.

This provides for increased accuracy in reading the resistance value. When the selector switch on the face of the meter is in the X1 position, the meter's scale is read directly, and simply reading the value indicates the correct resistance.

When the selector is in the X10 position, multiply the value on the scale faceplate indicated by the pointer by a factor of 10. In the X10 position, for instance, if the pointer indicated a resistance of 30 the value would actually represent a resistance of  $10 \times 30$  (300 ohms). Similarly, when the selector switch is in the X100 position, the value on the faceplate is multiplied by 100. In the X100 position, with the pointer indicating 2 K (or 2,000 ohms), the actual reading would be  $2 \text{ K} \times 100$  (200 k $\Omega$ ).

A 0  $\Omega$  ADJ (adjust) control knob allows the meter to be adjusted to compensate for test-lead resistance and battery voltage level in resistance measurements. To adjust this control, the user would "short" the leads by touching them together and then adjust the control to give a 0  $\Omega$  reading on the faceplate. This adjustment eliminates

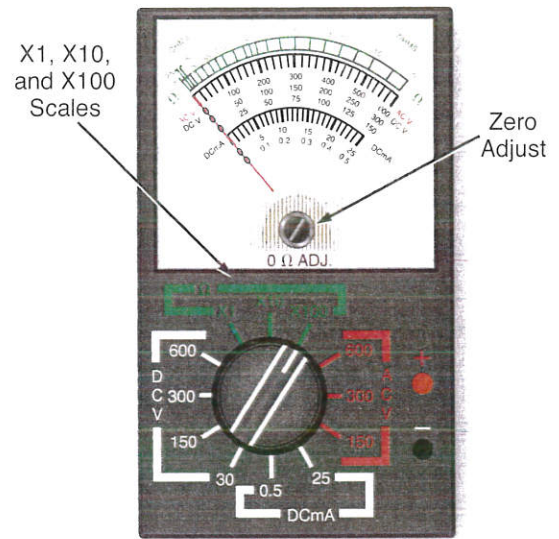
the resistance of the test leads from any resistance reading taken with the meter and must be done every time the meter is used and whenever the scale is changed from one range to another. The zero on the meter should be checked periodically, as the zero value may drift as the batteries weaken.

## DIGITAL METERS

Figure 1-30 shows a digital multimeter that can be used to measure resistance. Digital meters are read differently than analog meters. As you can see, the moving pointer and multiscale faceplate are no longer present. In the digital multimeter, they have been replaced by a liquid crystal display (LCD).

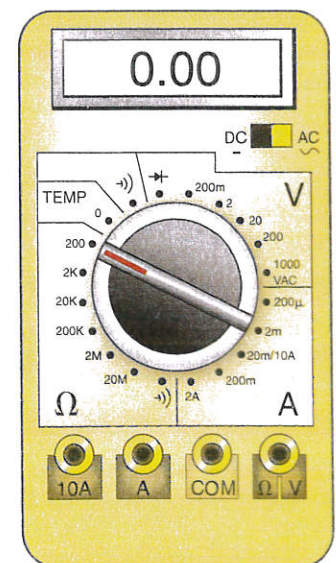
On a digital meter, a single value is digitally displayed that represents the resistance being measured. A selector switch is used to select the maximum resistance to be read on the selected scale. The amount of information shown depends on the type of display on the meter. Meters may display two and one-half digits (up to 199), three digits (999), three and one-half digits (1999), or four digits (9999).

## Ohmmeter Ranges



**Figure 1-29** Ohmmeter ranges often use the same reading scale but use multipliers to calculate the actual ohm measurement.

## Digital Multimeter



**Figure 1-30** A typical digital multimeter can be used to measure ohms as well.

The meter shown is classified as a three-and-one-half-digit meter. This means that the display has three digits that can show any value from 0 to 9 and a fourth digit that can indicate either a 0 or a 1. The maximum reading for this meter is 1999. A decimal point is used to scale this reading. Scales shown for this meter include 200, 2 K, 20 K, 200 K, 2 M, and 20 M. These scales represent the maximum resistance readable for that scale and would be displayed as indicated in Table 1-3.

On the digital meter, when a value exceeds the maximum value that can be displayed for that scale, the meter indicates the overscale condition by displaying a 1 or a 9 or by flashing 9999. When the value of resistance being measured represents a resistance value below the scale of the meter (as might occur if a 200  $\Omega$  resistor were to be checked while the meter was set on the 2 M scale), the meter will indicate the underscale condition by displaying a 0.00.

When measuring resistance on the digital meter shown in Figure 1-30, if you encounter a 1 you should increase the scale reading (turn the selector knob counterclockwise on the meter shown) to bring the meter within scale. If you encounter a 0.00 on the display, you should decrease the scale reading (turn the selector knob clockwise) until you have the correct reading. Other meters may differ. Be sure to understand how the meter you are using operates.

One additional resistance scale, indicated by the symbol  $\rightarrow$ , is used for continuity tests. A continuity test is

used to indicate a current path. Continuity exists between two points. This type of test is used when the user is concerned not about the specific resistance in the current path but only that a continuous current path exists in the circuit. When set to this scale, the meter will indicate a 1 for an open circuit and a 000 for a closed or shorted circuit. In addition, with some meters an audible signal is heard when a closed continuous circuit is encountered.

The digital multimeter does not have a 0  $\Omega$  ADJ control, as zero adjustment is normally not required for digital multimeters. Some digital multimeters have autoranging capabilities that automatically adjust the meter's range to suit the value being measured.

## MEASURING RESISTANCE IN A CIRCUIT

When measuring resistance with either type of meter, the procedure to obtain accurate measurement of the value of resistance is the same. The digital meter is easier to read when the resistance of a specific component is required. Digital meters are less desirable, however, when reading the resistance of circuit components that have a quickly changing resistance (such as a resistive sensor in which the resistance depends on some physical variable, such as light level or temperature). The main reason for this is that the variable being measured is rapidly changing and the process required within the digital meter to read, interpret, and display the measured value often exceeds the time between the changes in that variable.

This does not mean that the digital meter is slow. Rather, it may be inappropriate for the type of variable being measured. For these types of quickly changing values, the analog meter is often a better choice. Note that many modern digital meters are equipped with an LCD analog bar that can be used for tracking changes. Because meters that measure resistance have their own power sources, all power must be removed from circuits before

**Table 1-3**

Ohmmeter scales and the maximum reading available with each scale are shown.

Scale	Maximum Reading ( $\Omega$ )	Display at Maximum
200	200	199.9
2 K	2,000	1.999
20 K	20,000	19.99
200 K	200,000	199.9
2 M	2,000,000	1.999
20 M	20,000,000	19.99

attempting to measure resistance. Circuit power sources will not only affect the reading on resistance measuring devices but potentially pose a safety hazard if left connected.

**CAUTION:** Never attempt to measure the resistance of a component in a circuit while power is applied to that circuit. To do so not only will damage or destroy the meter used for the test but might injure the individual performing the test.

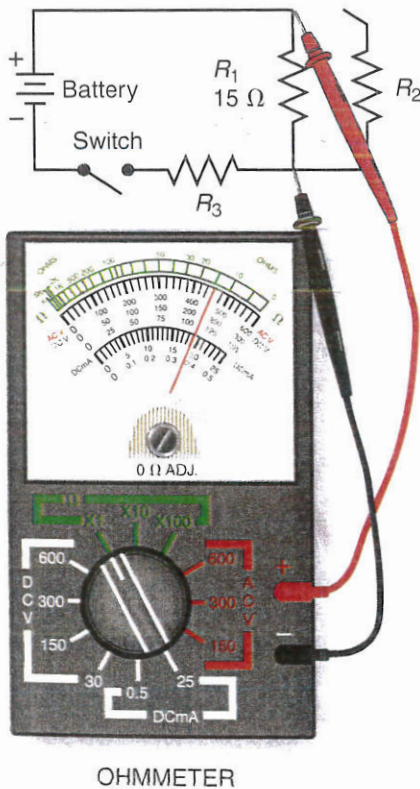
Other components connected in a circuit might also affect the accuracy of resistance measurements. When measuring resistance, you must verify that the only current path available is the one through the component whose resistance you wish to measure. Generally, when measuring the resistance of com-

ponents in a circuit, the polarity of the ohmmeter is not important. Most resistive components are not sensitive to the polarity of the voltage applied to those components during a resistance test.

Electronics devices such as diodes and transistors are polarized. Therefore, caution must be applied to ensure that the polarity of the meter's internal source is correct for the test to be accurate. Figure 1-31 shows the proper way to measure the resistance of resistor  $R_1$ . The power source and all other current paths have been isolated from the component whose resistance is to be measured.

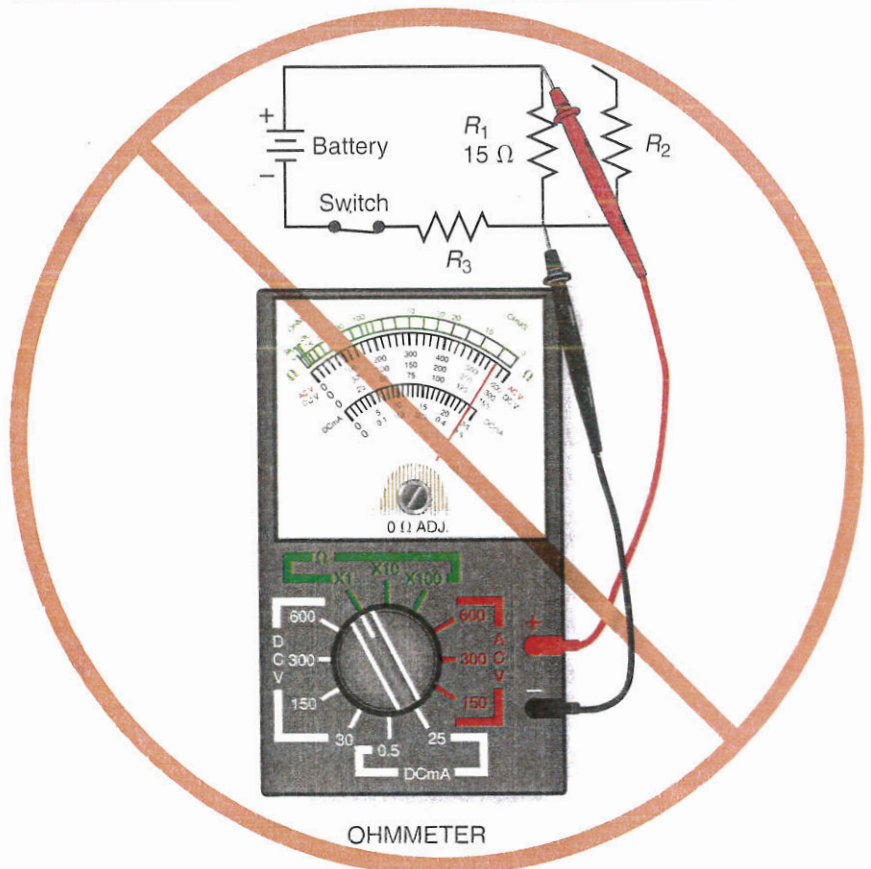
Figure 1-32 shows a circuit in which the resistance measurement would be in error because the power is still connected to the circuit.

**Ohmmeter: Proper Connection**



**Figure 1-31** Correct ohmmeter connection on a component is illustrated above. When the switch is open, the power source will not affect the measurement.

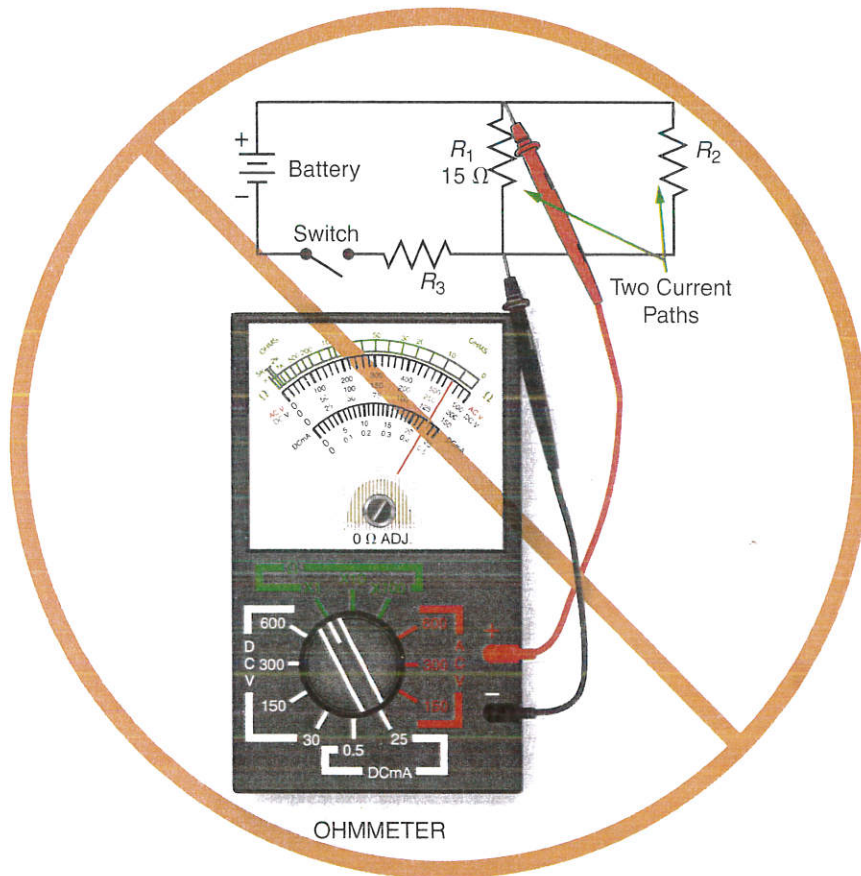
**Ohmmeter: Improper Connection**



**Figure 1-32** An improper connection with ohmmeter and power source still connected is shown. When the switch is closed, the power source will affect the measurement.

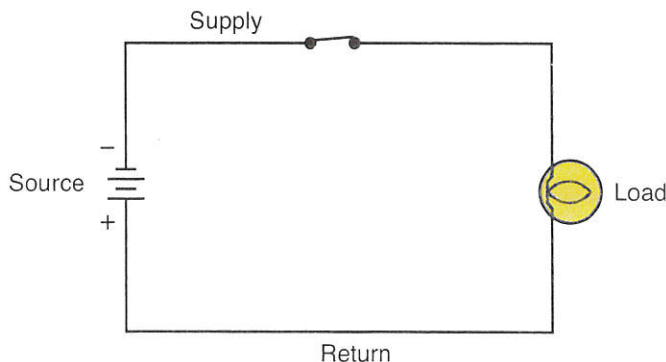
The reading would show that the resistance of  $R_1$  was higher (or lower) than the actual value because of the presence of the circuit power source, which would subtract from (or add to) the ohmmeter's own internal power source.

### Ohmmeter: Improper Connection



**Figure 1-33** An improper ohmmeter connection with more than one resistance in the path is shown above.

### Simple Complete Circuit



**Figure 1-34** A simple complete circuit with voltage source, load resistance, and current flow path is depicted above.

**CAUTION:** This connection could also be dangerous. Do not do this.

Figure 1-33 shows a circuit in which the resistance measurement would be in error because more than one current path exists for current to flow in the circuit. The internal current source from the ohmmeter would flow through both  $R_1$  and  $R_2$ , and the resistance reading would represent the equivalent resistance of resistors  $R_1$  and  $R_2$  combined—which would be lower than the resistance of  $R_1$  alone.

### A CIRCUIT

As we have been discussing the three essential quantities of electrical theory, we have referred to a **circuit** (Figure 1-34). For electricity to provide useful work, there must be a path for current to flow from a source of pressure (pump) through conductors (pipes) to a device (water wheel), and then the electrons must be able to get back to the source to reach the positive terminal of the source.

For a circuit to be complete, it must have a source (which will provide the force needed for electrons to flow), a supply path, and a return path for electrons to flow from the source, through the load, and then back to the source. In other words, the circuit must provide a path back to the *original* source which caused the electrons to flow. Once a path back to the source is connected, the circuit is complete, and as long as the “pump” has power supplied, it will continue to force electrons to flow in a completed system.

### CLOSED CIRCUIT

All of the knowledge you have can now be combined to create a circuit. You know that a potential difference (voltage) must exist to cause electrons to flow (current) within a conductor. And you know that all conductors will have some resistance (ohms) to the current flow. There are many types of circuits you may encounter in your career as an electrical worker.

Because of the ever-changing designs for new electrical systems and circuits, not all are alike. You must become familiar with these differences to be successful. This section does not attempt to cover these circuits in detail but does give you an overview.

For current to flow, there must be a complete path (closed circuit, Figure 1-35). Note that the electrons flow from the battery through the motor and back to the battery. The battery causes the potential difference for the electron flow. Another way to think of it is that the electrons make a solid chain through the circuit. If one electron moves, they all move in a circular path. The circuit is a “closed loop.”

### OPEN CIRCUIT

Circuits are designed to deliver current to a component that consumes electricity, known as an electrical load. Remember that the component does not use up electrons, because they must be returned. It does not consume voltage but does create a change in pressure. This circuit allows electrons to flow through the component and back to the source. If we create a break in the circuit (as in Figure 1-36), the electrons cannot return to the source and no electrons can “flow” in the circuit. As many nonelectrical people may say: There must be a short! Contrary to this misconception, the situation when no current flows is

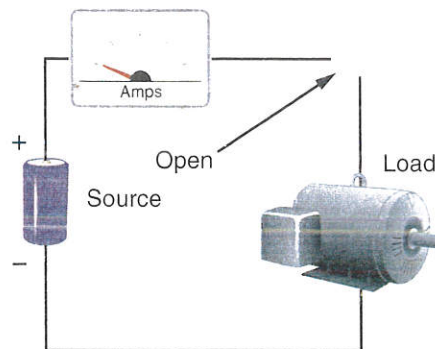
an “open” circuit. As you can see from the diagram, the circuit is open and the ammeter reads zero amps.

If there is a break (open) somewhere in the circuit, the electrons cannot continue to flow (Figure 1-36). This is called an open circuit. The potential difference (voltage) still exists, but the electrons cannot move (there can be no current). This is another way of saying that  $R$  is infinite ( $R = \infty$ ).

### SHORT CIRCUIT

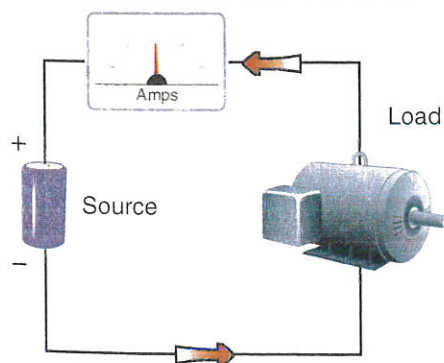
The correct definition of a short circuit is represented by that shown in Figure 1-37. In this case, the current has found a shorter path back to the source than going through the resistance of the full circuit.

#### Open Circuit



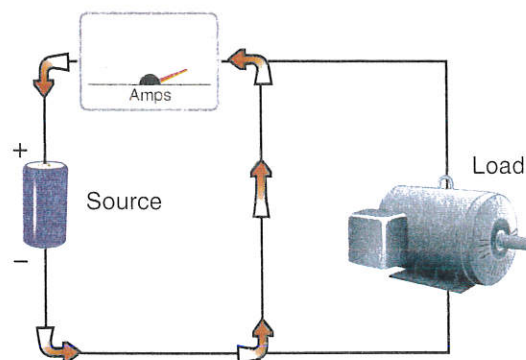
**Figure 1-36** An open circuit has no current flow.

#### Closed Circuit Path



**Figure 1-35** Above is an illustration of a closed circuit path.

#### Short Circuit



**Figure 1-37** A short circuit has almost no resistance and a high-current flow.

When the circuit does not exert much resistance, the current increases, often beyond the capability of the supply to provide enough electrons. The source therefore shuts down, or a fuse opens the circuit. In the case of a short circuit that has had a fuse open, the circuit may first appear as an open circuit. The circuit with an open link in the fuse is an open circuit, but it was caused by a short circuit. The short circuit is characterized by maximum current, whereas an open circuit is characterized by zero current.

## OHM'S LAW OF PROPORTIONALITY

Ohm's law is a law of proportionality, stating that it takes 1 volt to push 1 amp through 1 ohm of resistance. Another way to look at it is that the current ( $I$ ) in a circuit is directly proportional to the voltage ( $E$ ) applied to the circuit and inversely proportional to the resistance ( $R$ ).

Figure 1-38 can help you remember the relationship. To find the value you are looking for, cover it with your

finger to see the relationship that remains. From Figure 1-38, you can derive the three equations you need to make any calculation using Ohm's law. Recall from earlier in this chapter that  $V$  is sometimes used in place of  $E$ .

$$E = I \times R$$

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

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

## CALCULATIONS INVOLVING OHM'S LAW

### Example

If a circuit has a total resistance of 20 ohms ( $\Omega$ ) and a current of 3 amps, what is the circuit voltage?

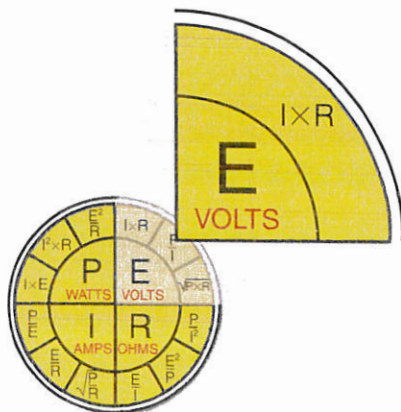
#### Solution:

Using Figure 1-38, cover the  $E$  with your finger and you have  $I \times R$  left over. Thus, the equation is:

$$E = 3 \text{ A} \times 20 \Omega$$

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

### Ohm's Law Circle



**Figure 1-38** Ohm's law circle is used to create a formula to find the unknown values in a circuit.

### Example

If a circuit has an applied voltage of 24 volts and has a current of 2 amps, what is the resistance of the circuit?

#### Solution:

Again, looking at Figure 1-38, cover the  $R$  and the equation becomes:

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

$$R = \frac{24 \text{ V}}{2 \text{ A}}$$

$$R = 12 \Omega$$

### Example

Solve for current in a circuit that has 120 ohms (resistance) and 240 volts of EMF.

#### Solution:

Referring to Figure 1-38, cover the  $I$  part of the diagram and the remaining variables are  $E$  and  $R$ , forming the equation:

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

$$I = \frac{240 \text{ V}}{120 \Omega}$$

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

Table 1-4

This table shows prefixes and numeric equivalents.

Number Value	Metric Prefix	Power of 10
1 000 000 000 000	Tera—T	$10^{12}$
1 000 000 000	Giga—G	$10^9$
1 000 000	Mega—M	$10^6$
1 000	Kilo—k	$10^3$
100	Hecto—h	$10^2$
10	Deka—da	$10^1$
1	Units or 1	$10^0$
0.1	Deci—d	$10^{-1}$
0.01	Centi—c	$10^{-2}$
0.001	Milli—m	$10^{-3}$
0.000 001	Micro— $\mu$	$10^{-6}$
0.000 000 001	Nano—n	$10^{-9}$
0.000 000 000 001	Pico—p	$10^{-12}$

## PREFIX MULTIPLIERS

As you have noticed in the preceding information, prefixes are often used to aid in dealing with small or large quantities of measure. These prefixes are used in many applications and are universally accepted because we use the powers of 10 in our decimal system. Electrical and electronic component and circuit values can be extremely small or very large.

Prefix multipliers are used to simplify the printing and use of small or large figures. For example, 0.001 is expressed using the prefix *milli*. Thus, 0.001 amperes may be expressed as 1 milliamperere. The method of applying such prefixes is straightforward. Divide the original value by the number value of the prefix and add the prefix. For example:

$$2,000 \text{ amperes} = 2,000/1,000 \text{ amperes} = 2 \text{ kiloamperes}$$

Note that prefix multipliers are sometimes abbreviated even further. The value 2 kiloamperes is usually expressed as 2 kA. Table 1-4 outlines the values, names, and powers of 10 for the most commonly used prefixes. When using prefixes, remember to convert the units to full unit values when

performing calculations. You cannot disregard the prefixes because there are significant figures involved with the computation.

### Example

A circuit has 12 k $\Omega$  and 120 V. Find the circuit current.

#### Solution:

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

$$I = \frac{120 \text{ V}}{12,000 \Omega}$$

$$I = 0.01 \text{ A (also denoted 10 mA)}$$

### Example

There is a complete circuit with 50 kV and a current of 50 A. What is the circuit resistance?

#### Solution:

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

$$R = \frac{50,000 \text{ V}}{50 \text{ A}}$$

$$R = 1,000 \Omega \text{ (also denoted 1 k}\Omega\text{)}$$

### Example

Find the voltage of a circuit when 30 mA flows through 60 k $\Omega$ .

**Solution:**

$$E = I \times R$$

$$E = .030 \text{ A} \times 60,000 \text{ ohms}$$

$$E = 1,800 \text{ V (also denoted 1.8 KV)}$$

## ELECTRICAL POWER

Another value that is helpful in designing and working on electrical circuits is the power requirement. In electricity, the unit of power is the **watt**. Power in a circuit is the amount of work being done per unit of time, represented as:

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

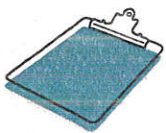
Power is what is consumed when a voltage (volts) is applied to a circuit and current (amps) flows through the

load. The relationship can be seen between the applied voltage and the current consumed by the load as power is consumed. This is represented as:

$$P = E \times I$$

The amount of power consumed by a load is directly related to the amount of voltage applied to the load and the amount of current flowing through the load. Using the water analogy, we can visualize a water wheel (Figure 1-39). As water flows to the water wheel, it causes the wheel to turn, producing mechanical work. If we increase the water flow (current), the wheel will turn faster or create more effort at the mechanical load. If we increase the pressure (voltage), the wheel will also do more work. The power (work / time) is dependent on the pressure and the flow (voltage and current).

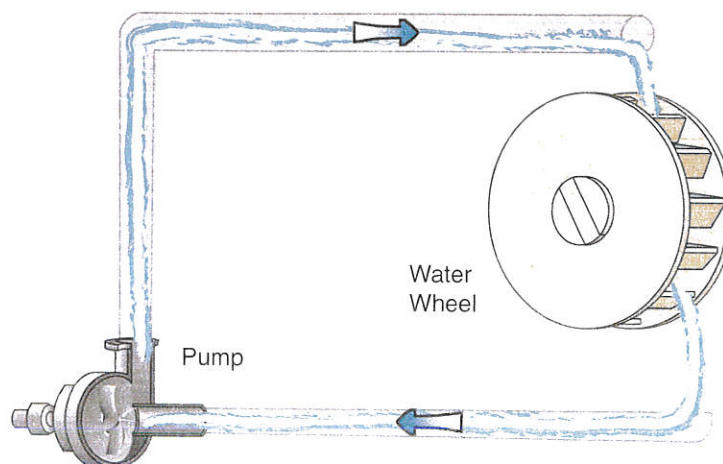
The load in the circuit uses the power to change or convert electrical energy into some other form of energy. For power to exist in an electrical circuit, this change must take place. The change may be in the form of current flow causing a heater element to heat up (change from electrical energy to heat) or a voltage supplied to a motor causing the motor to rotate (electrical energy to mechanical energy). The key point to remember is that the change or conversion from one form to another must take place.



### FieldNote!

The electrical unit of measurement for power is named after James Watt for his work on the power delivered by the steam engine.

### Water Wheel Analogy



**Figure 1-39** A water wheel analogy explains the concept of work: energy per time.

The more current that is allowed to flow through a circuit, the hotter the circuit becomes. This heat is produced by the collision of the flowing free electrons with the fixed atoms. But that is not the strange part. If the current is doubled, the heat produced will go up by four times, and if the current is tripled the heat produced goes up by nine times!

This showed early scientists that the heat produced, and hence the work being done in the circuit, was proportional to the force applied but not to the current. The proportion was of an unexpected nonlinear nature.

The heat produced by the current through the resistance in the circuit is called  $I^2R$  losses because it is heat lost in the system, also known as watt losses. The formula is found by combining the formula  $P = I \times E$  with the formula  $E = I \times R$ . By substituting ( $I \times R$ ) for  $E$  in the  $P = I \times (E)$  formula, i.e.,

$$(P = I \times [I \times R]),$$

you get

$$P = I^2R$$

Because of Joule's work on electrical heat, he is credited with proving the relationship between electrical power and current and was given the honor of having a unit named after him (the joule). The **joule** is an amount or unit of energy used to measure the heat or work produced or consumed in a system. In an electrical circuit, this is the heat produced or the work done in the circuit due to the amount of current flowing through it. The work used in heating a circuit is called lost work because this work cannot be used to move anything.

Because of the heat generated in electrical components, specifically resistors, a rating system has been developed so that components will not overheat during normal operation. This power rating is calculated with the following equations:

$$P = \frac{E^2}{R}$$

$$P = I \times E$$

Further, in solving for each of the values  $I$ ,  $E$ , and  $R$ , a relationship diagram can be derived. Using Figure 1-40,



## FieldNote!

English physicist James Prescott Joule (1818–1889) dealt with this problem of nonlinear proportionality. He wrote a paper in 1840 called "On the Production of Heat by Voltaic Electricity." In that paper, he explained his experiments—which we will not go into here. His conclusions are called Joule's law.

Joule's law states that "the total amount of heat produced in a conductor is directly proportional to the resistance times the square of the current" (see TechTip below). Mathematically, the heat (power) produced can be represented as:

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



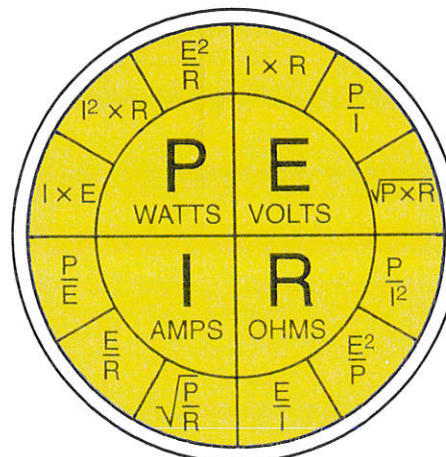
## TechTip!

Heat and light are produced with current and voltage. Heat is produced when current flows through the element in this light. This heat is lost work.



you can solve most equations involving power, current, voltage, and resistance. The chart shown in Figure 1-40 is derived by combining the formula  $E = I \times R$  with the formula  $P = I \times E$ . Other variations of the relationship between these variables can be found, such as  $I = \frac{P}{E}$  and  $E = \frac{P}{I}$ .

### Formula Chart



**Figure 1-40** A formula chart can be used to track watts and Ohm's law.

### Example

What is the voltage requirement for a circuit with resistance  $150\ \Omega$  and a current of  $12\ \text{A}$ , as shown in Figure 1-41?

#### Solution:

Using Figure 1-40, you can see that in the voltage quadrant there are three formulas to choose from. Because you know resistance and current, the equation becomes:

$$E = I \times R$$

$$E = 12\ \text{A} \times 150\ \Omega$$

$$E = 1,800\ \text{V}$$

### Example

What is the power lost due to heat in a motor that draws  $20\ \text{A}$  of current and has a resistance of  $5\ \Omega$ ?

#### Solution:

In Figure 1-40, the power quadrant shows that because you know current and resistance, the formula to use is:

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

$$P = 20^2 \times 5$$

$$P = 2,000\ \text{W}$$

### Example

A room heater has a rating of  $2,000\ \text{W}$  and uses  $120\ \text{V}$  to power it. What is the resistance of the heater?

#### Solution:

In Figure 1-40, the resistance quadrant shows that because you know the power and the voltage, the formula to use is:

$$P = \frac{E^2}{R}$$

or

$$R = \frac{E^2}{P}$$

$$R = \frac{120^2}{2,000}$$

$$R = 7.2\ \Omega$$

### Example

Using Figure 1-42, what is the power consumed by the lamp?

#### Solution:

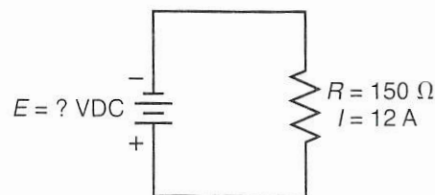
In Figure 1-40, the power quadrant shows that because you know the voltage and the current, the formula you use to solve for the circuit power is:

$$P = I \times E$$

$$P = 0.5\ \text{A} \times 10\ \text{V}$$

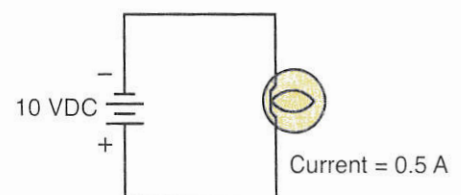
$$P = 5\ \text{W}$$

#### Example Calculation



**Figure 1-41** Use this circuit for the example calculations.

#### Example Calculation



**Figure 1-42** Use this simple DC circuit with lamp load for example calculations.

### Example

Assume, based on the circuit in Figure 1-42, that the circuit power was 75 W and the circuit voltage was 3 V. Calculate the circuit current.

#### Solution:

In Figure 1-40, the current quadrant shows that because you know the circuit power and circuit voltage, the formula you use to solve for the circuit is:

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

$$I = \frac{75 \text{ W}}{3 \text{ V}}$$

$$I = 25 \text{ A}$$

### Example

Assume that the circuit in Figure 1-42 has a circuit current of 7 amps and consumes 42 W of power. Calculate the circuit voltage.

#### Solution:

In Figure 1-40, the voltage quadrant shows that because you know the circuit current and the circuit power, the formula you use to solve for the circuit voltage would be:

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

$$E = \frac{42 \text{ W}}{7 \text{ A}}$$

$$E = 6 \text{ V}$$

## SAFETY AND ARCS

Electricity is a versatile form of energy and is also lethal. The electrical power can create electrocutions, create arc blasts and arc burns, ignite combustible vapors, and heat materials to a point that creates combustion. As an electrical worker, it is your job to keep the public safe as you deliver this power for their use. It is also your job, and maybe your life or livelihood, to

know how to work safely when around electrical circuits. According to the United States Occupational Safety and Health Administration (OSHA), there is one electrocution every day in the United States.

There are only two outcomes to an electrical shock. Either the victim survives and has some discomfort for a short duration (or lasting effects) or the victim dies from the shock. OSHA places the threshold voltage of electric shock at 50 V. This means that at 50 V of electrical pressure there is enough pressure to push current through your bare skin and into a circuit created by your body. Once a circuit is created through your body, the current through your body's blood and tissue creates severe damage. The electrical current that has entered your body also disrupts the electrical signals from your brain to your muscles, including your heart and lungs.

See Table 1-5 for the physiological damage to your body as current flows.

**Table 1-5**

Physiological effects of current on the human body are listed.

Amount of Current (mA)	Physical Reaction	Possible Results
1-4	Tingling sensation	Little danger from brief contact
5-10	Muscular contractions (can vary)	Difficult or impossible to let go/break away
11-39	Extreme-Severe contractions (throughout body)	No voluntary control while current continues
40-99	Respiratory arrest—until flow ceases Treatment—1st need to remove victim Secondary cardiac arrest can result	Short duration—breathing may resume Longer—may need resuscitation (CPR/ALST)
100-200	Ventricular fibrillation (possible seizures), burns, and tissue damage	Trained medical support must begin immediately, even if brief contact
201 and above	Respiration and cardiac arrest, severe burns, internal bleeding	Death

Note that the amount of current that creates muscular paralysis is quite small, meaning that you may not be able to free yourself from a live circuit. As the current flow increases, especially if it flows through your chest cavity and your vital organs, the heart may go into ventricular fibrillation with as little as 100 milliamps. **CAUTION: Do not create a path for current to flow through your body.**

Never work on a live circuit unless you must. There will be times when you need to work on live circuits, but OSHA and your employers do not want you to take chances if it is not necessary. The rules you need to follow are covered in National Fire Protection Association (NFPA) Document 70E, regarding safe work practices for electrical work. This document is a system for following the OSHA guidelines when working around electrical equipment. One of the main directives is to work deenergized whenever possible.

The systems should be turned off and tested to be sure there is no electrical power. They should then be locked out with your own lock and tagged to

identify that you are working on the system; this is referred to as lockout/tag-out (LOTO). Only you are supposed to remove your own lock when you finish working. You must not remove another worker's lock. There are specific procedures to follow to guarantee safe work practices for you and your co-workers and to maintain compliance with OSHA rules.

OSHA guidelines and the related NFPA 70E have established rules for working on live equipment. As the rules are updated, new editions of the regulations are published. You and your employer are responsible for being up to date on the regulations as they apply to your safety practices. Specifically, you need to be aware of the distance requirements designed to provide safety from contact with live parts of a system. There are charts that tell you what the approach distances are for equipment operating at different voltages.

Three main categories of approach distances are the limited approach, restricted approach, and prohibited approach (Figure 1-43).

OSHA Approach Distances					
Nominal System Voltage Range	Flash Protection Boundary	Limited Approach Boundary		Restricted Approach Boundary	Prohibited Approach Boundary
Phase to Phase		Exposed Moveable Conductor	Exposed Fixed Circuit Part	Includes Standard Inadvertent Movement Adder	Includes Reduced Inadvertent Movement Adder
<b>Energized Part to Employee (Distance in Feet—Inches)</b>					
300 V & less	3 ft 0 in.	10 ft 0 in.	3 ft 6 in.	Avoid Contact	
Over 300 V, not over 750 V	3 ft 0 in.	10 ft 0 in.	3 ft 6 in.	1 ft 0 in.	0 ft 1 in.
Over 750 V, not over 2 kV	4 ft 0 in.	10 ft 0 in.	4 ft 0 in.	2 ft 0 in.	0 ft 3 in.
Over 2 kV, not over 15 kV	16 ft 0 in.	10 ft 0 in.	5 ft 0 in.	2 ft 2 in.	0 ft 7 in.
Over 15 kV, not over 36 kV	19 ft 0 in.	10 ft 0 in.	6 ft 0 in.	2 ft 7 in.	0 ft 10 in.

**Figure 1-43** Examples of OSHA approach distances near live power are listed above.

Each distance has special conditions, with the “prohibited” being the category that assumes you may be in contact with the live electrical conductor. This means that you need specific “voltage-rated” tools (Figure 1-44), including voltage-rated gloves (Figure 1-45) and safety glasses.

Another hazard of working on live parts is the risk of arc flash and arc blast. As you already know, when electricity moves through the air it creates an arc (such as lightning). It creates extreme heat—up to 35,000 degrees Fahrenheit at the arc. This extreme heat melts copper conductors and just about everything else near the arc. The extreme heat and light are known as the arc flash. This flash can burn unprotected skin, and its heat can set clothes on fire. The flash can cause temporary blindness or long-term eye problems. You must be protected from this extreme heat and light.

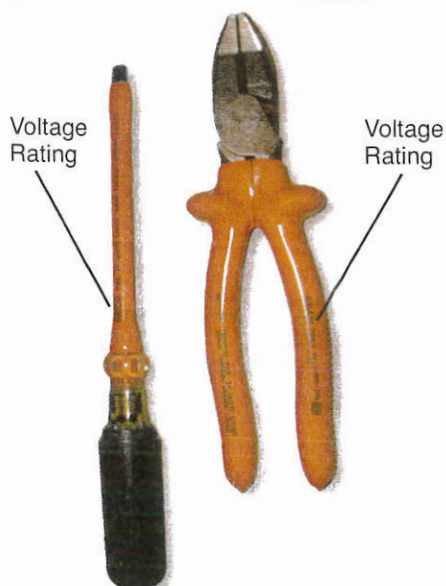
Use fire-rated (FR) clothing designed for the amount of heat that could be present. This heat is expressed as calories per square centimeter of “incident energy.” Different categories of FR clothes create the

needed protection. To protect yourself adequately, a “flash hazard analysis” is calculated on the basis of the amount of current present if a short circuit occurs, the time the arc is allowed to burn, and the distance the person is from the arc.

The distance you may see on a rating is called the “flash protection boundary.” This distance refers to how far you must be from the flash to sustain a burn that is “just curable” according to OSHA. “Just curable” means that it might be a second-degree burn but not a third-degree burn. Ask your safety representative about clothing and gear that protects you from arc flash injuries.

The other dimension of an arc is the blast or the explosion that occurs as the gases expand around the superheated arc. The blast propels materials and molten metal toward you. It may blow you out of the equipment or pelt you with molten material, creating bodily injury. The hot gases that are expanding may knock the air from your lungs. Your natural reaction is to try to breathe again, possibly inhaling hot gases and molten metal.

#### Voltage-Rated Tools



**Figure 1-44** Voltage-rated tools must have a voltage rating marked on them.

#### Personal Protective Equipment



**Figure 1-45** Gloves for working on live equipment must have voltage rating marks and must be tested.

### Ground Fault Circuit Interrupter



**Figure 1-46** Ground fault circuit interrupter (GFCI) receptacle style.

We need to follow all safety rules as we learn to work efficiently and effectively. A basic knowledge of fire extinguishing and the types of extinguisher to use on electrical fires is essential. Look around your surroundings and try to determine the fastest escape route if there were a fire or another emergency. Assess the type of equipment and the construction materials around you. Is the building construction wood or concrete and steel? Are there flammable materials or gases used for welding or for temporary heating stored nearby? Are the housekeeping and cleanup adequate to prevent injury or fires? Are there fire extinguishers nearby?

Look to be sure you are using the right type of extinguisher on a fire. Type A fires are combustibles such as wood, paper, and cloth (on which type A ex-

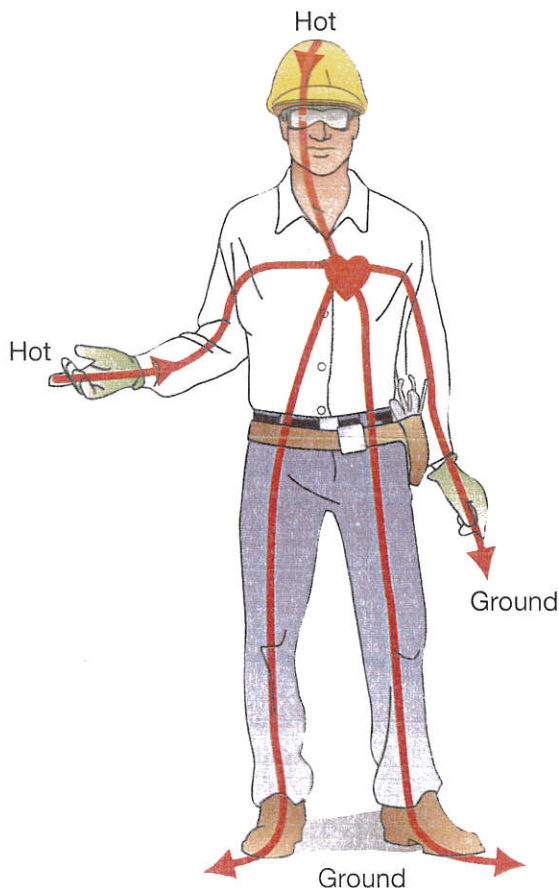
tinguishers are used). Type B fires are flammable liquids and gases. Type C fires are electrical fires where the source may still be energized. These fires are smothered by type C extinguishers. Never use water on a live electrical fire. Type D fires are combustible metals.

There are several types of circuit protections designed to prevent electrical circuits from starting fires or electrocuting people. Fuses or circuit breakers are intended to protect the premises from fire caused by overheating wiring or from ignition due to short circuits. The fuse is an in-line device that will melt open if the current through the circuit conductor (wire) becomes too great based on the accepted limits of the conductor (wire) size. As the current exceeds the specified value, the fuse melts open (or the circuit breaker trips), severing the circuit path to the conductor (wire). Therefore, the circuit is allowed to cool before it can generate enough heat to cause a fire. The protective device can open in time with a slight overload, or may open quickly with a large overload of current (as in a short circuit).

Another type of protection is for personnel. A device called a ground fault circuit interrupter (GFCI) is used to monitor not only the amount of current leaving the source (as a circuit breaker does) but the current returning to the source. In a class A GFCI, the amount of current going and coming must be within 5 mA of each other. If there is a larger discrepancy than that, the protection will shut off the circuit. The assumption is that the current left the source and may be returning through a person to the source and not through the intended wiring. See Figure 1-46 for an example of a home receptacle type of GFCI.

Figure 1-47 illustrates the case where current passes through a person rather than the wiring. If you refer to Table 1-5 you will notice that 5 mA is the threshold where a person may not be able to let go of a live circuit and the current is passing through their body. If the circuit shuts off at this point, little

### Possible Current Paths



**Figure 1-47** These possible current paths through the body can cause severe damage.

permanent damage results. The person feels the shock but will be okay. This is considered personnel protection.

Another type of protection now mandated in the *National Electrical Code*<sup>®</sup> is called an arc fault circuit interrupter (AFCI, Figure 1-48). The AFCI is designed to determine if there is an arc in the protected circuitry that could start a fire. If a cord-and-plug-connected device has a faulty cord and is actually arcing across the broken cord, it may not draw enough current to trip a circuit breaker but may cause enough heat to start a fire. This is a particularly common occurrence in bedrooms where cords get pinched behind beds or dressers. The AFCI circuit detects an arcing fault and shuts off the circuit.

#### Arc Fault Circuit Interrupter



**Figure 1-48** Arc fault circuit interrupter (AFCI).

## SUMMARY

What is electricity and how do we measure it? You have not looked at the electrical systems from the subatomic view yet, but you have gained a little insight into how electricity is actually measured and an understanding of what the essential components of an electrical circuit are. You have been introduced to the ideas of current flow, electrical pressure or voltage, the resistance to current flow measured in ohms, and electrical work measured in watts.

You have been able to see how meters are connected to measure circuit quantities and use these measured quantities with Ohm's law to determine circuit parameters. With these measurements, we found that some quantities are very large and some are very small, leading to the "shorthand" method of using prefixes to describe

the multipliers used in notation. Prefixes such as milli (m) and micro ( $\mu$ ) as well as kilo (K) and mega (M) are in everyday use in the electrical field, and it will take some time to get used to them.

As you start making measurements and working with live power, it is essential that you stay alert and have a solid understanding of the dangers involved with electrical work. A short explanation of electrical safety was included to make you aware of some of the safety systems available to you. You are ultimately responsible for your own safety. Do not take chances and do not assume you can just try electrical connections you are not sure of. As you continue to learn about electrical systems, you will become more capable and be able to do more complex jobs, but always think about the safest way of accomplishing the task.

## CHAPTER GLOSSARY

**Ampere** The unit of electrical current flow, often abbreviated as amp or just A. It is a measure of the movement of electrons as 1 coulomb per second past a fixed point.

**Circuit** A completed path for current to flow from a source of current through a load and back to the source of current.

**Conventional current flow** The theory in which current flows from a positive charge to a negative charge; also known as hole flow or positive current flow.

**Coulomb** The unit of electrical charge equal to the total charge possessed by  $6.25 \times 10^{18}$  electrons. Abbreviated C.

**Current** The flow of electrons through a material. Measured in amperes.

**Electricity** A class of phenomena that results from the interaction of objects that exhibit a charge (electrons and protons). In its static form, electricity exhibits many similarities with another naturally occurring force—magnetism.

**Electromotive force (EMF)** Electrical pressure created between a region of positive charge (fewer electrons) and a region of negative charge (more electrons), measured in volts and represented in formulas with "E".

**Electron current flow** The theory in which current flows from a negative charge to a positive charge.

**Joule** A joule refers to the amount of energy. One joule of energy used each second is equal to 1 W of work. One joule is the amount of energy used when 0.737 pounds is lifted a distance of 1 foot.

**Ohm's law** The mathematical relationship among current, electrical potential, and electrical resistance, measured in amperes (amps), volts, and ohms, respectively.

**Ohm** The unit of electrical resistance, often shown as the Greek letter omega ( $\Omega$ ).

**Resistance** The physical opposition to electrical current. Resistance (measured in ohms) is caused by the energy loss that occurs when an electron displaces other electrons in a valence ring.

**Watt (W)** The unit of electrical power. One horsepower is equal to 745.7 W or approximately 746 W.

## REVIEW QUESTIONS

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1. Define current flow in terms of amperes and coulombs.
  2. Write Ohm's law in its three forms.
  3. Describe the concept of electron current flow.
  4. What is conventional current flow (also called hole flow)?
  5. What is a coulomb, and how does it relate to electric current?
  6. Calculate the resistance of a circuit with 10 mA and 100 V.
  7. Calculate the current of a circuit with 50 k  $\Omega$  and 500 mV.
  8. Describe the differences among closed circuits, open circuits, and short circuits.
  9. If a circuit has 50 V and 10 A of current, find the watts dissipated.
  10. Explain the different ways of measuring current in a circuit.
- For questions 11 through 15, choose the correct term in parentheses.
11. When connecting a voltmeter, connect in (series, parallel) with the component.
  12. Electrocutation is caused by (current, voltage) as it passes through your body.
  13. An essential precaution while using an ohmmeter when measuring resistance in a circuit is to have power (connected, disconnected).
  14. When connecting an analog ammeter, the negative meter lead goes to the (positive, negative) side of the circuit.
  15. At the flash protection boundary, you could receive a burn that is (just curable, incurable) on exposed skin.