2 VOLTAGE, CURRENT, AND RESISTANCE

CHAPTER OUTLINE

2–1 Atomic Structure
2–2 Electrical Charge
2–3 Voltage
2–4 Current
2–5 Resistance
2–6 The Electric Circuit
2–7 Basic Circuit Measurements
2–8 Electrical Safety
Application Activity

CHAPTER OBJECTIVES

- Describe the basic structure of atoms
- Explain the concept of electrical charge
- Define *voltage* and discuss its characteristics
- Define *current* and discuss its characteristics
- Define *resistance* and discuss its characteristics
- Describe a basic electric circuit
- Make basic circuit measurements
- Recognize electrical hazards and practice proper safety procedures

KEY TERMS

- Atom
- Electron
- Free electron
- Conductor
- Semiconductor
- Insulator
- Charge
- Coulomb's law
- Coulomb
- Voltage
- Volt
- Voltage source
- Power supply
- Current
- Ampere
- Current source
- Resistance
- Ohm
- Conductance
- Siemens
- Resistor
- Potentiometer
- Rheostat
- Strain gauge
- Circuit
- Load
- Closed circuit
- Open circuit
- Pole
- Throw
- AWG
- Ground
- Reference ground
- Voltmeter
- Ammeter
- Ohmmeter
- DMM
- Electrical shock

APPLICATION ACTIVITY PREVIEW

In this application activity, you will see how the theory presented in this chapter is applied to a practical circuit that simulates part of a car's instrument panel lighting system. An automobile's lights are examples of simple types of electric circuits. When you turn on the headlights and taillights, you are connecting the lamps to the battery, which provides the voltage and produces current through each lamp. The current causes the lamps to emit light. The lamps themselves have resistance that limits the amount of current. The instrument panel lamp in most cars can be adjusted for brightness. By turning a knob, you change the resistance in the circuit, thereby causing the current to change. The amount of current through the lamp determines its brightness.

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Study aids for this chapter are available at http://www.pearsonhighered.com/careersresources/

INTRODUCTION

The theoretical concepts of electrical current, voltage, and resistance are introduced in this chapter. You will learn how to express each of these quantities in the proper units and how each quantity is measured. The essential elements that form a basic electric circuit and how they are put together are covered.

Types of devices that generate voltage and current are introduced. Also, you will see a variety of components that are used to introduce resistance into electric circuits. The operation of protective devices such as fuses and circuit breakers are discussed, and mechanical switches commonly used in electric circuits are introduced. You will learn how to control and measure voltage, current, and resistance using laboratory instruments.

Voltage is essential in any kind of electric circuit. Voltage is the potential energy of electrical charge required to make the circuit work. Current is also necessary for electric circuits to operate, but it takes voltage to produce the current. Current is the movement of electrons through a circuit. Resistance in a circuit limits the amount of current. A water system can be used as an analogy for a simple circuit. Voltage can be considered analogous to the pressure required to force water through the pipes. Current through wires can be thought of as analogous to the water moving through the pipes. Resistance can be thought of as analogous to the restriction on the water flow produced by adjusting a valve.

2–1 ATOMIC STRUCTURE

All matter is made of atoms; and all atoms consist of electrons, protons, and neutrons. In this section, you will learn about the structure of an atom, including electron shells and orbits, valence electrons, ions, and energy levels. The configuration of certain electrons in an atom is the key factor in determining how well a given conductive or semiconductive material conducts electric current.

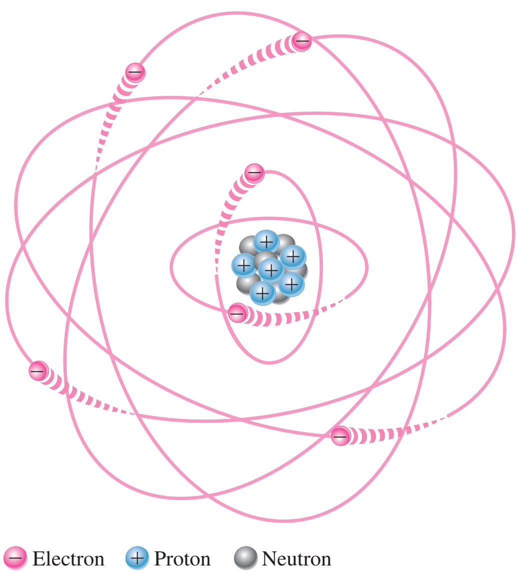
After completing this section, you should be able to

- **Describe the basic structure of atoms**
    - Define *nucleus*, *proton*, *neutron*, and *electron*
    - Define *atomic number*
    - Define *shell*
    - Explain what a valence electron is
    - Describe ionization
    - Explain what a free electron is
    - Define *conductor*, *semiconductor*, and *insulator*

HISTORY NOTE

Niels Bohr was a Danish physicist that is best known for his planetary model of the structure of the atom, which he first described in a 1913 paper. His atomic model with some modifications still stands as a useful tool to explain chemical and physical properties of the elements. Bohr received the Nobel Prize in 1922 and later element 107 was named in his honor (Bohrium, Bh).

An **atom** is the smallest particle of an **element** that retains the characteristics of that element. An **element** is a substance that cannot be broken down into a simpler substance by chemical means. The number of known elements is now 118, although only 94 of these occur naturally. Each of these known elements has atoms that are different from the atoms of all other elements. This gives each element a unique atomic structure. According to the classic Bohr model, an atom is visualized as having a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons, as illustrated in Figure 2–1. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons**. The basic particles of negative charge are called **electrons**, which orbit the nucleus. The positive charge on a proton and the negative charge on an electron are the smallest charges that can exist in isolation.



▲ **FIGURE 2–1**

The Bohr model of an atom showing electrons in circular orbits around the nucleus. The "tails" on the electrons indicate they are in motion.

Each type of atom has a certain number of protons that distinguishes it from the atoms of all other elements. For example, the simplest atom is that of hydrogen, which has one proton and one electron, as pictured in Figure 2–2(a). As another example, the helium atom, shown in Figure 2–2(b), has two protons and two neutrons in the nucleus and two electrons orbiting the nucleus.

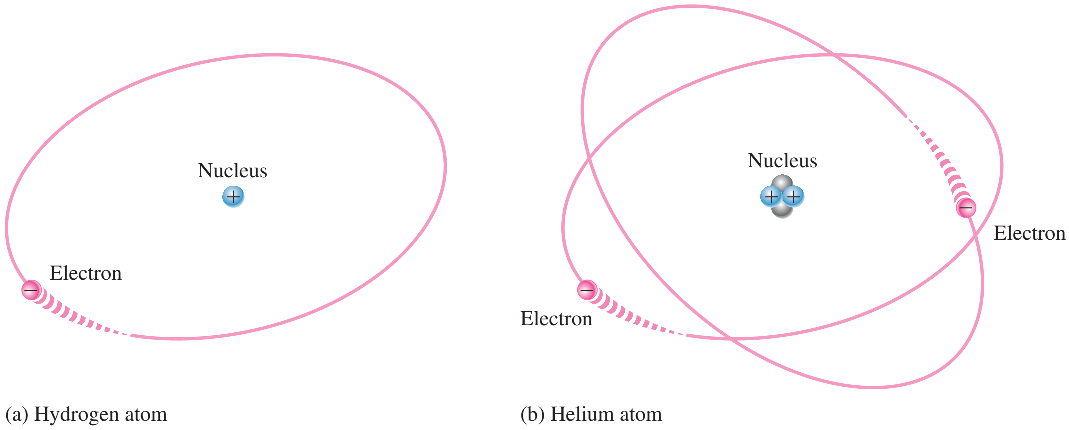


FIGURE 2–2

The two simplest atoms, hydrogen and helium.

Atomic Number

All elements are arranged in the periodic table of the elements in order according to their **atomic number**. The atomic number equals the number of protons in the nucleus. For example, hydrogen has an atomic number of 1 and helium has an atomic number of 2. In their normal (or neutral) state, all atoms of a given element have the same number of electrons as protons; the positive charges cancel the negative charges, and the atom has a net charge of zero, making it electrically balanced.

Shells, Orbits, and Energy Levels

As you have seen in the Bohr model, electrons orbit the nucleus of an atom at certain distances from the nucleus and are restricted to these specific orbits. Each orbit corresponds to a different energy level within the atom known as a **shell**. The shells are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. Electrons further from the nucleus are at higher energy levels.

The line spectrums of hydrogen from the Bohr model of the atom shows that the electrons can only absorb or emit a specific amount of energy that represents the exact difference between the levels. Figure 2–3 shows the energy levels within the

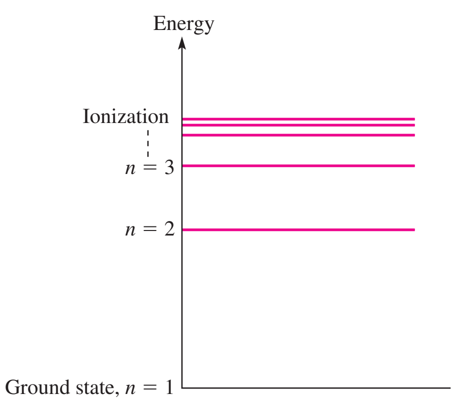


FIGURE 2–3

Energy levels in hydrogen.

hydrogen atom. The lowest level ($n = 1$) is called the *ground state* and represents the most stable atom with a single electron in the first shell. If this electron acquires a specific amount of energy by absorbing a photon, it can be raised to one of the higher energy levels. In this higher state, it can emit a photon with exactly the same energy and return to the ground state. Transitions between the levels account for various phenomena we see in electronics, such as the color of light from a light-emitting diode.

After Bohr's work, Erwin Schroedinger (1887–1961) proposed a mathematical theory for the atom that explained more complicated atoms. He suggested that the electron has a wavelike property, and he considered the simplest case as having a three-dimensional standing wave pattern due to vibrations. Schroedinger theorized the standing wave of an electron with a spherical shape could have only certain wavelengths. This wave-mechanics model of the atom gave the same equation for the electron energy in hydrogen as Bohr's model, but in the wave-mechanics model, more complicated atoms could be explained by involving shapes other than spheres and adding a designation for the orientation of a given shape within the atom. In both models, electrons near the nucleus have less energy than those further out, which was the basic concept of the energy levels.

The idea of discrete energy levels within the atom is still a foundation for understanding the atom, and the wave-mechanics model has been very successful at predicting the energy levels for various atoms. The wave-mechanics model of the atom used the shell number, called the *principal quantum number,* in the energy equation. Three other quantum numbers describe each electron within the atom. All electrons in an atom have a unique set of quantum numbers.

When an atom is part of a large group, as in a crystal, the discrete energy levels broaden into energy bands, which is an important idea in solid-state electronics. The bands also differentiate between conductors, semiconductors, and insulators.

Valence Electrons

Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Electrons with the highest energy levels exist in the outermost shell of an atom and are relatively loosely bound to the atom. This outermost shell is known as the **valence** shell, and electrons in this shell are called **valence electrons**. These valence electrons contribute to chemical reactions and bonding within the structure of a material, and they determine the material's electrical properties.

Energy Levels and Ionization Energy

If an electron absorbs a photon with sufficient energy, it escapes from the atom and becomes a **free electron** that can move under the influence of an electric or magnetic field. This is indicated by the ionization energy level in Figure 2–3. Any time an atom or group of atoms is left with a net charge, it is called an **ion**. When an electron escapes from the neutral hydrogen atom (designated H), the atom is left with a net positive charge and becomes a *positive ion* (designated H^+). In other cases, an atom or group of atoms can acquire one or more extra electrons, in which case it is called a *negative ion*.

The Copper Atom

Copper is the most commonly used metal in **electrical** applications. The copper atom has 29 electrons that orbit the nucleus in four shells. The number of electrons in each shell follows a predictable pattern according to the formula, $2N^2$, where N is the number of the shell. The first shell of any atom can have up to two electrons, the second shell up to eight electrons, the third shell up to 18 electrons, and the fourth shell up to 32 electrons.

A copper atom is represented in Figure 2–4. Notice that the fourth or outermost shell, the valence shell, has only one valence electron. The inner shells are called the *core*. When the valence electron in the outer shell of the copper atom gains sufficient thermal energy,

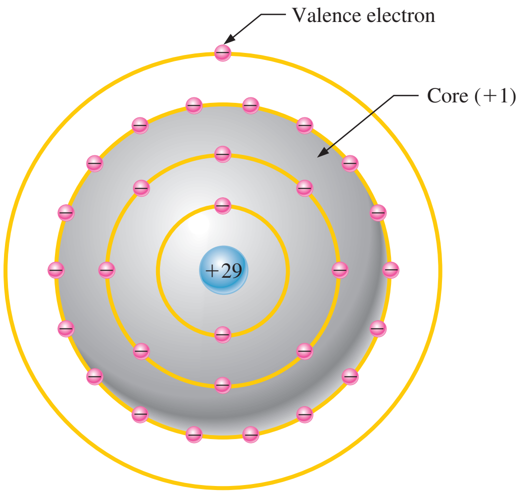


FIGURE 2–4

The copper atom.

it can break away from the parent atom and become a free electron. In a piece of copper at room temperature, a "sea" of these free electrons is present. These electrons are not bound to a given atom but are free to move in the copper material. Free electrons make copper an excellent conductor and make electrical current possible.

Categories of Materials

Three categories of materials are used in electronics: conductors, semiconductors, and insulators.

Conductors **Conductors** are materials that readily allow current. They have a large number of free electrons and are characterized by one to three valence electrons in their structure. Most metals are good conductors. Silver is the best conductor, and copper is next. Copper is the most widely used conductive material because it is less expensive than silver. Copper wire is commonly used as a conductor in electric circuits.

Semiconductors **Semiconductors** are classed below the conductors in their ability to carry current because they have fewer free electrons than do conductors. Semiconductors have four valence electrons in their atomic structures. However, because of their unique characteristics, certain semiconductor materials are the basis for **electronic** devices such as the diode, transistor, and integrated circuit. Silicon and germanium are common semiconductive materials.

Insulators **Insulators** are nonmetallic materials that are poor conductors of electric current; they are used to prevent current where it is not wanted. Insulators have no free electrons in their structure. The valence electrons are bound to the nucleus and not considered "free." Most practical insulators used in electrical and electronic applications are compounds such as glass, porcelain, teflon, and polyethylene, to name a few.

SECTION 2–1 CHECKUP
Answers are at the end of the chapter.

1. What is the basic particle of negative charge?
2. Define *atom*.
3. What does an atom consist of?
4. Define *atomic number*.
5. Do all elements have the same types of atoms?
6. What is a free electron?
7. What is a shell in the atomic structure?
8. Name two conductive materials.

2–2 Electrical Charge

As you know, an electron is the smallest particle that exhibits negative electrical charge. When an excess of electrons exists in a material, there is a net negative electrical charge. When a deficiency of electrons exists, there is a net positive electrical charge.

After completing this section, you should be able to

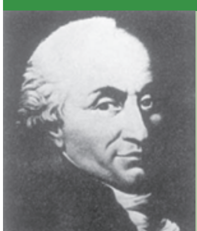
- **Explain the concept of electrical charge**
  - Name the unit of charge
  - Name the types of charge
  - Discuss attractive and repulsive forces
  - Determine the amount of charge on a given number of electrons

The charge of an electron and that of a proton are equal in magnitude but opposite in polarity. Electrical **charge** is an electrical property of matter that exists because of an excess or deficiency of electrons. Charge is symbolized by the letter Q. Static electricity is the presence of a net positive or negative charge in a material. Everyone has experienced the effects of static electricity from time to time, for example, when attempting to touch a metal surface or another person or when the clothes in a dryer cling together.

As suggested originally by Michael Faraday, there is an electric field surrounding every charge that is directed radially away from the charge. Any other charge that enters the region will experience a force due to the presence of the field created by this charge. *It is the electric field that exerts the force on another charge*. Likewise, the second charge has its own field that exerts a force on the first change. Physicists define the electric field at some point as the force exerted on a test charge at the point divided by the charge. The electric field is a vector quantity; this means it has a direction and magnitude.

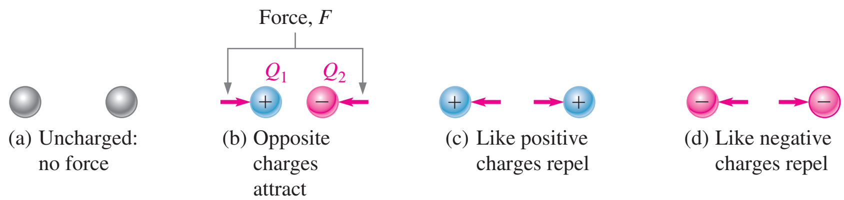
Materials with charges of opposite polarity are attracted to each other, and materials with charges of the same polarity are repelled, as indicated in Figure 2–5. A force acts between charges, as evidenced by the attraction or repulsion. In the case of oppositely charged plates, there will be an electric field between the plates due to all of the charges present. This electric field is represented by arrows drawn from the positive plate to the negative plate. This field exerts a force on all of the charges as illustrated by Figure 2–6.

HISTORY NOTE



Charles Augustin Coulomb, 1736–1806

Coulomb, a Frenchman, spent many years as a military engineer. When bad health forced him to retire, he devoted his time to scientific research. He is best known for his work on electricity and magnetism due to his development of the inverse square law for the force between two charges. The unit of electrical charge is named in his honor. (Photo credit: Leaflet on COULOMB by H. Volkringer – Research Director at CNRS

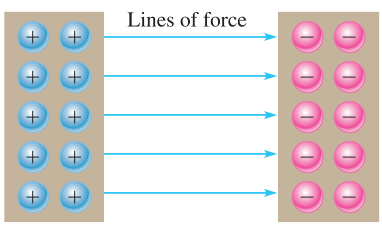


▲ **FIGURE 2–5**

Attraction and repulsion of electrical charges.

► **FIGURE 2–6**

Electric field between two oppositely charged surfaces as represented by lines of force.



Coulomb's law states

A force (F) exists between two point-source charges (Q_1, Q_2) that is directly proportional to the product of the two charges and inversely proportional to the square of the distance (d) between the charges.

Coulomb: The Unit of Charge

Electrical charge (Q) is measured in coulombs, symbolized by C.

One coulomb is the total charge possessed by 6.25×10^{18} electrons.

A coulomb is a very large amount of charge. A single electron has a charge of only 1.6×10^{-19} C. The total charge Q, expressed in coulombs, for a given number of electrons is stated in the following formula:

$$Q = \frac{\text{number of electrons}}{6.25 \times 10^{18}\ \text{electrons/C}}$$

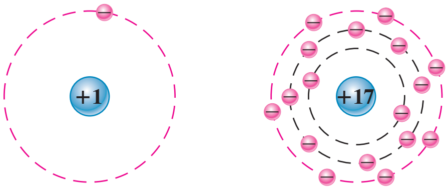
Equation 2–1

Positive and Negative Charge

Consider a neutral atom—that is, one that has the same number of electrons and protons and thus has no net charge. As you know, when a valence electron is pulled away from the atom by the application of energy, the atom is left with a net positive charge (more protons than electrons) and becomes a *positive ion*. If an atom acquires an extra electron in its outer shell, it has a net negative charge and becomes a *negative ion*.

The amount of energy required to free a valence electron is related to the number of electrons in the outer shell. An atom can have up to eight valence electrons. The more complete the outer shell, the more stable the atom and thus the more energy is required to remove an electron. Figure 2–7 illustrates the creation of a positive ion and a negative ion when a hydrogen atom gives up its single valence electron to a chlorine atom, forming gaseous hydrogen chloride (HCl). When the gaseous HCl is dissolved in water, hydrochloric acid is formed.

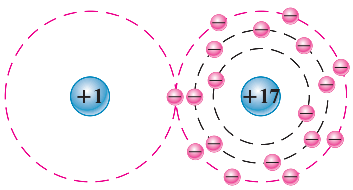
FIGURE 2–7
Example of the formation of positive and negative ions.



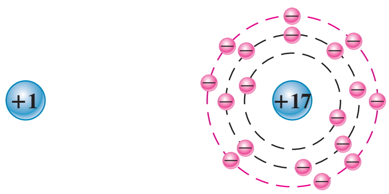
Hydrogen atom
(1 proton, 1 electron)

Chlorine atom
(17 protons, 17 electrons)

(a) The neutral hydrogen atom has a single valence electron.



(b) The atoms combine by sharing the valence electron to form gaseous hydrogen chloride (HCl).



Positive hydrogen ion
(1 proton, no electrons)

Negative chloride ion
(17 protons, 18 electrons)

(c) When dissolved in water, hydrogen chloride gas separates into positive hydrogen ions and negative chloride ions. The chlorine atom retains the electron given up by the hydrogen atom forming both positive and negative ions in the same solution.

EXAMPLE 2–1

How many coulombs do 93.8×10^{16} electrons represent?

Solution

$$Q = \frac{\text{Number of electrons}}{6.25 \times 10^{18}\ \text{electrons/C}} = \frac{93.8 \times 10^{16}\ \text{electrons}}{6.25 \times 10^{18}\ \text{electrons/C}} = 15 \times 10^{-2}\ \text{C} = \mathbf{0.15\ C}$$

*Related Problem**

How many electrons does it take to have 3 C of charge?

*Answers are at the end of the chapter.

SECTION 2–2 CHECKUP

1. What is the symbol for charge?
2. What is the unit of charge, and what is the unit symbol?
3. What causes positive and negative charge?
4. How much charge, in coulombs, is there in 10×10^{12} electrons?

2–3 Voltage

As you have seen, a force of attraction exists between a positive and a negative charge. A certain amount of energy must be exerted, in the form of work, to overcome the force and move the charges a given distance apart. All opposite charges possess a certain potential energy because of the separation between them. The difference in potential energy per charge is the potential difference or **voltage**. Voltage is the driving force, sometimes called electromotive force or emf, in electric circuits and is what establishes current.

After completing this section, you should be able to

- **Define *voltage* and discuss its characteristics**
    - State the formula for voltage
    - Name and define the unit of voltage
    - Describe the basic sources of voltage

HISTORY NOTE

Alessandro Volta 1745–1827

Volta, an Italian, invented a device to generate static electricity and he also discovered methane gas. Volta investigated reactions between dissimilar metals and developed the first battery in 1800. Electrical potential, more commonly known as voltage, and the unit of voltage, the volt, are named in his honor. (Photo credit: AIP Emilio Segrè Visual Archives, Lande Collection.)

Voltage, symbolized by V, is defined as energy or work per unit charge.

$$V = \frac{W}{Q} \qquad \text{Equation 2–2}$$

where V is voltage in volts (V), W is energy in joules (J), and Q is charge in coulombs (C). Some sources use E instead of V to stand for voltage, but V is used throughout this text.

As an analogy, consider a water tank that is supported several feet above the ground. A given amount of energy must be exerted in the form of work to pump water up to fill the tank. Once the water is stored in the tank, it has a certain potential energy which, if released, can be used to perform work.

The Volt

The unit of voltage is the volt, symbolized by V.

One volt is the potential difference (voltage) between two points when one joule of energy is used to move one coulomb of charge from one point to the other.

EXAMPLE 2–2

If 50 J of energy are required to move 10 C of charge, what is the voltage?

Solution

$$V = \frac{W}{Q} = \frac{50\ \text{J}}{10\ \text{C}} = \mathbf{5\ V}$$

Related Problem How much energy is required to move 50 C from one point to another when the voltage between the two points is 12 V?

The Voltage Source

A **voltage source** provides electrical energy or electromotive force (emf), more commonly known as *voltage*. Voltage can be produced by means of chemical energy, light energy, or magnetic energy combined with mechanical motion.

The Ideal Voltage Source An ideal voltage source can provide a constant voltage for any current required by a circuit. The ideal voltage source does not exist but can be closely approximated in practice. For purposes of analysis the ideal source is assumed unless otherwise specified.

Voltage sources can be either dc or ac. A common symbol for a dc voltage source is shown in Figure 2–8(a) and one for an ac voltage source is shown in part (b). AC voltage sources will be used later in the book.

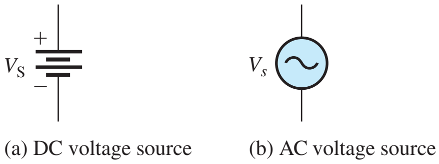


FIGURE 2–8

Symbols for voltage sources.

A graph showing voltage versus current for an ideal dc voltage source is illustrated in Figure 2–9. As you can see, the voltage is constant for any current (within limits) from the source. For a practical voltage source connected in a circuit, the voltage decreases slightly as the current increases, as shown by the dashed curve. Current is always drawn from a voltage source when a load such as a resistance is connected to it.

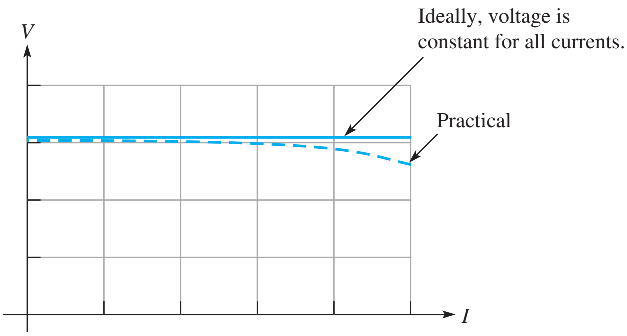


FIGURE 2–9

Voltage source graph.

Types of DC Voltage Sources

Batteries A **battery** is a type of voltage source that converts chemical energy directly into electrical energy. As you know, work (or energy) per charge is the basic unit for voltage, and a battery adds energy to each unit of charge. It is something of a misnomer to talk about "charging a battery" because a battery does not store charge but rather stores chemical potential energy. All batteries use a specific type of chemical reaction called an *oxidation-reduction reaction*. In this type of reaction, electrons are transferred from one reactant to the other. If the chemicals used in the reaction are separated, it is possible to cause the electrons to travel in the external circuit, creating current. There is an equal current internally in the battery that is composed of moving ions. Ions move through the conductive solution in the battery (the *electrolyte*). As long as there is an external path for the electrons, the reaction can proceed, and stored chemical energy is converted to electrical current. If the path is broken, the reaction stops and the battery is said to be in equilibrium. In a battery, the terminal that supplies electrons has a surplus of electrons and is the negative electrode or **anode**. The electrode that acquires electrons has a positive potential and is the **cathode**.

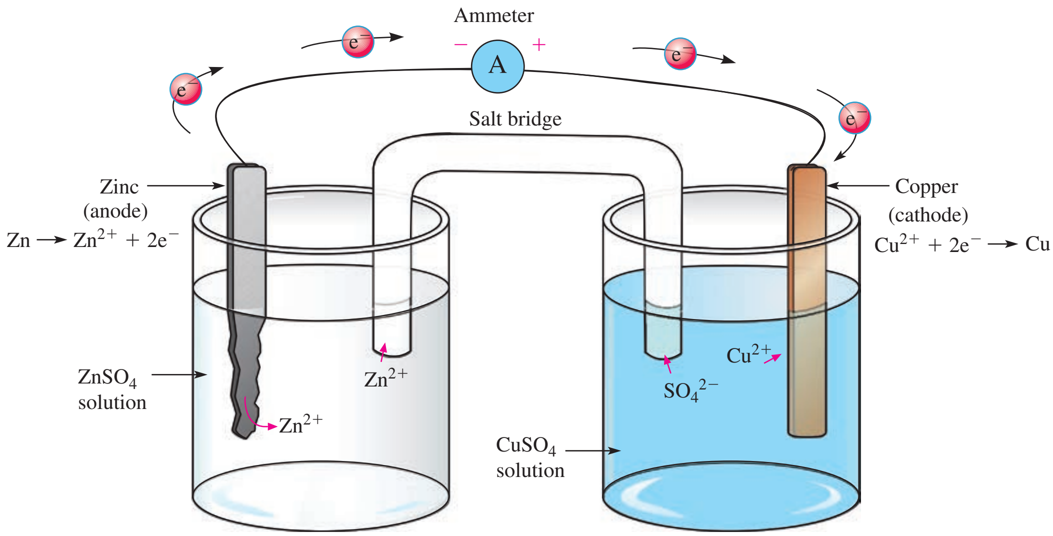


FIGURE 2–10

A copper-zinc battery. The reaction can only occur if an external path is provided for the electrons. As the reaction proceeds, the Zn anode is eaten away and Cu^{2+} ions combine with electrons to form copper metal on the cathode.

SAFETY NOTE

Lead-acid batteries can be dangerous because sulfuric acid is highly corrosive and battery gases (primarily hydrogen) are explosive. The acid in the battery can cause serious eye damage if it contacts the eye and can cause skin burns or destroy clothing. You should always wear eye protection when working on or around batteries and wash well after handling batteries.

When removing a battery from service, make sure the switch is off. When a cable is removed, a spark may be created and ignite the explosive battery gases.

TECH NOTE

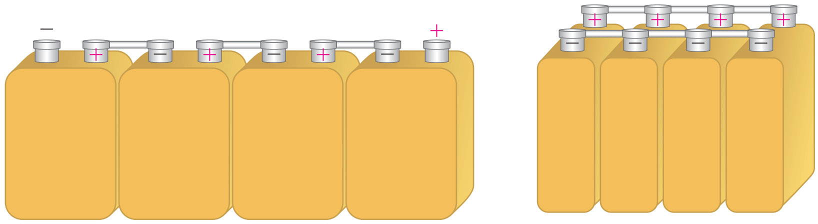
To store a lead-acid battery for an extended period, it should be fully charged and placed in a cool, dry location that is protected from freezing or excessive heat. A battery will self-discharge over time, so it needs to be periodically checked and recharged when it is less than 70% fully charged. Battery manufacturers will have specific recommendations for storage on their websites.

Figure 2–10 shows a nonrechargeable single-cell copper-zinc battery that we will use for illustration of battery operation. The copper-zinc cell is simple to construct and illustrates concepts common to all nonrechargeable batteries. A zinc electrode and a copper electrode are immersed in solutions of zinc sulfate ($ZnSO_4$) and copper sulfate ($CuSO_4$), which are separated by a salt bridge that prevents the Cu^{2+} ions from reacting directly with the Zn metal. The zinc metal electrode supplies Zn^{2+} ions to the solution and electrons to the external circuit, so this electrode is constantly eaten away as the reaction proceeds. The salt bridge allows ions to pass through it to maintain charge balance in the cell. There are no free electrons in the solutions, so an external path for electrons is provided through an ammeter (in our case) or other load. On the cathode side, the electrons that were given up by the zinc combine with copper ions from the solution to form copper metal, which deposits on the copper electrode. The chemical reactions (shown in the diagram) occur at the electrode. Different types of batteries have different reactions, but all involve transfer of electrons in the external circuit.

A single cell will have a certain fixed voltage. In the copper-zinc cell, the voltage is 1.1 V. In a lead-acid cell, the kind used in car batteries, a potential difference of about 2.1 V is between the anode and cathode. The voltage of any cell depends on the cell chemistry. Nickel-cadmium cells are about 1.2 V and lithium cells can be as high as almost 4 V. Cell chemistry also determines the shelf life and discharge characteristics for a battery. For example, a lithium-MnO_2 battery typically has five times the shelf life of a comparable carbon-zinc battery.

Although the voltage of a battery cell is fixed by its chemistry, the capacity is variable and depends on the quantity of materials in the cell. Essentially, the *capacity* of a cell is the number of electrons that can be obtained from it and is measured by the amount of current that can be supplied over time.

Batteries normally consist of multiple cells that are electrically connected together internally. The way that the cells are connected and the type of cells determine the voltage and current capacity of the battery. If the positive electrode of one cell is connected to the negative electrode of the next and so on, as illustrated in Figure 2–11(a), the battery voltage is the sum of the individual cell voltages. This is called a series connection. To increase battery current capacity, the positive electrodes of several cells are connected together and all the negative electrodes are connected together, as illustrated in Figure 2–11(b). This is called a parallel connection. Also, by using larger cells, which have a greater quantity of material, the ability to supply current can be increased but the voltage is not affected.



(a) Series-connected cells increase voltage.

(b) Parallel-connected cells increase current capacity.

FIGURE 2–11

Cells connected to form batteries.

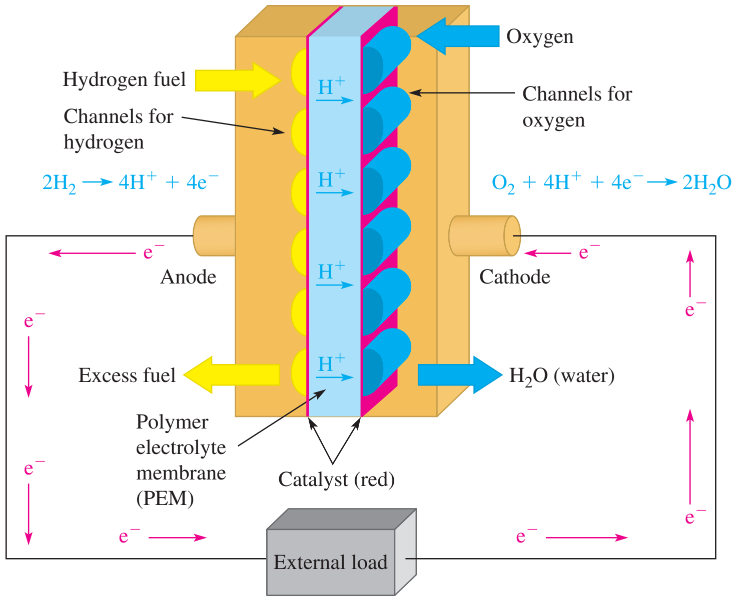
Batteries are divided into two major classes, *primary* and *secondary*. Primary batteries are used once and discarded because their chemical reactions are irreversible. Secondary batteries can be recharged and reused many times because they are characterized by reversible chemical reactions.

Primary and secondary batteries are available in a variety of shapes and sizes. Some of the sizes that you are most familiar with are AAA, AA, C, D, and 9 V but there are many others that are less common. Batteries are also typed according to their chemical makeup. A few common types of primary and secondary batteries are listed below.

- *Alkaline-*MnO_2 This is a primary battery that is commonly used in palm-type computers, photographic equipment, toys, radios, and recorders.
- *Carbon-zinc* This is a primary battery used in flashlights and small appliances.
- *Lead-acid* This is a secondary (rechargeable) battery that is commonly used in automotive, marine, and other similar applications.
- *Lithium-ion* This is a secondary battery that is commonly used in all types of portable electronics. This type of battery is increasingly being used in defense, aerospace, and automotive applications.
- *Lithium-*MnO_2 This is a primary battery that is commonly used in photographic and electronic equipment, smoke alarms, personal organizers, memory backup, and communications equipment.
- *Nickel-metal hydride* This is a secondary (rechargeable) battery that is commonly used in portable computers, cell phones, camcorders, and other portable consumer electronics.
- *Silver oxide* This is a primary battery that is commonly used in watches, photographic equipment, hearing aids, and electronics requiring high-capacity batteries.
- *Zinc air* This is a primary battery that is commonly used in hearing aids, medical monitoring instruments, pagers, and other frequency-use applications.

Fuel Cells A **fuel cell** is a device that converts electrochemical energy into dc voltage directly. Fuel cells combine a fuel (usually hydrogen) with an oxidizing agent (usually oxygen). In the hydrogen fuel cell, hydrogen and oxygen react to form water, which is the only by-product. The process is clean, quiet, and more efficient than burning. Fuel cells and batteries are similar in that they both are electrochemical devices that produce electricity using an oxidation-reduction reaction. However, a battery is a closed system with all its chemicals stored inside, whereas in a fuel cell, the chemicals (hydrogen and oxygen) constantly flow into the cell where they combine and produce electricity.

Hydrogen fuel cells are usually classified by their operating temperature and the type of electrolyte they use. Some types work well for use in stationary power generation plants. Others may be useful for small portable applications or for powering cars. For example, the type that holds the most promise for automotive applications is the



▲ **FIGURE 2–12**

Simplified diagram of a fuel cell.

polymer exchange membrane fuel cell (PEMFC), which is a type of hydrogen fuel cell. A simplified diagram is shown in Figure 2–12 to illustrate the basic operation.

The channels disperse pressurized hydrogen gas and oxygen gas equally over the surface of the catalyst, which facilitates the reaction of the hydrogen and oxygen. When an H_2 molecule comes in contact with the platinum catalyst on the anode side of the fuel cell, it splits into two H^+ ions and two electrons (e^-). The hydrogen ions are passed through the polymer electrolyte membrane (PEM) onto the cathode. The electrons pass through the anode and into the external circuit to create current.

When an O_2 molecule comes in contact with the catalyst on the cathode side, it breaks apart, forming two oxygen ions. The negative charge of these ions attracts two H^+ ions through the electrolyte membrane and together they combine with electrons from the external circuit to form a water molecule (H_2O), which is passed from the cell as a by-product. In a single fuel cell, this reaction produces only about 0.7 V. To get higher voltages, multiple fuel cells are connected in series.

Current research on fuel cells is ongoing and is focused on developing reliable, smaller, and cost-effective components for vehicles and other applications. The conversion to fuel cells also requires research on how best to obtain and provide hydrogen fuel where it is needed. Potential sources for hydrogen include using solar, geothermal, or wind energy to break apart water. Hydrogen can also be obtained by breaking down coal or natural gas molecules, which are rich in hydrogen.

Solar Cells The operation of solar cells is based on the **photovoltaic effect**, which is the process whereby light energy is converted directly into electrical energy. The most common type of solar cell is the crystalline silicon cell, which is shown in Figure 2–13. Briefly, it consists of a sandwich of two layers of different types of semiconductive materials, which are connected to a conductive grid on top and a conductive layer on the bottom. The two semiconductor layers are modified in manufacturing by adding certain impurities to the crystal structure so that each has unique properties. The top layer, called an *n*-layer, has "extra" electrons in its structure and the bottom layer, called the *p*-layer, has vacancies (called "holes") in its structure. When the two layers are joined, a region called the depletion region is formed at the boundary (studied in more detail in a Devices course). Free electrons from the *n*-layer cross into the *p*-layer to fill the holes near the boundary leaving the *n*-layer positively charged. This process creates a barrier that makes it increasingly difficult for additional electrons to cross and the process stops.

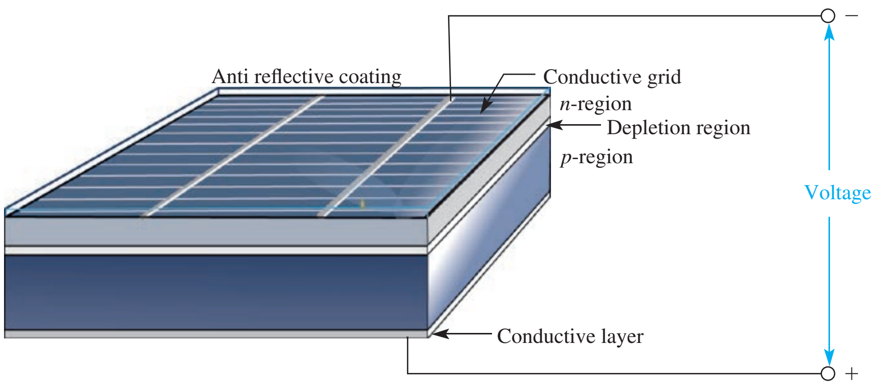


FIGURE 2–13

A crystalline silicon cell.

The charge separation in the creation of the depletion layer creates an electric field at the junction. When sunlight enters the cell, it can provide energy to free electrons. In the *n*-layer, electrons would cross the depletion layer except the electric field prevents them from doing so. Only electrons in the *p*-layer can move across the depletion layer. When a conductive path is added as an external circuit, electrons can travel through this path and recombine with holes in the *p*-layer, thus creating an electric current.

Although solar cells can be used in room light for powering a calculator, research is focusing more on converting sunlight to electricity. There is considerable research in increasing the efficiency of solar cells and photovoltaic (PV) modules today because they are a very clean source of energy using sunlight. A complete system for continuous power generally requires a battery backup to provide energy when the sun is not shining. Solar cells are well suited for remote locations where energy sources are unavailable and are used in providing power to satellites.

DC Generator Electrical **generators** convert mechanical energy into electrical energy using a principle called *electromagnetic induction* (see Chapter 10). A conductor is rotated through a magnetic field, and a voltage is produced across the conductor. A typical generator is pictured in Figure 2–14.

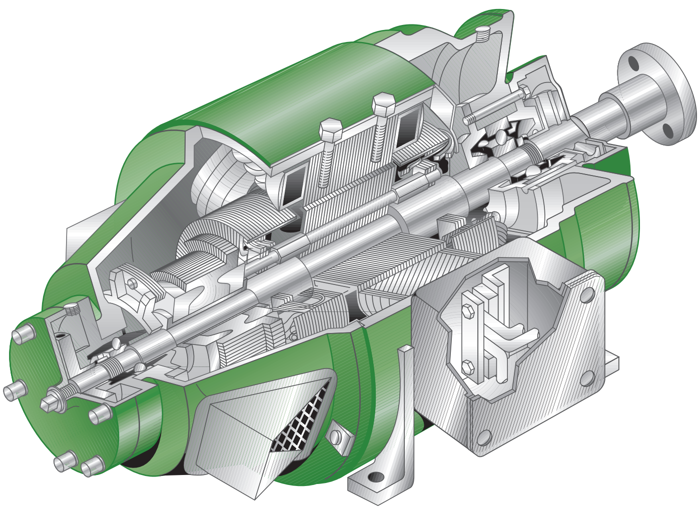


FIGURE 2–14

Cutaway view of a dc voltage generator.

The Electronic Power Supply Electronic **power supplies** convert the ac voltage from a wall outlet to a dc voltage that can be varied over a specified range. Typical laboratory power supplies are shown in Figure 2–15.

Thermocouples The **thermocouple** is a thermoelectric type of voltage source that is commonly used to sense temperature. A thermocouple is formed by the junction of two dissimilar metals, and its operation is based on the **Seebeck effect** that describes the voltage generated at the junction of the metals as a function of temperature.

Standard types of thermocouple are characterized by the specific metals used. These standard thermocouples produce predictable output voltages for a range of

▶ FIGURE 2–15

Electronic power supplies. (Courtesy of B+K Precision.)

temperatures. The most common is type K, made of chromel and alumel. Other types are also designated by letters as E, J, N, B, R, and S. Most thermocouples are available in wire or probe form.

Piezoelectric Sensors These sensors act as voltage sources and are based on the **piezoelectric effect** where a voltage is generated when a piezoelectric material is mechanically deformed by an external force. Quartz and ceramic are two types of piezoelectric material. Piezoelectric sensors are used in applications such as pressure sensors, force sensors, accelerometers, microphones, ultrasonic devices, and many others.

SECTION 2–3 CHECKUP

1. Define *voltage*.
2. What is the unit of voltage?
3. What is the voltage when 24 J of energy are required to move 10 C or charge?
4. List six sources of voltage.
5. What types of chemical reaction occurs in both batteries and fuel cells?

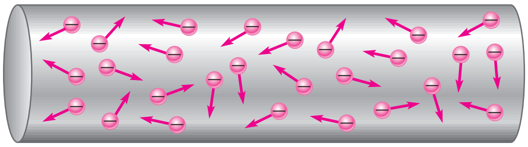
2–4 CURRENT

Voltage provides energy to electrons, allowing them to move through a circuit. In metallic conductors, the movement of electrons is the current, which results in work being done in an electrical circuit.

After completing this section, you should be able to

- **Define *current* and discuss its characteristics**
  - Explain the movement of electrons
  - State the formula for current
  - Name and define the unit of current

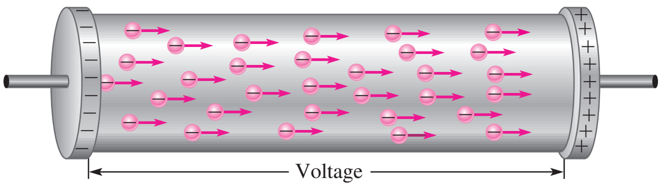
As you have learned, free electrons are available in all conductive and semiconductive materials. These outer-shell electrons drift randomly in all directions, from atom to atom, within the structure of the material, as indicated in Figure 2–16. These electrons are loosely bound to the positive metal ions in the material, but because of thermal energy, they are free to move about the crystalline structure of the metal.



◀ **FIGURE 2–16**

Random motion of free electrons in a material.

If a voltage is placed across a conductive or semiconductive material, one end becomes positive and the other negative, as indicated in Figure 2–17. The repulsive force produced by the negative voltage at the left end causes the free electrons (negative charges) to move toward the right. The attractive force produced by the positive voltage at the right end pulls the free electrons to the right. The result is a net movement of the free electrons from the negative end of the material to the positive end, as shown in Figure 2–17.



◀ **FIGURE 2–17**

Electrons flow from negative to positive when a voltage is applied across a conductive or semiconductive material.

The movement of these free electrons from the negative end of the material to the positive end is the electrical current, symbolized by I.

Electrical current is the rate of flow of charge.

Current in a metallic material is determined by net the number of electrons (amount of charge) that flow past a point in a unit of time.

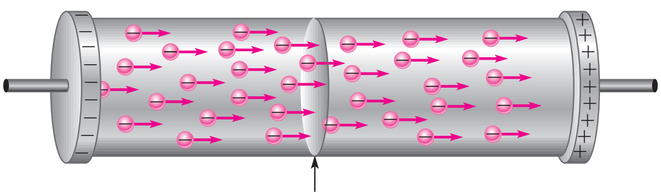
$$I = \frac{Q}{t}$$

Equation 2–3

where I is current in amperes (A), Q is charge in coulombs (C), and t is time in seconds (s).

One ampere (1 A) is the amount of current that exists when a number of electrons having a total charge of one coulomb (1 C) move through a given cross-sectional area in one second (1 s).

See Figure 2–18. Remember, one coulomb is the charge carried by 6.25×10^{18} electrons.



When a number of electrons having a total charge of 1 C pass through a cross-sectional area in 1 s, there is 1 A of current.

▲ **FIGURE 2–18**

Illustration of 1 A of current (1 C/s) in a material.

HISTORY NOTE

André Marie Ampère 1775–1836

In 1820 Ampère, a Frenchman, developed a theory of electricity and magnetism that was fundamental for 19th-century developments in the field. He was the first to build an instrument to measure charge flow (current). The unit of electrical current is named in his honor. (Photo credit: AIP Emilio Segrè Visual Archives.)

EXAMPLE 2–3

Ten coulombs of charge flow past a given point in a wire in 2 s. What is the current in amperes?

Solution

$$I = \frac{Q}{t} = \frac{10\text{ C}}{2\text{ s}} = \mathbf{5\text{ A}}$$

Related Problem If there are 2.0 A of current through the filament of a lamp, how many coulombs of charge move through the filament in 1.5 s?

Generally, we think of free electrons as the current carrier, but there are other ways charge moves. In a battery, when electrons flow in the external circuit, ions move internally to balance the charge of the moving electrons. This forms a current composed of ions carrying the charge. Another case where ions carry the charge is in a plasma. A plasma is a high temperature gas that has lost its electrons. The moving gas ions and free electrons both comprise current.

The Current Source

The Ideal Current Source As you know, an ideal voltage source can provide a constant voltage for any load. An ideal **current source** can provide a constant current in any load. Just as in the case of a voltage source, the ideal current source does not exist but can be approximated in practice. We will assume ideal unless otherwise specified.

The symbol for a current source is shown in Figure 2–19(a). The graph for an ideal current source is a horizontal line as illustrated in Figure 2–19(b). This is called the *IV* characteristic. Notice that the current is constant for any voltage across the current source. In a practical current source, the current decreases slightly with voltage, as shown by the dashed line.

SAFETY NOTE

Current sources change the output voltage in order to supply a constant current to the load. For example, a meter calibrator can have a different output voltage that depends on the meter under test. You should never touch the leads from a current source; the voltage can be high, and a shock will result, particularly if the load is high resistance load or the load is disconnected when the current source is turned on.

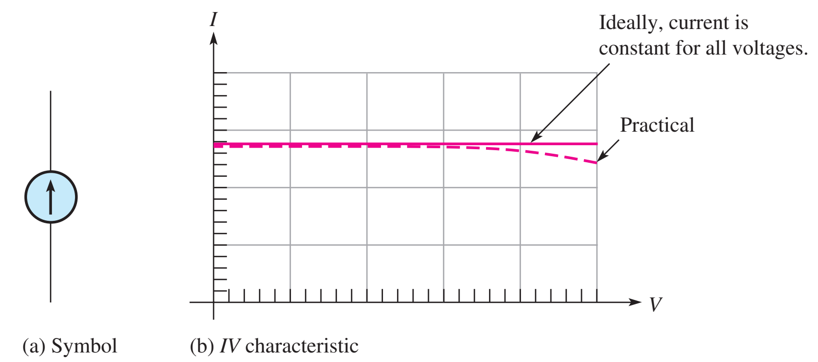


FIGURE 2–19

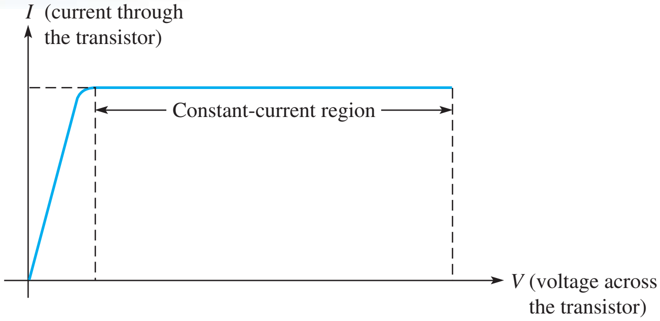
The current source.

Practical Current Sources Power supplies are normally thought of as voltage sources because they are the most common type of source in the laboratory. However, current sources are another type of energy source. Current sources may be "stand-alone" instruments or may be combined with other instruments, such as a voltage source, DMM, or function generator. Examples of combination instruments are the source-measurement units shown in Figure 2–20. These units can be set up as voltage or current sources and include a built-in DMM, as well as other instruments. They are used primarily for testing transistors and other semiconductors.

In most transistor circuits, the transistor acts as a current source because part of the *IV* characteristic curve is a horizontal line as shown by the transistor characteristic in Figure 2–21. The flat part of the graph indicates where the transistor current is constant over a range of voltages. The constant-current region is used to form a constant-current source.

◀ FIGURE 2–20

Typical source-measurement instruments. (Courtesy of Keithley Instruments.)



◀ FIGURE 2–21

Characteristic curve of a transistor showing the constant-current region.

SECTION 2–4 CHECKUP

1. Define *current* and state its unit.
2. How many electrons make up one coulomb of charge?
3. What is the current in amperes when 20 C flow past a point in a wire in 4 s?
4. What defines an ideal current source?

2–5 RESISTANCE

When there is current in a solid conductor, the free electrons move through the material and occasionally collide with atoms. These collisions cause the electrons to lose some of their energy, and thus their movement is restricted. The more collisions, the more the flow of electrons is restricted. This restriction varies and is determined by the type of material. The property of a material that restricts the flow of electrons is called *resistance*, designated with an *R*.

After completing this section, you should be able to

- **Define *resistance* and discuss its characteristics**
  - Name and define the unit of resistance
  - Describe the basic types of resistors
  - Determine resistance value by color code or labeling

When electrons that are moving through a material collide with atoms, they lose some of their energy, thus restricting their movement. The more collisions, the more the flow of electrons is restricted. This restriction varies and is determined by the type of material. The property of a material to restrict or oppose the flow of electrons is called resistance, *R*.

Resistance is the opposition to current.

Resistance is expressed in ohms, symbolized by the Greek letter omega (Ω).

One ohm (1 Ω) of resistance exists if there is one ampere (1 A) of current in a material when one volt (1 V) is applied across the material.

The schematic symbol for resistance is shown in Figure 2–22.

▲ FIGURE 2–22

Resistance symbol.

Conductance The reciprocal of resistance is **conductance**, symbolized by G. It is a measure of the ease with which current is established. The formula is

Equation 2–4

$$G = \frac{1}{R}$$

The unit of conductance is the **siemens**, abbreviated S. For example, the conductance of a 22 kΩ resistor is

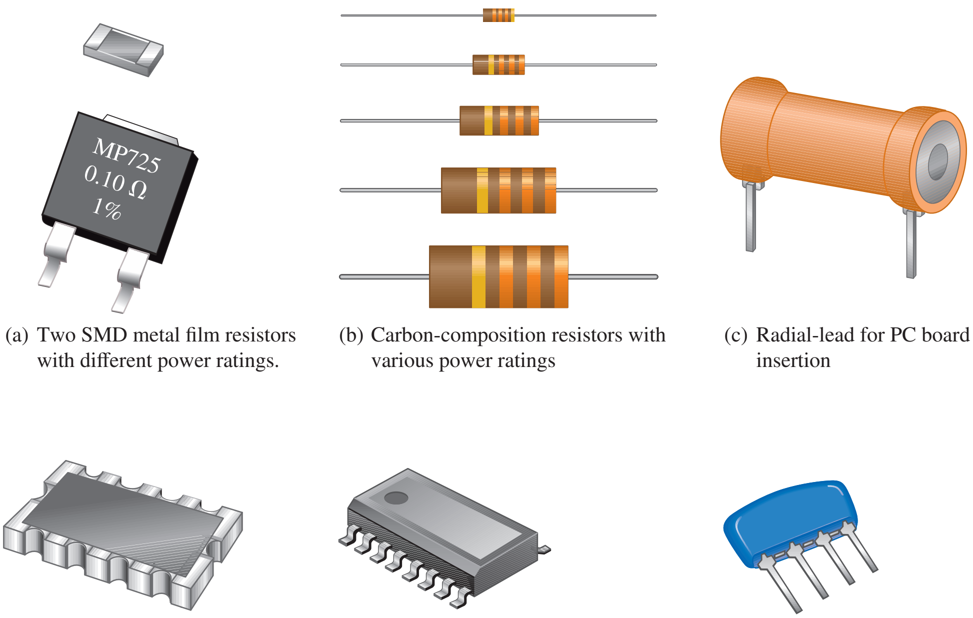
$$G = \frac{1}{22\ \text{k}\Omega} = 45.5\ \mu\text{S}$$

The obsolete unit of *mho* (ohm spelled backwards) was previously used for conductance.

Resistors

A component that is specifically designed to have a certain amount of resistance is called a **resistor**. The principal applications of resistors are to limit current in a circuit, to divide voltage, and, in certain cases, to generate heat. Although resistors come in many shapes and sizes, they can all be placed in one of two main categories: fixed or variable.

Fixed Resistors Fixed resistors are available with a large selection of resistance values that are set during manufacturing and cannot be changed easily. They are constructed using various methods and materials. Figure 2–23 shows several common types. The top row shows single, fixed resistors. The lower row shows array resistors. Part (a) shows two surface mount devices (SMD) that are metal film resistors with a fixed value. Surface mount resistors are the most common types of fixed resistor that is widely used on printed circuit (pc) boards. SMD resistors have the advantage of small size and are available in a wide range of resistance values and power ratings. They are placed on a pc board by machines very rapidly without the need for drilling holes. Another common type of fixed resistor is the carbon-composition resistor shown in Figure 2–23(b). These resistors are constructed with leads that can be bent and inserted into holes drilled in a pc board. Some fixed resistors, such as the one illustrated



(a) Two SMD metal film resistors with different power ratings.

(b) Carbon-composition resistors with various power ratings

(c) Radial-lead for PC board insertion

(d) Chip resistor array

(e) Resistor network (surface mount)

(f) Resistor network (simm)

▲ FIGURE 2–23

Typical fixed resistors.

HISTORY NOTE

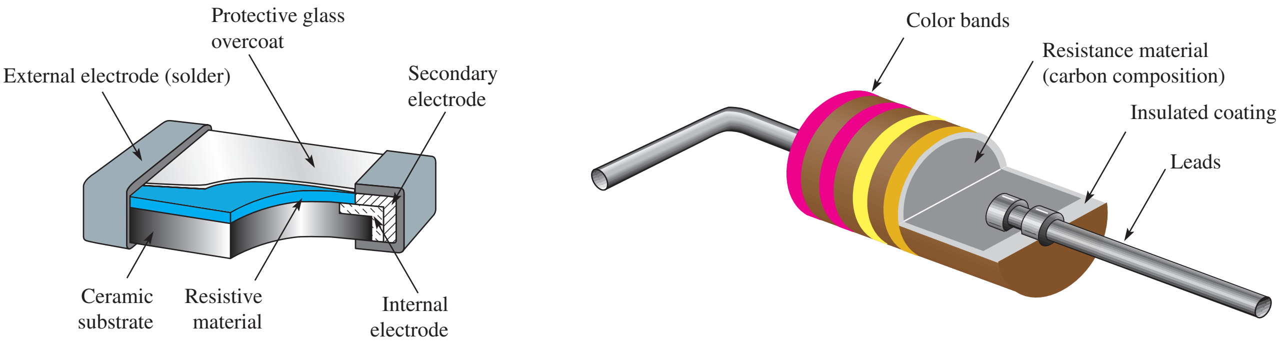
Georg Simon Ohm 1787–1854

Ohm was born in Bavaria and struggled for years to gain recognition for his work in formulating the relationship of current, voltage, and resistance. This mathematical relationship is known today as Ohm's law and the unit of resistance is named in his honor. (Photo credit: Library of Congress Prints and Photographs Division[LC-USZ62-40943].)

HISTORY NOTE

Ernst Werner von Siemens 1816–1872

Siemens was born in Prussia. While in prison for acting as a second in a duel, he began to experiment with chemistry, which led to his invention of the first electroplating system. In 1837, Siemens began making improvements in the early telegraph and contributed greatly to the development of telegraphic systems. The unit of conductance is named in his honor. (Photo credit: AIP Emilio Segrè Visual Archives, E. Scott Barr Collection.)



(a) Cutaway view of an SMD metal film resistor

(b) Cutaway view of a carbon-composition resistor

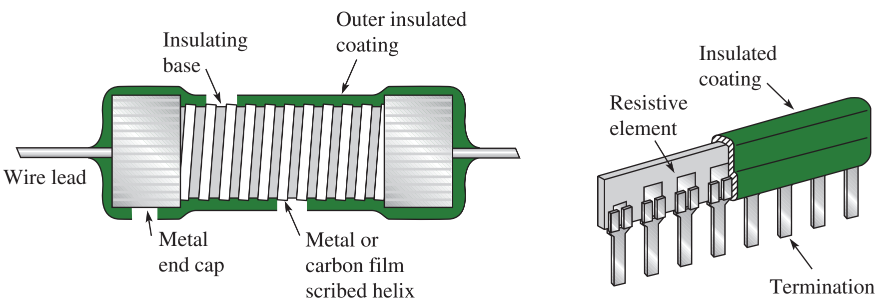
▲ **FIGURE 2–24**

Two types of fixed resistors (not to scale).

in (c), have radial leads that can go directly into a pc board without requiring a bending operation. The resistors shown in (d), (e), and (f) are array resistors. These are constructed as multiple resistors in a single package. In some cases, array resistors have a single common lead. Array resistors are another means of speeding construction of circuits because a single placement operation can place multiple resistors on a board.

Construction of two common types of resistors is illustrated in Figure 2–24. In (a), an SMD metal film resistor is shown. The end caps form the connection points to the resistive film, which is mounted on a substrate and covered with an insulating glass layer. Resistance is determined by the resistivity and physical size of the film. For precision resistors, the film is laser trimmed. In (b), a carbon-composition type is illustrated. It is constructed with a mixture of finely ground carbon, insulating filler, and a resin binder. The ratio of carbon to insulating filler sets the resistance value. The mixture is formed into rods, and conductive lead connections are made. The entire resistor is then encapsulated in an insulated coating for protection.

Other types of fixed resistors include carbon film, metal film, and wirewound. In film resistors, a resistive material is deposited evenly onto a high-grade ceramic rod. The resistive film may be carbon (carbon film) or nickel chromium (metal film). In these types of resistors, the desired resistance value is obtained by removing part of the resistive material in a helical pattern along the rod using a spiraling technique, as shown in Figure 2–25(a). Very close **tolerance** can be achieved with this method. Film resistors are also available in the form of resistor networks, as shown in Figure 2–25(b).



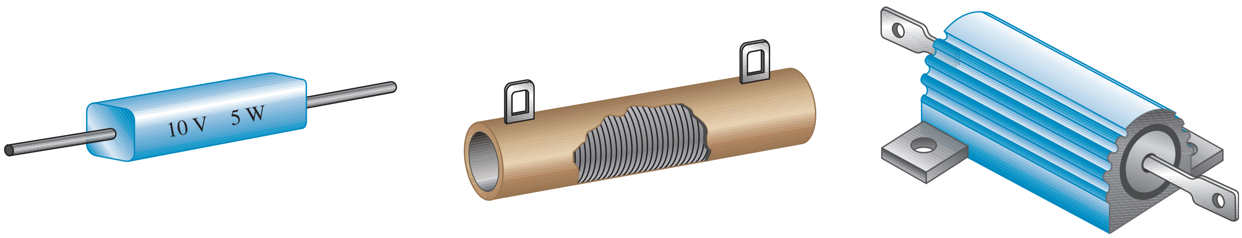
(a) Film resistor showing spiraling technique

(b) Resistor network

◀ **FIGURE 2–25**

Construction views of typical film resistors.

Wirewound resistors are constructed with resistive wire wound around an insulating rod and then sealed. Normally, wirewound resistors are used in applications that require higher power ratings. Since both film resistors and wirewound resistors are constructed with a coil of wire, they can have significant inductance and are not used at higher frequencies. (Inductance is discussed in Chapter 13.) Some typical wirewound resistors are shown in Figure 2–26.



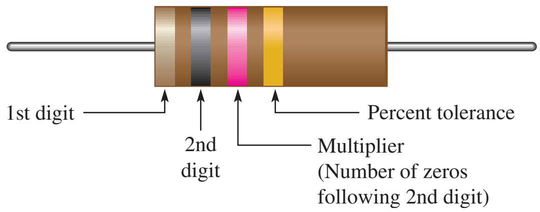
▲ **FIGURE 2–26**

Typical wirewound power resistors.

Resistor Color Codes Fixed resistors with value tolerances of 5% or 10% are color coded with four bands to indicate the resistance value and the tolerance. This color-code band system is shown in Figure 2–27, and the color code is listed in Table 2–1. The bands are always closer to one end.

► **FIGURE 2–27**

Color-code bands on a 4-band resistor.



The color code is read as follows:

1. Start with the band closest to one end of the resistor. The first band is the first digit of the resistance value. If it is not clear which is the banded end, start from the end that does not begin with a gold or silver band.
2. The second band is the second digit of the resistance value.

► **TABLE 2–1**

Resistor 4-band color code.

	DIGIT	COLOR
Resistance value, first three bands: First band—1st digit Second band—2nd digit Third band—multiplier (number of zeros following the 2nd digit)	0	Black
	1	Brown
	2	Red
	3	Orange
	4	Yellow
	5	Green
	6	Blue
	7	Violet
	8	Gray
	9	White
Fourth band—tolerance	±5%	Gold
	±10%	Silver

3. The third band is the number of zeros following the second digit, or the multiplier. The multiplier is actually a power of ten multiplier; thus a black band in the third position represents multiplying by 10^0 or 1.

4. The fourth band indicates the percent tolerance and is usually gold or silver.

For example, a 5% tolerance means that the *actual* resistance value is within ±5% of the color-coded value. Thus, a 100 Ω resistor with a tolerance of ±5% can have an acceptable range of values from a minimum of 95 Ω to a maximum of 105 Ω.

For resistance values less than 10 Ω, the third band is either gold or silver. Gold represents a multiplier of 0.1, and silver represents 0.01. For example, a color code of red, violet, gold, and silver represents 2.7 Ω with a tolerance of ±10%. A table of standard resistance values is in Appendix A.

EXAMPLE 2–4

Find the resistance value in ohms and the percent tolerance for each of the color-coded resistors shown in Figure 2–28.

FIGURE 2–28

Solution

(a) First band is red = 2, second band is violet = 7, third band is orange = 3 zeros, fourth band is silver = 10% tolerance.

$$R = \mathbf{27{,}000\ \Omega\ \pm 10\%}$$

(b) First band is brown = 1, second band is black = 0, third band is brown = 1 zero, fourth band is silver = 10% tolerance.

$$R = \mathbf{100\ \Omega\ \pm 10\%}$$

(c) First band is green = 5, second band is blue = 6, third band is green = 5 zeros, fourth band is gold = 5% tolerance.

$$R = \mathbf{5{,}600{,}000\ \Omega\ \pm 5\%}$$

Related Problem A certain resistor has a yellow first band, a violet second band, a red third band, and a gold fourth band. Determine its value in ohms and its percent tolerance.

Five-Band Color Code Certain precision resistors with tolerances of 2%, 1%, or less are generally color coded with five bands, as shown in Figure 2–29. Begin at the band closest to one end. The first band is the first digit of the resistance value, the second band is the second digit, the third band is the third digit, the fourth band is the multiplier (number of zeros after the third digit or power of ten multiplier), and the fifth band indicates the percent tolerance. Table 2–2 shows the 5-band color code.

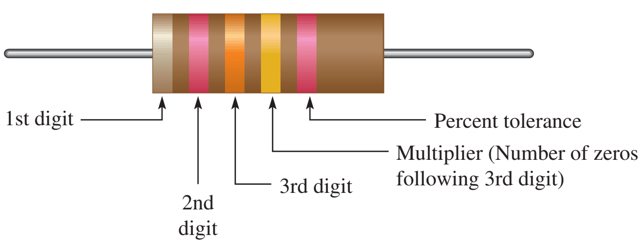


FIGURE 2–29

Color-code bands on a 5-band resistor.

TABLE 2–2

Resistor 5-band color code.

	DIGIT	COLOR
Resistance value, first	0	Black
three bands:	1	Brown
	2	Red
First band—1st digit	3	Orange
Second band—2nd digit	4	Yellow
Third band—3rd digit	5	Green
Fourth band—multiplier	6	Blue
(number of zeros	7	Violet
following 3rd digit)	8	Gray
	9	White
Fourth band—multiplier	0.1	Gold
	0.01	Silver
	±2%	Red
	±1%	Brown
Fifth band—tolerance	±0.5%	Green
	±0.25%	Blue
	±0.1%	Violet

EXAMPLE 2–5

Find the resistance value in ohms and the percent tolerance for each of the color-coded resistors shown in Figure 2–30.

FIGURE 2–30

Solution

(a) First band is red $= 2$, second band is violet $= 7$, third band is black $= 0$, fourth band is gold $= \times 0.1$, fifth band is red $= \pm 2\%$ tolerance.

$$R = 270 \times 0.1 = \mathbf{27\ \Omega\ \pm 2\%}$$

(b) First band is yellow $= 4$, second band is black $= 0$, third band is red $= 2$, fourth band is black $= 0$, fifth band is brown $= \pm 1\%$ tolerance.

$$R = \mathbf{402\ \Omega\ \pm 1\%}$$

(c) First band is orange $= 3$, second band is orange $= 3$, third band is red $= 2$, fourth band is orange $= 3$, fifth band is green $= \pm 0.5\%$ tolerance.

$$R = \mathbf{332{,}000\ \Omega\ \pm 0.5\%}$$

Related Problem A certain resistor has a yellow first band, a violet second band, a green third band, a gold fourth band, and a red fifth band. Determine its value in ohms and its percent tolerance.

Exceptions There are some exceptions to the color codes given. One case you may see is a zero ohm resistor with a single black band. A zero ohm resistor is sometimes used as a jumper on a PC board; it has the advantage of being able to be placed using a machine that places other components on the board. Another exception is for certain military resistors, which may include a reliability band. Check with the manufacturer's specification sheet if you are not sure how a resistor is marked.

Resistor Label Codes Not all types of resistors are color coded. Many, including surface-mount resistors, use typographical marking to indicate the resistance value and tolerance. These label codes consist of either all numbers (numeric) or a combination of numbers and letters (alphanumeric). In some cases when the body of the resistor is large enough, the entire resistance value and tolerance are stamped on it in standard form.

Numeric labeling uses three digits to indicate the resistance value, as shown in Figure 2–31 using a specific example. The first two digits give the first two digits of the resistance value, and the third digit gives the multiplier or number of zeros that follow the first two digits. This code is limited to values of 10 Ω or greater. Notice that the label for a 10 Ω resistor is 100 and a 100 Ω resistor is 101.

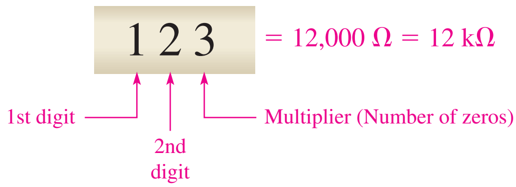


FIGURE 2–31

Example of three-digit labeling for a resistor.

Another common type of marking is a three- or four-character label that uses both digits and letters. An alphanumeric label typically consists of only three digits or two or three digits and one of the letters R, K, or M. The letter is used to indicate the multiplier, and the position of the letter indicates the decimal point placement. The letter R indicates a multiplier of 1 (no zeros after the digits), the K indicates a multiplier of 1,000 (three zeros after the digits), and the M indicates a multiplier of 1,000,000 (six zeros after the digits). In this format, values from 100 to 999 consist of three digits and no letter to represent the three digits in the resistance value. Surface-mount devices can also include a zero ohm resistor, used as a means of crossing a trace on a pc board. Figure 2–32 shows four examples of this type of resistor label.

FIGURE 2–32

Examples of the alphanumeric resistor label.

EXAMPLE 2–6

Interpret the following alphanumeric resistor labels:

(a) 470 **(b)** 471 **(c)** 68K **(d)** 10M **(e)** 5R6

Solution

(a) 470 = **47 Ω** **(b)** 471 = **470 Ω** **(c)** 68K = **68 kΩ**

(d) 10M = **10 MΩ** **(e)** 5R6 = **5.6 Ω**

Related Problem What is the resistance indicated by 1K25?

One system of labels for resistance tolerance values uses the letters F, G, and J:

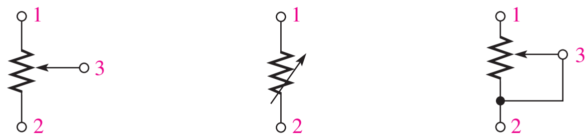
$$F = \pm 1\% \qquad G = \pm 2\% \qquad J = \pm 5\%$$

For example, 620F indicates a 620 Ω resistor with a tolerance of ±1%, 4R6G is a 4.6 Ω ±2% resistor, and 56KJ is a 56 kΩ ±5% resistor. Although these codes are the most commonly used ones, there are variations in markings and manufacturers may use a different system. Check with the manufacturer if you are not sure.

Variable Resistors Variable resistors are designed so that their resistance values can be changed easily. Two basic uses for variable resistors are to divide voltage and to control current. The variable resistor used to divide voltage is called a **potentiometer**. The variable resistor used to control current is called a **rheostat**. Schematic symbols for these types are shown in Figure 2–33. The potentiometer is a three-terminal device, as indicated in part (a). Terminals 1 and 2 have a fixed resistance between them, which is the total resistance. Terminal 3 is connected to a moving contact (**wiper**). You can vary the resistance between 3 and 1 or between 3 and 2 by moving the contact.

FIGURE 2–33

Potentiometer and rheostat symbols.

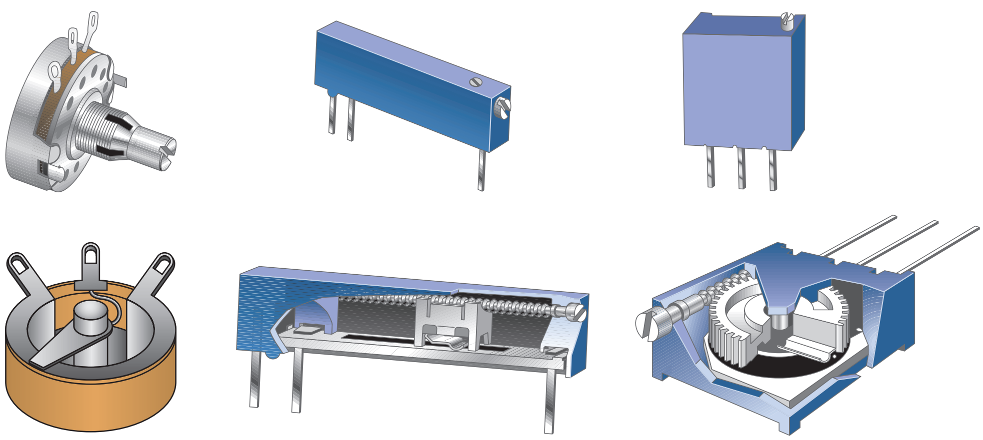


(a) Potentiometer (b) Rheostat (c) Potentiometer connected as a rheostat

Figure 2–33(b) shows the rheostat as a two-terminal variable resistor. Part (c) shows how you can use a potentiometer as a rheostat by connecting terminal 3 to either terminal 1 or terminal 2. Parts (b) and (c) are equivalent symbols. Some typical potentiometers are pictured in Figure 2–34.

FIGURE 2–34

Typical potentiometers and construction views.



Potentiometers and rheostats can be classified as linear or tapered, as shown in Figure 2–35, where a potentiometer with a total resistance of 100 Ω is used as an example. As shown in part (a), in a linear potentiometer, the resistance between either terminal and the moving contact varies linearly with the position of the moving contact. For example, one-half of the total contact movement results in one-half the total resistance. Three-quarters of the total movement results in three-quarters of the total resistance between the moving contact and one terminal, or one-quarter of the total resistance between the other terminal and the moving contact.

In the **tapered** potentiometer, the resistance varies nonlinearly with the position of the moving contact, so that one-half of a turn does not necessarily result in one-half the total resistance. This concept is illustrated in Figure 2–35(b), where the nonlinear values are arbitrary.

The potentiometer is used as a voltage-control device because when a fixed voltage is applied across the end terminals, a variable voltage is obtained at the wiper contact

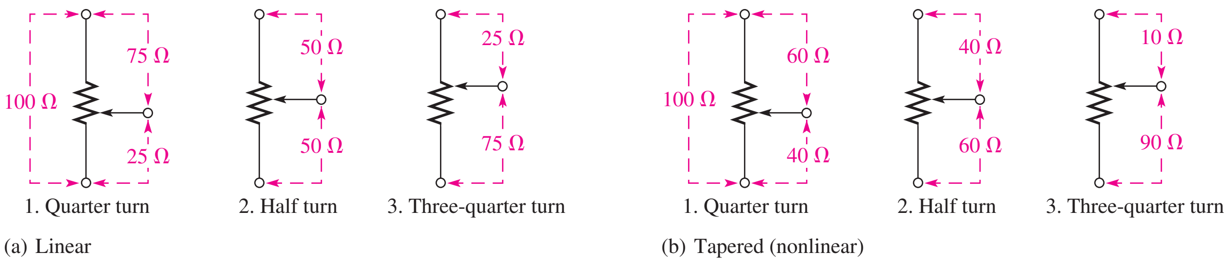


FIGURE 2–35

Examples of linear and tapered potentiometers.

with respect to either end terminal. The rheostat is used as a current-control device because the current can be changed by changing the wiper position.

Variable Resistance Sensors Many sensors operate on the concept of a variable resistance, in which a physical quantity alters the electrical resistance. Depending on the sensor and the measurement requirements, the change in resistance may be determined directly or indirectly using the resistance change to alter a voltage or current.

Examples of resistance sensors include **thermistors** that change resistance as a function of temperature, **photoconductive** cells that change resistance as a function of light, and **strain gauges** that change resistance when a force is applied to them. Strain gauges are widely used in scales and applications where mechanical motion needs to be sensed. The measuring instruments need to be very sensitive because the change in resistance is very small. Figure 2–36 shows symbols for these various resistance sensors.

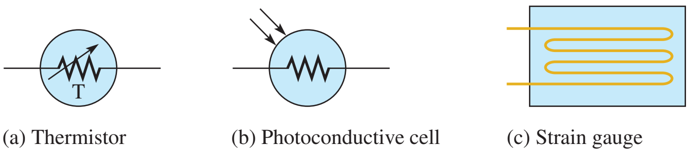


FIGURE 2–36

Symbols for resistance sensors.

SECTION 2–5 CHECKUP

1. Define *resistance* and name its unit.
2. What are the two main categories of resistors? Briefly explain the difference between them.
3. In the 4-band resistor color code, what does each band represent?
4. Determine the resistance and percent tolerance for each of the following color codes:
   (a) yellow, violet, red, gold **(b)** blue, red, orange, silver
   (c) brown, gray, black, gold **(d)** red, red, blue, red, green
5. What resistance value is indicated by each alphanumeric label:
   (a) 33R **(b)** 5K6 **(c)** 900 **(d)** 6M8
6. What is the basic difference between a rheostat and a potentiometer?
7. Name three resistance sensors and the physical quantity that affects their resistance.

2–6 THE ELECTRIC CIRCUIT

A basic electric circuit is an arrangement of physical components that use voltage, current, and resistance to perform some useful function.

After completing this section, you should be able to

- **Describe a basic electric circuit**
  - Relate a schematic to a physical circuit
  - Define *open circuit* and *closed circuit*

- Describe various types of protective devices
- Describe various types of switches
- Explain how wire sizes are related to gauge numbers
- Define *ground* or *common*

SAFETY NOTE

To avoid electrical shock, never touch a circuit while it is connected to a voltage source. If you need to handle a circuit, remove a component, or change a component, first make sure the voltage source is disconnected.

Direction of Current

For a few years after the discovery of electricity, people assumed all current consisted of moving positive charges. However, in the 1890s, the electron was identified as the charge carrier in solid conductors.

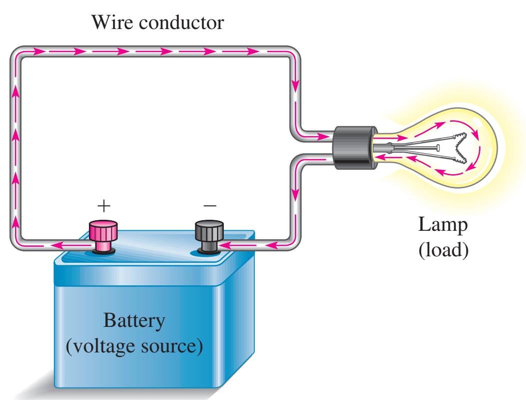
Today, there are two accepted conventions for the direction of electrical current. *Electron flow direction,* preferred by many in the fields of electrical and electronics technology, assumes for analysis purposes that current is out of the negative terminal of a voltage source, through the circuit, and into the positive terminal of the source. *Conventional current direction* assumes for analysis purposes that current is out of the positive terminal of a voltage source, through the circuit, and into the negative terminal of the source. By following the direction of conventional current, there is a rise in voltage across a source (negative to positive) and a drop in voltage across a resistor (positive to negative).

Since you cannot actually see current, only its effects, it actually makes no difference which direction of current is assumed as long as it is used *consistently.* The results of electric circuit analysis are not affected by the direction of current that is assumed for analytical purposes. The direction used for analysis is largely a matter of preference, and there are many proponents for each approach.

Conventional current direction is also used in electronics technology and is used almost exclusively at the engineering level. Conventional current direction is used throughout this text.

The Basic Circuit

Basically, an electric **circuit** consists of a voltage source, a load, and a path for current between the source and the load. Figure 2–37 shows in pictorial form an example of a simple electric circuit: a battery connected to a lamp with two conductors (wires). The battery is the voltage source, the lamp is the **load** on the battery because it draws current from the battery, and the two wires provide the current path from the positive terminal of the battery to the lamp and back to the negative terminal of the battery. Current goes through the filament of the lamp (which has a resistance), causing it to emit visible light. Current through the battery occurs by chemical action.



▶ FIGURE 2–37

A simple electric circuit.

In many practical cases, one terminal of the battery is connected to a common or ground point. For example, in most automobiles, the negative battery terminal is connected to the metal chassis of the car. The chassis is the ground for the automobile electrical system and acts as a conductor that completes the circuit.

The Electric Circuit Schematic An electric circuit can be represented by a **schematic** using standard symbols for each element, as shown in Figure 2–38 for the simple circuit in Figure 2–37. A schematic, in an organized manner, shows how the various components in a given circuit are interconnected so that the operation of the circuit can be determined.

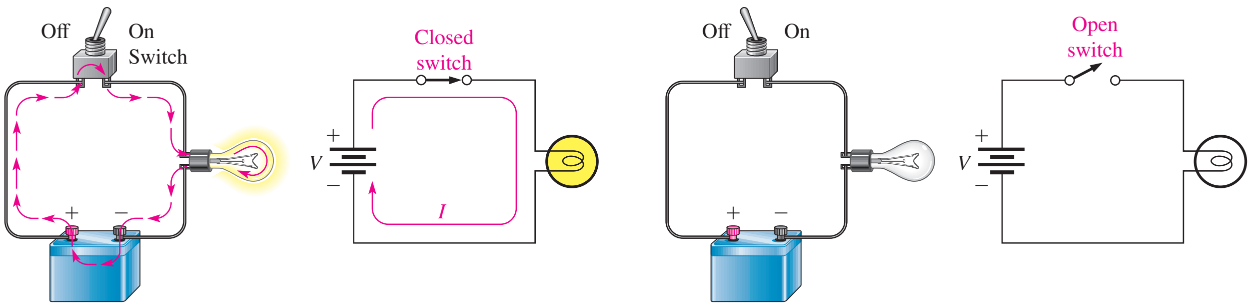
▲ FIGURE 2–38

Schematic for the circuit in Figure 2–37.

Current Control and Protection

The example circuit in Figure 2–37 illustrated a **closed circuit**—that is, a circuit in which the current has a complete path. When the current path is broken, the circuit is called an **open circuit**.

Mechanical Switches **Switches** are commonly used for controlling the opening or closing of circuits. For example, a switch is used to turn a lamp on or off, as illustrated in Figure 2–39. Each circuit pictorial is shown with its associated schematic. The type of switch indicated is a single-pole–single-throw (SPST) toggle switch. The term **pole** refers to the movable arm in a switch; the number of poles determine the number of independent circuits the switch can control. The term **throw** indicates the number of contacts that are affected (either opened or closed) by a single switch action (a single movement of a pole).



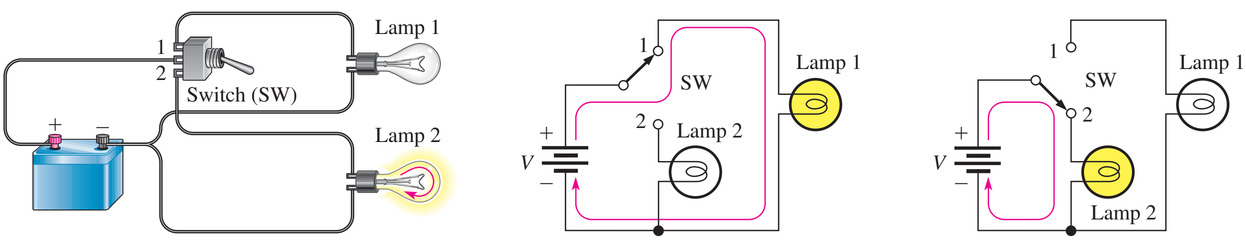
(a) There is current in a *closed* circuit because there is a complete current path (switch is ON or in the *closed* position). Current is almost always indicated by a red arrow in this text.

(b) There is no current in an *open* circuit because the path is broken (switch is OFF or in the *open* position).

▲ FIGURE 2–39

Illustration of closed and open circuits using an SPST switch for control.

Figure 2–40 shows a somewhat more complicated circuit using a single-pole–double-throw (SPDT) type of switch to control the current to two different lamps. When one lamp is on, the other is off, and vice versa, as illustrated by the two schematics in parts (b) and (c), which represent each of the switch positions.



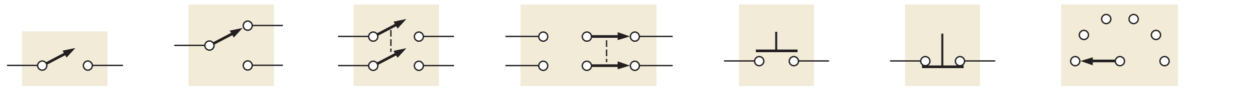
(a) Pictorial

(b) A schematic showing Lamp 1 on and Lamp 2 off

(c) A schematic showing Lamp 2 on and Lamp 1 off

▲ FIGURE 2–40

An example of an SPDT switch controlling two lamps.



(a) SPST (b) SPDT (c) DPST (d) DPDT (e) NOPB (f) NCPB (g) Single-pole rotary (6-position)

▲ **FIGURE 2–41**

Switch symbols.

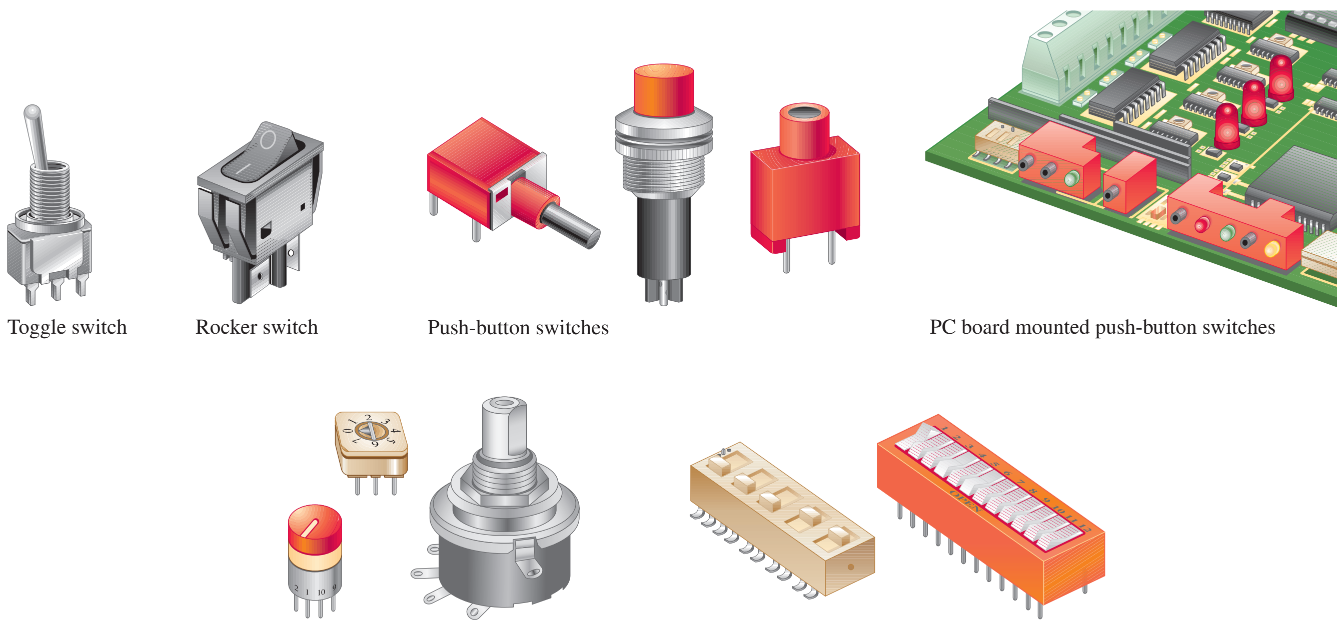
TECH NOTE

Small electronic parts can be damaged easily if you apply too much heat to them when soldering. Small switches frequently are constructed with plastic that can melt and render the switch useless. Manufacturers usually supply a maximum time and temperature that can be applied to a part without damage. A small heat sink can be temporarily connected between the point where solder is applied and the sensitive region of the component.

In addition to the SPST and the SPDT switches (symbols are shown in Figure 2–41(a) and (b)), the following other types are important:

- *Double-pole–single-throw (DPST)* The DPST switch permits simultaneous opening or closing of two sets of contacts. The symbol is shown in Figure 2–41(c). The dashed line indicates that the contact arms are mechanically linked so that both move with a single switch action.
- *Double-pole–double-throw (DPDT)* The DPDT switch provides connection from one set of contacts to either of two other sets. The schematic symbol is shown in Figure 2–41(d).
- *Push-button (PB)* In the normally open push-button switch (NOPB), shown in Figure 2–41(e), connection is made between two contacts when the button is depressed, and connection is broken when the button is released. In the normally closed push-button switch (NCPB), shown in Figure 2–41(f), connection between the two contacts is broken when the button is depressed.
- *Rotary* In a rotary switch, connection between one contact and any one of several others is made by turning a knob. A symbol for a simple six-position rotary switch is shown in Figure 2–41(g).

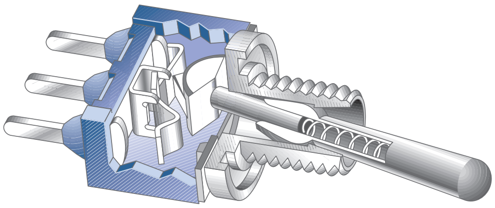
Figure 2–42 shows several varieties of mechanical switches, and Figure 2–43 shows the construction view of a typical toggle switch.



Toggle switch — Rocker switch — Push-button switches — PC board mounted push-button switches — Rotary switches — DIP switches for mounting on PC boards

▲ **FIGURE 2–42**

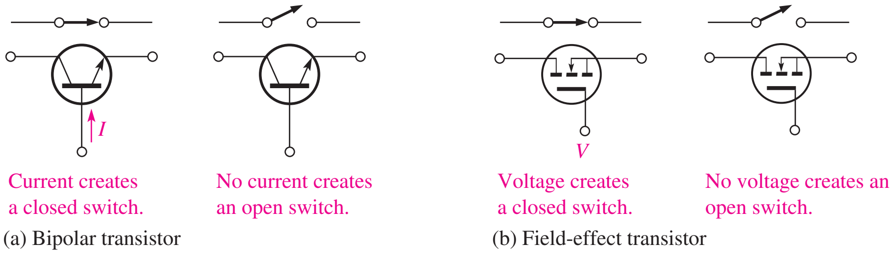
Typical mechanical switches.



◀ FIGURE 2–43

Construction view of a typical toggle switch.

Semiconductor Switches Transistors are widely used as switches in many applications. The transistor can be used as the equivalent of a single-pole–single-throw switch. You can open and close a circuit path by controlling the state of the transistor. Two types of transistor symbols are shown in Figure 2–44 with their mechanical switch equivalents.



◀ FIGURE 2–44

Transistor switches.

Here is a greatly simplified description of operation. One type, called the *bipolar transistor,* is controlled by current. When there is current at a specific terminal, the transistor acts as a closed switch; when there is no current at that terminal, the transistor acts as an open switch, as illustrated in Figure 2–44(a). Another type, called the *field-effect transistor,* is controlled by voltage. When there is voltage at a specific terminal, the transistor acts as a closed switch; when there is no voltage at that terminal, the transistor acts as an open switch, as illustrated in part (b).

Protective Devices **Fuses** and **circuit breakers** are used to deliberately create an open circuit when the current exceeds a specified number of amperes due to a malfunction or other abnormal condition in a circuit. For example, a 20 A fuse or circuit breaker will open a circuit when the current exceeds 20 A.

The basic difference between a fuse and a circuit breaker is that when a fuse is "blown," it must be replaced; but when a circuit breaker opens, it can be reset and reused repeatedly. Both of these devices protect against damage to a circuit due to excess current or prevent a hazardous condition created by the overheating of wires and other components when the current is too great. Several typical fuses and circuit breakers, along with their schematic symbols, are shown in Figure 2–45.

Two basic categories of fuses in terms of their physical configuration are cartridge type and plug type (screw in). Cartridge-type fuses have various-shaped housings with leads or other types of contacts, as shown in Figure 2–45(a). A typical plug-type fuse is shown in part (b). Fuse operation is based on the melting temperature of a wire or other metal element. As current increases, the fuse element heats up and when the rated current is exceeded, the element reaches its melting temperature and opens, thus removing power from the circuit.

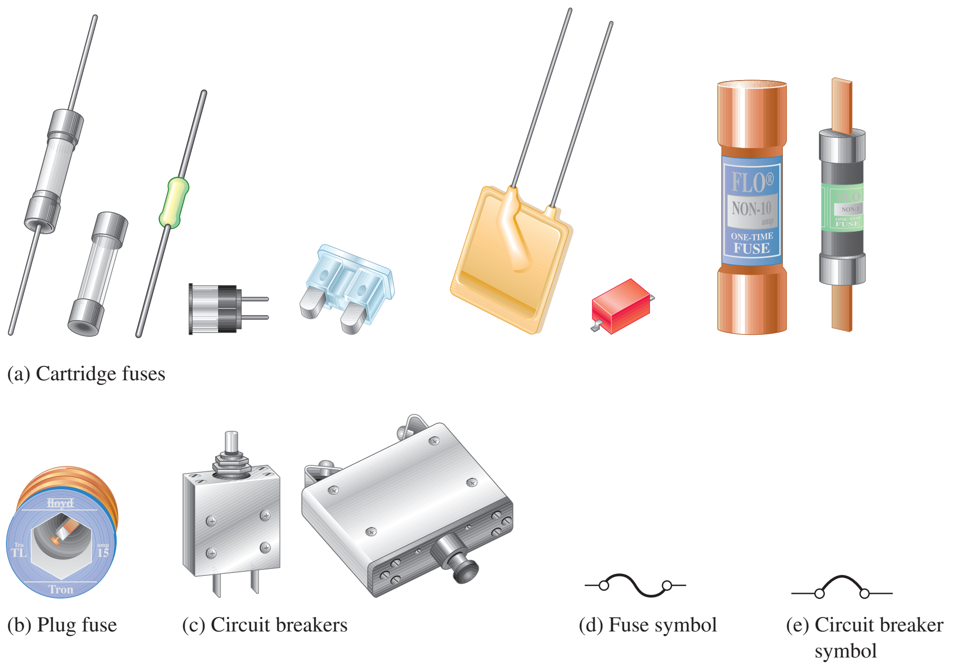
Two common types of fuses are the fast-acting and the time-delay (slow-blow). Fast-acting fuses are type F and time-delay fuses are type T. In normal operation, fuses are often subjected to intermittent current surges that may exceed the rated current, such as when power to a circuit is turned on. Over time, this reduces the fuse's ability to withstand short surges or even current at the rated value. A slow-blow fuse can tolerate greater and longer duration surges of current than the typical fast-acting fuse. A fuse symbol is shown in Figure 2–45(d).

SAFETY NOTE

Always use fully insulated fuse pullers to remove and replace fuses in an electrical box. Even if the disconnect switch is in the off position, line voltage is still present in the box. Never use metal tools to remove and replace fuses.

SAFETY NOTE

Fuses and circuit breakers should always be on the hot side in a circuit rather than neutral or ground side. This reduces he risk of a shock because the circuit after the open is no longer energized by the source voltage. Although the danger is less, it is NOT eliminated because certain components in circuits can retain a charge after the source is disconnected.



▲ **FIGURE 2–45**

Typical fuses and circuit breakers and their symbols.

Typical circuit breakers are shown in Figure 2–45(c) and the symbol is shown in part (e). Generally, a circuit breaker detects excess current either by the heating effect of the current or by the magnetic field it creates. In a circuit breaker based on the heating effect, a bimetallic spring opens the contacts when the rated current is exceeded. Once opened, the contact is held open by mechanical means until manually reset. In a circuit breaker based on a magnetic field, the contacts are opened by a sufficient magnetic force created by excess current and must be mechanically reset.

Wires

Wires are the most common form of conductive material used in electrical applications. They vary in diameter and are arranged according to standard gauge numbers, called **AWG** (American Wire Gauge) sizes. As the gauge number increases, the wire diameter decreases. The size of a wire is also specified in terms of its cross-sectional area, as illustrated in Figure 2–46. A unit of cross-sectional area used for wires is the **circular mil**, abbreviated CM. One circular mil is the area of a wire with a diameter of 0.001 inch (1 mil). You can find the cross-sectional area by expressing the diameter in thousandths of an inch (mils) and squaring it, as follows:

Equation 2–5

$$A = d^2$$

where A is the cross-sectional area in circular mils and d is the diameter in mils. Table 2–3 lists the AWG sizes with their corresponding cross-sectional area and resistance in ohms per 1,000 ft at 20°C.

► **FIGURE 2–46**

Cross-sectional area of a wire.

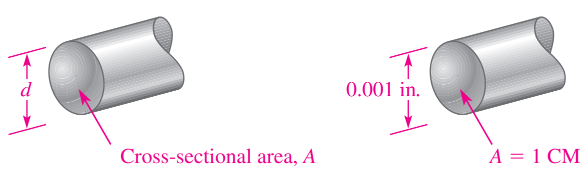


TABLE 2–3

American Wire Gauge (AWG) sizes and resistances for solid round copper.

AWG #	AREA (CM)	RESISTANCE (Ω/1000 FT AT 20°C)	AWG #	AREA (CM)	RESISTANCE (Ω/1000 FT AT 20°C)
0000	211,600	0.0490	19	1,288.1	8.051
000	167,810	0.0618	20	1,021.5	10.15
00	133,080	0.0780	21	810.10	12.80
0	105,530	0.0983	22	642.40	16.14
1	83,694	0.1240	23	509.45	20.36
2	66,373	0.1563	24	404.01	25.67
3	52,634	0.1970	25	320.40	32.37
4	41,742	0.2485	26	254.10	40.81
5	33,102	0.3133	27	201.50	51.47
6	26,250	0.3951	28	159.79	64.90
7	20,816	0.4982	29	126.72	81.83
8	16,509	0.6282	30	100.50	103.2
9	13,094	0.7921	31	79.70	130.1
10	10,381	0.9989	32	63.21	164.1
11	8,234.0	1.260	33	50.13	206.9
12	6,529.0	1.588	34	39.75	260.9
13	5,178.4	2.003	35	31.52	329.0
14	4,106.8	2.525	36	25.00	414.8
15	3,256.7	3.184	37	19.83	523.1
16	2,582.9	4.016	38	15.72	659.6
17	2,048.2	5.064	39	12.47	831.8
18	1,624.3	6.385	40	9.89	1049.0

EXAMPLE 2–7 What is the cross-sectional area of a wire with a diameter of 0.005 inch?

Solution

$$d = 0.005 \text{ in.} = 5 \text{ mils}$$
$$A = d^2 = 5^2 = \mathbf{25\ CM}$$

Related Problem What is the cross-sectional area of a 0.0015 in. diameter wire?

Wire Resistance Although copper wire conducts electricity extremely well, it still has some resistance, as do all conductors except specialized extremely low-temperature superconductors. The resistance of a wire depends on three physical characteristics: (a) type of material, (b) length of wire, and (c) cross-sectional area. In addition, temperature can also affect the resistance.

Each type of conductive material has a characteristic called its *resistivity*, ρ. For each material, ρ is a constant value at a given temperature. The formula for the resistance of a wire of length l and cross-sectional area A is

$$R = \frac{\rho l}{A} \qquad \text{Equation 2–6}$$

This formula shows that resistance increases with an increase in resistivity and length and decreases with an increase in cross-sectional area. For resistance to be calculated in ohms, the length must be in feet, the cross-sectional area in circular mils, and the resistivity in CM-Ω/ft.

EXAMPLE 2–8

Find the resistance of a 100 ft length of copper wire with a cross-sectional area of 810.1 CM. The resistivity of copper is 10.37 CM-Ω/ft.

Solution

$$R = \frac{\rho l}{A} = \frac{(10.37\text{ CM-}\Omega/\text{ft})(100\text{ ft})}{810.1\text{ CM}} = \mathbf{1.280\ \Omega}$$

Related Problem Use Table 2–3 to determine the resistance of 100 ft of copper wire with a cross-sectional area of 810.1 CM. Compare with the calculated result.

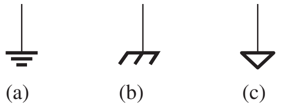
Example 2–8 illustrates calculating the resistance of a 100 ft length of AWG 21 wire. From Table 2–1, the resistance of AWG 21 wire is 12.80 Ω/1000 ft. You can find the resistance of 100 ft of this wire by using the table value and noting that 100 ft is 10% of 1000 ft. Thus, the resistance of 100 ft is 1.280 Ω.

As mentioned, Table 2–3 lists the resistance of the various standard wire sizes in ohms per 1,000 feet at 20°C. For example, a 1,000 ft length of 14 gauge copper wire has a resistance of 2.525 Ω. A 1,000 ft length of 22 gauge wire has a resistance of 16.14 Ω. For a given length, the smaller wire has more resistance. Thus, for a given voltage, larger wires can carry more current than smaller ones.

Ground

Ground is the reference point in electric circuits. The term *ground* originated from the fact that one conductor of a circuit was typically connected with an 8-foot long metal rod driven into the earth itself. Today, this type of connection is referred to as an *earth ground*. In household wiring, earth ground is indicated with a green or bare copper wire. Earth ground is normally connected to the metal chassis of an appliance or a metal electrical box for safety. Unfortunately, there have been exceptions to this rule, which can present a safety hazard if a metal chassis is not at earth ground. It is a good idea to confirm that a metal chassis is actually at earth ground potential before doing any work on an instrument or appliance.

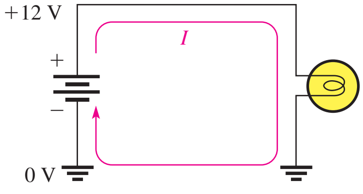
Another type of ground is called a *reference ground*. **Reference ground** refers to a common point in a circuit from which voltages are typically measured. Voltages are always specified with respect to another point. If that point is not stated explicitly, the reference ground is understood. Reference ground defines 0 V for the circuit. The reference ground can be at a completely different potential than the earth ground; it can be a very high voltage. Reference ground is also called **common** and labeled COM or COMM because it represents a common conductor. When you are wiring a protoboard in the laboratory, you will normally reserve one of the bus strips (a long line along the length of the board) for this common conductor.



▲ FIGURE 2–47

Commonly used ground symbols.

Three ground symbols are shown in Figure 2–47. Unfortunately, there is not a separate symbol to distinguish between earth ground and reference ground. The symbol in (a) represents either an earth ground or a reference ground, (b) shows a chassis ground, and (c) is an alternate reference symbol typically used when there is more than one common connection (such as analog and digital ground in the same circuit). In this book, the symbol in part (a) will be used throughout.



▲ FIGURE 2–48

A simple circuit with ground connections.

Figure 2–48 illustrates a simple circuit with ground connections. The current is from the positive terminal of the 12 V source, through the lamp, and back to the negative terminal of the source through the ground connection. Ground provides a return path for the current back to the source because all of the ground points are electrically the same point. The voltage at the top of the circuit is +12 V with respect to ground.

SECTION 2–6 CHECKUP

1. What are the basic elements of an electric circuit?
2. What is an open circuit?
3. What is a closed circuit?
4. What is the difference between a fuse and a circuit breaker?
5. Which wire is larger in diameter, AWG 3 or AWG 22?
6. What is ground (common) in an electric circuit?

2–7 BASIC CIRCUIT MEASUREMENTS

In working on electrical or electronic circuits, you will frequently need to measure voltage, current, or resistance using meters safely and correctly.

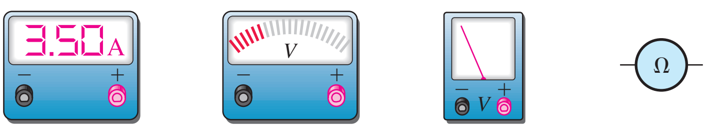
After completing this section, you should be able to

- **Make basic circuit measurements**
  - Properly measure voltage in a circuit
  - Properly measure current in a circuit
  - Properly measure resistance
  - Set up and read basic meters

Voltage, current, and resistance measurements are commonly required in electronics work. The instrument used to measure voltage is a **voltmeter**, the instrument used to measure current is an **ammeter**, and the instrument used to measure resistance is an **ohmmeter**. Commonly, all three instruments are combined into a single instrument called a **multimeter**, in which you can choose what specific quantity to measure by selecting the appropriate function with a switch.

Meter Symbols

Throughout this book, certain symbols will be used in circuits to represent meters, as shown in Figure 2–49. You may see any of four types of symbols for voltmeters, ammeters, or ohmmeters, depending on which symbol most effectively conveys the information required. The digital meter symbol is used when specific values are to be indicated in a circuit. The bar graph meter symbol and sometimes the analog meter symbol are used to illustrate the operation of a circuit when *relative* measurements or changes in quantities, rather than specific values, need to be depicted. A changing quantity may be indicated by an arrow in the display showing an increase or decrease. The generic symbol is used to indicate placement of meters in a circuit when no values or value changes need to be shown.



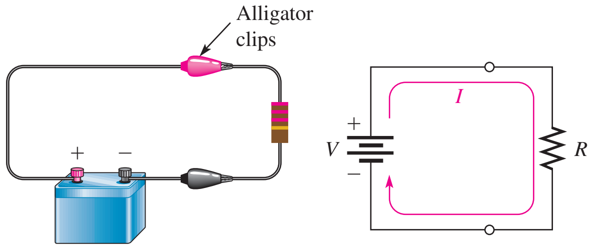
(a) Digital (b) Bar graph (c) Analog (d) Generic

FIGURE 2–49

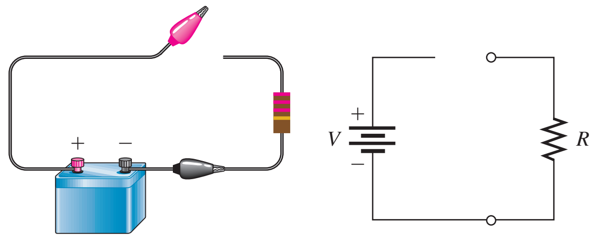
Examples of meter symbols used in this book. Each of the symbols can be used to represent either an ammeter (A), a voltmeter (V), or an ohmmeter (Ω).

Measuring Current

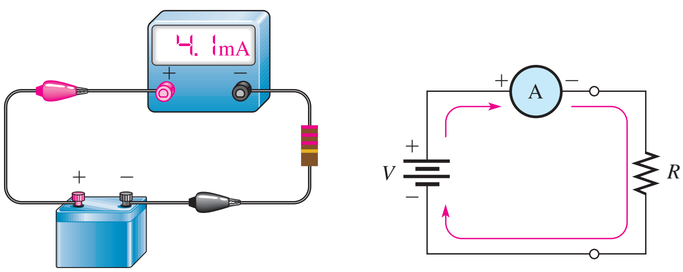
Figure 2–50 illustrates how to measure current with an ammeter. Part (a) shows a simple circuit in which the current through the resistor is to be measured. First make sure the range setting of the ammeter is greater than the expected current and then connect the ammeter in the current path by first opening the circuit, as shown in part (b). Then insert the meter as shown in part (c). Such a connection is a series connection. The polarity of the meter must be such that the current is in at the positive terminal and out at the negative terminal.



(a) Circuit in which the current is to be measured



(b) Open the circuit either between the resistor and the positive terminal or between the resistor and the negative terminal of source.



(c) Install the ammeter in the current path with polarity as shown (negative to negative, positive to positive).

▲ FIGURE 2–50

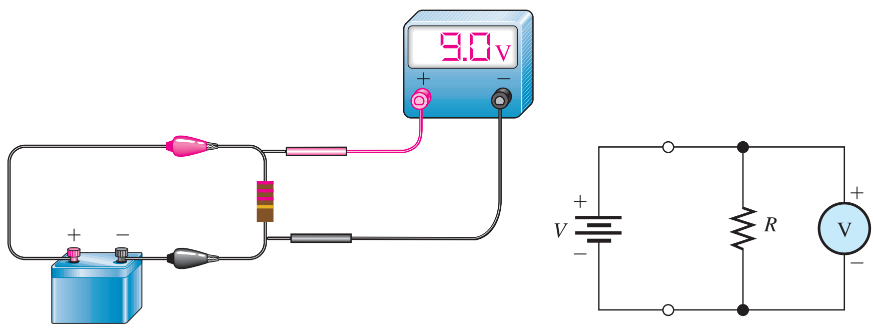
Example of an ammeter connection in a simple circuit to measure current.

SAFETY NOTE

Never wear rings or any type of metallic jewelry while working on a circuit. These items may accidentally come in contact with the circuit, causing shock and/or damage to the circuit. With high-energy sources, such as a car battery, a short across jewelry (watch or ring) can become hot instantly, causing severe burns.

Measuring Voltage

To measure voltage, connect the voltmeter across the component for which the voltage is to be found. Such a connection is a parallel connection. The negative terminal of the meter must be connected to the negative side of the circuit, and the positive terminal of the meter must be connected to the positive side of the circuit. Figure 2–51 shows a voltmeter connected to measure the voltage across the resistor.

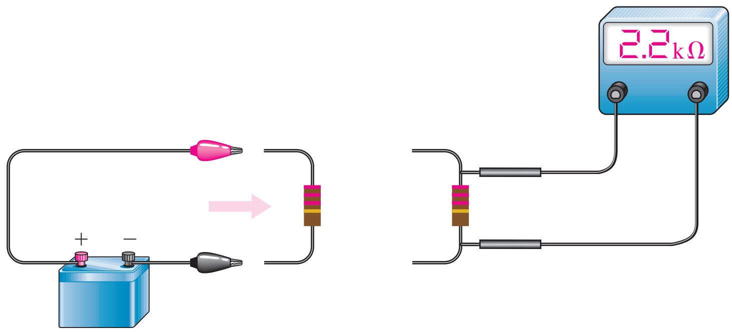


▲ FIGURE 2–51

Example of a voltmeter connection in a simple circuit to measure voltage.

Measuring Resistance

To measure resistance, first turn off the power and disconnect one end or both ends of the resistor from the circuit; then connect the ohmmeter across the resistor. This procedure is shown in Figure 2–52.



(a) Disconnect the resistor from the circuit to avoid damage to the meter and/or incorrect measurement.

(b) Measure the resistance. (Polarity is not important.)

◄ **FIGURE 2–52**

Example of using an ohmmeter to measure resistance.

Digital Multimeters

A **DMM** (digital multimeter) is a multifunction electronic instrument that can measure voltage, current, and resistance. DMMs are the most widely used type of electronic measuring instrument. Generally, DMMs provide more functions, better accuracy, greater ease of reading, and greater reliability than do many analog meters. Analog meters have at least one advantage over DMMs, however. They can track short-term variations and trends in a measured quantity that many DMMs are too slow to respond to. Figure 2–53 shows typical DMMs. The meter in Figure 2–53(a) is portable, so it is handy for typical measurement requirements. In cases where very high accuracy is required, a bench DMM such as the one shown in Figure 2–53(b) is useful.

(a) (b)

▲ **FIGURE 2–53**

Typical digital multimeters (DMMs).
(Courtesy of B + K Precision.)

DMM Functions The basic functions found on most DMMs include the following:

- Ohms
- DC voltage and current
- AC voltage and current

SAFETY NOTE

Manufacturers use the CE mark to indicate that a product meets all the essential requirements of the European Directives for health and safety. For example, DMMs that meet the directive IEC 61010-1 are in compliance and can use the CE mark on the DMM. This mark is used on many products in various countries much like the UL (underwriters lab) mark that originated in the United States. It also shows compliance with safety standards.

Many DMMs provide additional functions. These include inductor or capacitor values, temperature and/or frequency measurements, transistor or diode tests, power measurement, and decibel measurement for audio amplifier tests. Some meters require manual selection of the ranges for the functions. Many meters provide automatic range selection and are called *autoranging.*

DMM Displays DMMs are available with either LCD (liquid-crystal display), LED (light-emitting diode), or vacuum fluorescent display (VFD). The LCD is the most commonly used readout in battery-powered instruments because it requires only very small amounts of current. A typical battery-powered DMM with an LCD readout operates on a 9 V battery that will last from a few hundred hours to 2,000 hours and more. The disadvantages of LCD readouts are that (a) they are difficult or impossible to see in low-light conditions and (b) they are relatively slow to respond to measurement changes, especially in very cold temperatures. Some DMMs overcome low light difficulties with LCDs by using a back lit display. LED displays and VFDs use significantly more power than liquid crystals, so are generally limited to bench instruments but have the advantage of rugged, bright displays. LEDs and VCDs are superior to LCDs in that they have very fast response times, and function well in very cold temperatures. LEDs, on the other hand, can be seen in the dark and respond quickly to changes in measured values.

DMM displays are primarily in a 7-segment format. In a standard 7-segment display, each digit consists of seven separate segments as shown in Figure 2–54(a). Each of the ten decimal digits is formed by the activation of appropriate segments, as illustrated in Figure 2–54(b). In addition to the seven segments, there is also decimal point.

(a) (b)

FIGURE 2–54

Seven-segment display.

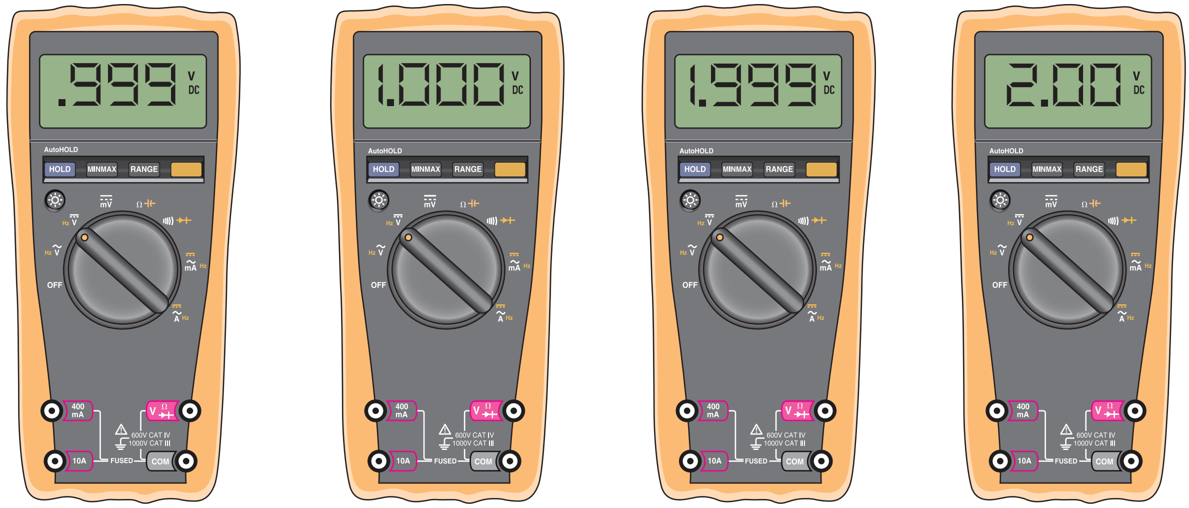
Resolution The **resolution** of a DMM is the smallest increment of a quantity that the meter can measure. The smaller the increment, the better the resolution. One factor that determines the resolution of a meter is the number of digits in the display.

Because many DMMs have 3½ digits in their display, we will use this case for illustration. A 3½-digit multimeter has three digit positions that can indicate from 0 through 9, and one digit position that can indicate only a value of 0 or 1. This latter digit, called the *half-digit,* is always the most significant digit in the display. For example, suppose that a DMM is reading 0.999 V, as shown in Figure 2–55(a). If the voltage increases by 0.001 V to 1 V, the display correctly shows 1.000 V, as shown in part (b). The "1" is the half-digit. Thus, with 3½ digits, a variation of 0.001 V, which is the resolution, can be observed.

Now, suppose that the voltage increases to 1.999 V. This value is indicated on the meter as shown in Figure 2–55(c). If the voltage increases by 0.001 V to 2 V, the half-digit cannot display the "2," so the display shows 2.00. The half-digit is blanked and only three digits are active, as indicated in part (d). With only three digits active, the resolution is 0.01 V rather than 0.001 V as it is with 3½ active digits. The resolution remains 0.01 V up to 19.99 V. The resolution goes to 0.1 V for readings of 20.0 V to 199.9 V. At 200 V, the resolution goes to 1 V, and so on.

The resolution capability of a DMM is also determined by the internal circuitry and the rate at which the measured quantity is sampled. DMMs with displays of 4½ through 8½ digits are also available.

Accuracy The **accuracy** is the degree to which a measured value represents the true or accepted value of a quantity. The accuracy of a DMM is established strictly by its internal circuitry and calibration. For typical DMMs, accuracies range from 0.01% to 0.5%, with some precision laboratory-grade DMMs going to 0.002%.



(a) Resolution: 0.001 V (b) Resolution: 0.001 V (c) Resolution: 0.001 V (d) Resolution: 0.01 V

▲ **FIGURE 2–55**

A 3$\frac{1}{2}$-digit DMM illustrates how the resolution changes with the number of digits in use.

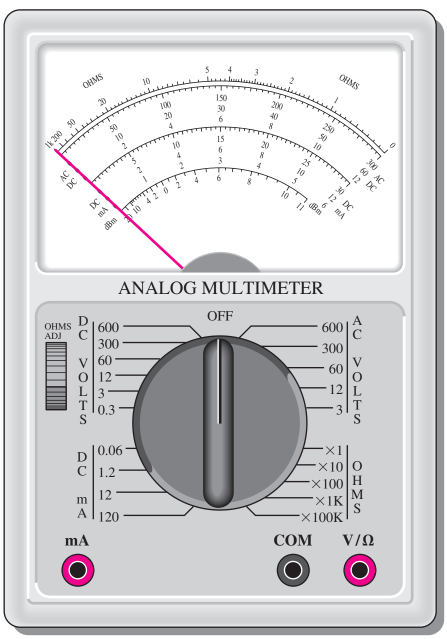
Categories for Multimeters The International Electrotechnical Commission (IEC) sets detailed standards for multimeter manufacturers in four categories. Category 1 is the lowest rating and covers standards for most low-energy circuits, such as the majority of circuits found in electronic equipment. Category 2 covers meters used for household appliances, portable tools, and similar loads. Category 3 covers three-phase distribution and electrical circuits in larger buildings. Category 4 is the highest rating and covers outdoor connections and connections to utility power and large industrial motors. The meter used for any measurement in a circuit should be rated at or above the category for the job.

SAFETY NOTE

There are many safety rules for working with meters that are designed to protect you. It is important to never work alone and always de-energize a circuit whenever possible before making measurements. When that is not possible, use protective equipment such as insulated tools, safety glasses, and insulated gloves. Avoid holding a meter when working on energized circuits—it is better to hang it up or set it on a resting place to avoid transient voltages. Take the time to be familiar with your equipment, its limitations and safety suggestions from the manufacturer. More safety suggestions are in Section 2–8.

Reading Analog Multimeters

Although the DMM is the predominate type of multimeter, you may occasionally have to use an analog meter. A representation of a typical analog multimeter is shown in Figure 2–56. This particular instrument can be used to measure both direct current (dc) and alternating current (ac) quantities as well as resistance values. It has



◀ **FIGURE 2–56**

A typical analog multimeter.

four selectable functions: dc volts (DC VOLTS), dc milliamperes (DC mA), ac volts (AC VOLTS), and OHMS. Most analog multimeters are similar to this one.

Within each function there are several ranges, as indicated by the brackets around the selector switch. For example, the DC VOLTS function has 0.3 V, 3 V, 12 V, 60 V, 300 V, and 600 V ranges. Thus, dc voltages from 0.3 V full-scale to 600 V full-scale can be measured. On the DC mA function, direct currents from 0.06 mA full-scale to 120 mA full-scale can be measured. On the ohm scale, the settings are ×1, ×10, ×100, ×1K, and ×100K.

The Ohm Scale Ohms are read on the top scale of the meter. This scale is nonlinear; that is, the values represented by each division (large or small) vary as you go across the scale. In Figure 2–56, notice how the scale becomes more compressed as you go from right to left.

To read the actual value in ohms, multiply the number on the scale as indicated by the pointer by the factor selected by the switch. For example, when the switch is set at ×100 and the pointer is at 20, the reading is $20 \times 100 = 2{,}000\ \Omega$.

As another example, assume that the switch is at ×10 and the pointer is at the seventh small division between the 1 and 2 marks, indicating 17 Ω (1.7×10). Now, if the meter remains connected to the same resistance and the switch setting is changed to ×1, the pointer will move to the second small division between the 15 and 20 marks. This, of course, is also a 17 Ω reading, illustrating that a given resistance value can often be read at more than one range switch setting. However, the meter should be *zeroed* each time the range is changed by touching the leads together and adjusting the needle.

The AC-DC and DC mA Scales The second, third, and fourth scales from the top, labeled "AC" and "DC," are used in conjunction with the DC VOLTS and AC VOLTS functions. The upper ac-dc scale ends at the 300 mark and is used with range settings, such as 0.3, 3, and 300. For example, when the switch is at 3 on the DC VOLTS function, the 300 scale has a full-scale value of 3 V; at the range setting of 300, the full-scale value is 300 V.

EXAMPLE 2–9

Determine the quantity (voltage, current, or resistance) that is being measured and its value for each specified switch setting on the meter in Figure 2–57.

(a) The switch is set on the DC VOLTS function and the 60 V range.

(b) The switch is set on the DC mA function and the 12 mA range.

(c) The switch is set on the OHMS function and the ×1K range.

Solution

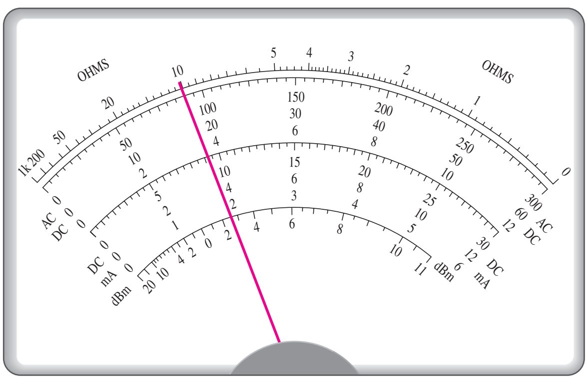
(a) The reading taken from the middle AC-DC scale is **18 V**.

(b) The reading taken from the lower AC-DC scale is **3.8 mA**.

(c) The reading taken from the ohms scale (top) is **10 kΩ**.

Related Problem In Figure 2–57 the switch is moved to the ×100 ohms setting. Assuming that the same resistance is being measured as in part (c), what will the needle do?

FIGURE 2–57



The middle ac-dc scale ends at 60. This scale is used in conjunction with range settings, such as 0.06, 60, and 600. For example, when the switch is at 60 on the DC VOLTS function, the full-scale value is 60 V. The lower ac-dc scale ends at 12 and is used in conjunction with switch settings, such as 1.2, 12, and 120. The three DC mA scales are used in a similar way to measure current.

SECTION 2–7 CHECKUP

1. Name the meters for measurement of (a) current, (b) voltage, and (c) resistance.
2. Show how to place two ammeters in the circuit of Figure 2–40 to measure the current through either lamp (be sure to observe the polarities). How can the same measurements be accomplished with only one ammeter?
3. Show how to place a voltmeter to measure the voltage across Lamp 2 in Figure 2–40.
4. List two common types of DMM displays, and discuss the advantages and disadvantages of each.
5. Define *resolution* in a DMM.
6. The analog multimeter in Figure 2–56 is set on the 3 V range to measure dc voltage. The pointer is at 150 on the upper ac-dc scale. What voltage is being measured?

2–8 ELECTRICAL SAFETY

Safety is a major concern when working with electricity. The possibility of an electric shock or a burn is always present, so caution should always be used. You provide a current path when voltage is applied across two points on your body, and current produces electrical shock. Electrical components often operate at high temperatures, so you can sustain skin burns when you come in contact with them. Also, the presence of electricity creates a potential fire hazard.

After completing this section, you should be able to

- **Recognize electrical hazards and practice proper safety procedures**
  - Describe the cause of electrical shock
  - List the groups of current paths through the body
  - Discuss the effects of current on the human body
  - List the safety precautions that you should observe when you work with electricity

Electric Shock

Current through your body, not the voltage, is the cause of **electrical shock**. Of course, it takes voltage across a resistance to produce current. When a point on your body comes in contact with a voltage and another point comes in contact with a different voltage or with ground, such as a metal chassis, there will be current through your body from one point to the other. The path of the current depends on the points across which the voltage occurs. The severity of the resulting electrical shock depends on the amount of voltage and the path that the current takes through your body. The current path through the body determines which tissues and organs will be affected.

Effects of Current on the Human Body The amount of current is dependent on voltage and resistance. The human body has resistance that depends on many factors, which include body mass, skin moisture, and points of contact of the body with a voltage potential. Table 2–4 shows the effects for various values of current in milliamperes.

Body Resistance Resistance of the human body is typically between 10 kΩ and 50 kΩ and depends on the two points between which it is measured. The moisture of the skin also affects the resistance between two points. The resistance determines

▸ **TABLE 2–4**

Physical effects of electrical current. Values vary depending on body mass.

CURRENT (MA)	PHYSICAL EFFECT
0.4	Slight sensation
1.1	Perception threshold
1.8	Shock, no pain, no loss of muscular control
9	Painful shock, no loss of muscular control
16	Painful shock, let-go threshold
23	Severe painful shock, muscular contractions, breathing difficulty
75	Ventricular fibrillation, threshold
235	Ventricular fibrillation, usually fatal for duration of 5 seconds or more
4,000	Heart paralysis (no ventricular fibrillation)
5,000	Tissue burn

the amount of voltage required to produce each of the effects listed in Table 2–4. For example, if you have a resistance of 10 kΩ between two given points on your body, 90 V across those two points will produce enough current (9 mA) to cause painful shock.

Utility Voltages

We tend to take utility voltages for granted, but they can be and have been lethal. It is best to be careful around any source of voltage (even low voltages can present a serious burn hazard). As a general rule, you should avoid working on any energized circuit, and check that the power is off with a known good meter. Most work in educational labs uses low voltages, but you should still avoid touching any energized circuit. If you are working on a circuit that is connected to utility voltages, the service should be disconnected, a notice should be placed on the equipment or place where the service is disconnected, and a padlock should be used to prevent someone from accidentally turning on the power. This procedure is called *lockout/tagout* and is widely used in industry. There are specific OSHA and industry standards for lockout/tagout.

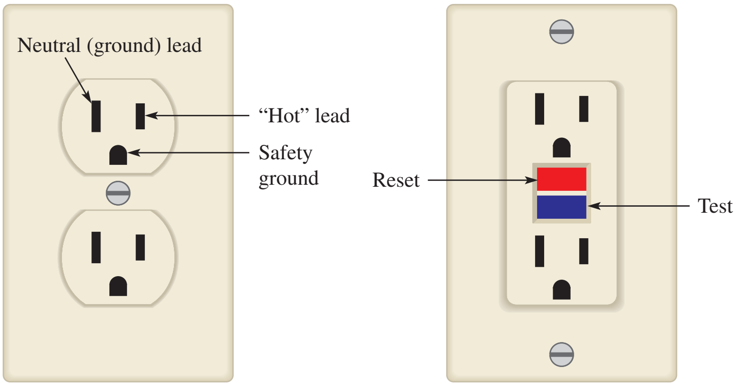
Most laboratory equipment is connected to the utility line ("ac") and in North America, this is 120 Vrms (rms is discussed in Section 11–3). A faulty piece of equipment can cause the "hot" lead to inadvertently become exposed. You should inspect cords for exposed wires and check equipment for missing covers or other potential safety problems. The single-phase utility lines in homes and electrical laboratories use three insulated wires that are referred to as the "hot" (black or red wire), neutral (white wire), and safety ground (green wire). The hot and neutral wires will have current, but the green safety line should never have current in normal operation. The safety wire is connected to the metal exterior of encased equipment and is also connected to conduit and the metal boxes for housing receptacles. Figure 2–58(a) shows the location of these conductors on a standard receptacle. Notice that the neutral line is larger than the hot line.

TECH TIP

Receptacle testers are designed for use with specific receptacle types including specialized outlets. They can pinpoint problems such as open lines, faulty wiring, or reversed polarity; they show results with a lighted LED or neon bulb. Some testers are designed to test ground fault circuit interrupters (GFCI) for proper operation.

The safety ground should be connected to the neutral at the service panel. The metal chassis of an instrument or appliance is also connected to ground. In the event that the hot wire is accidentally in contact with ground, the resulting high current should trip the circuit breaker or open a fuse to remove the hazard. However, a broken or missing ground lead may not have high current until it is contacted by a person. This danger is one obvious reason for ensuring that line cords have not been altered by removing the ground pin.

Many circuits are further protected with a special device called a ground-fault circuit interrupter (GFCI, which is sometimes called just GFI). If a fault occurs in a GFCI circuit, a sensor detects that the current in the hot line and the neutral line are not equal as they should be and trips the circuit breaker. The GFCI breaker is very fast acting and can trip faster than the breaker on the main panel. GFCI breakers are required in areas where a shock hazard exists such as wherever there is water



(a) Standard receptacle and connections

(b) GFCI receptacle

FIGURE 2–58

Standard electrical outlets.

or moisture. Pools, bathrooms, kitchens, basements, and garages should all have GFCI outlets. Figure 2–58(b) shows a ground-fault receptacle with reset and test buttons. When the test button is pressed, the circuit should immediately be opened. The reset button restores power.

Safety Precautions

There are many practical things that you should do when you work with electrical and electronic equipment. Some important precautions are listed here.

- Avoid contact with any voltage source. Turn power off before you work on circuits when touching circuit parts is required.
- Do not work alone. A telephone should be available for emergencies.
- Do not work when tired or taking medications that make you drowsy.
- Remove rings, watches, and other metallic jewelry when you work on circuits.
- Do not work on equipment until you know proper procedures and are aware of potential hazards.
- Make sure power cords are in good condition and grounding pins are not missing or bent.
- Keep your tools properly maintained. Make sure the insulation on metal tool handles is in good condition.
- Handle tools properly and maintain a neat work area.
- Wear safety glasses when appropriate, particularly when soldering and clipping wires.
- Always shut off power and discharge capacitors before you touch any part of a circuit. Capacitors can be discharged with a special capacitor discharge tool that releases the charge in a controlled manner.
- Know the location of the emergency power-off switch and emergency exits.
- Never try to override or tamper with safety devices such as an interlock switch.
- Always wear shoes and keep them dry. Do not stand on metal or wet floors when working on electrical circuits. Stand on a rubber mat if possible.
- Never handle instruments when your hands are wet.
- Never assume that a circuit is off. Double-check it with a known good meter before handling.
- Set the limiter on electronic power supplies to prevent currents larger than necessary to supply the circuit under test.

SAFETY NOTE

A GFCI outlet does not prevent shock or injury in all cases. If you are touching the hot and neutral wires without being grounded, no ground fault is detected and the GFCI breaker will not trip. In another case, the GFCI may prevent electrocution but not the initial electric shock before it interrupts the circuit. The initial shock could cause a secondary injury, such as a fall.

- When making circuit connections, always make the connection to the point with the highest voltage as your last step.
- Avoid contact with the terminals of power supplies.
- Always use wires with insulation and connectors or clips with insulating shrouds.
- Keep cables and wires as short as possible. Connect polarized components properly.
- Be aware of and follow all workplace and laboratory rules. Do not have drinks or food near equipment.
- If another person cannot let go of an energized conductor, switch the power off immediately. If that is not possible, use any available nonconductive material to try to separate the body from the contact.
- Use a lockout/tagout procedure to avoid someone turning power on while you are working on a circuit.

SECTION 2–8 CHECKUP

1. What causes physical pain and/or damage to the body when electrical contact is made?
2. It's OK to wear a ring when working on an electrical circuit. (T or F)
3. Standing on a wet floor presents no safety hazard when working with electricity. (T or F)
4. A circuit can be rewired without removing the power if you are careful. (T or F)
5. Electrical shock can be extremely painful or even fatal. (T or F)
6. What does GFCI stand for?

Application Activity

In this application activity, a dc voltage is applied to a circuit in order to produce current through a lamp to provide light. You will see how the current is controlled by resistance. The circuit simulates an instrument panel illumination circuit, which allows you to increase or decrease the amount of light on the instruments.

The instrument panel illumination circuit operates from a 12 V battery that is the voltage source for the circuit. The circuit uses a potentiometer connected as a rheostat, controlled by a knob on the instrument panel, which is used to set the amount of current through the lamp to back-light the instruments. The brightness of the lamp is proportional to the amount of current through the lamp. The switch used to turn the lamp on and off is the same one used for the headlights. There is a fuse for circuit protection in case of a short circuit.

Figure 2–59 shows the schematic for the illumination circuit, and Figure 2–60 shows the breadboarded circuit. A laboratory dc power supply is used in the place of an actual battery. The protoboard in Figure 2–60 is a type that is commonly used for constructing circuits on the test bench.

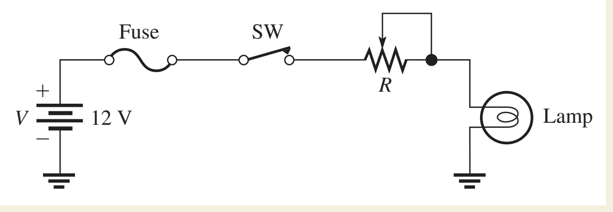
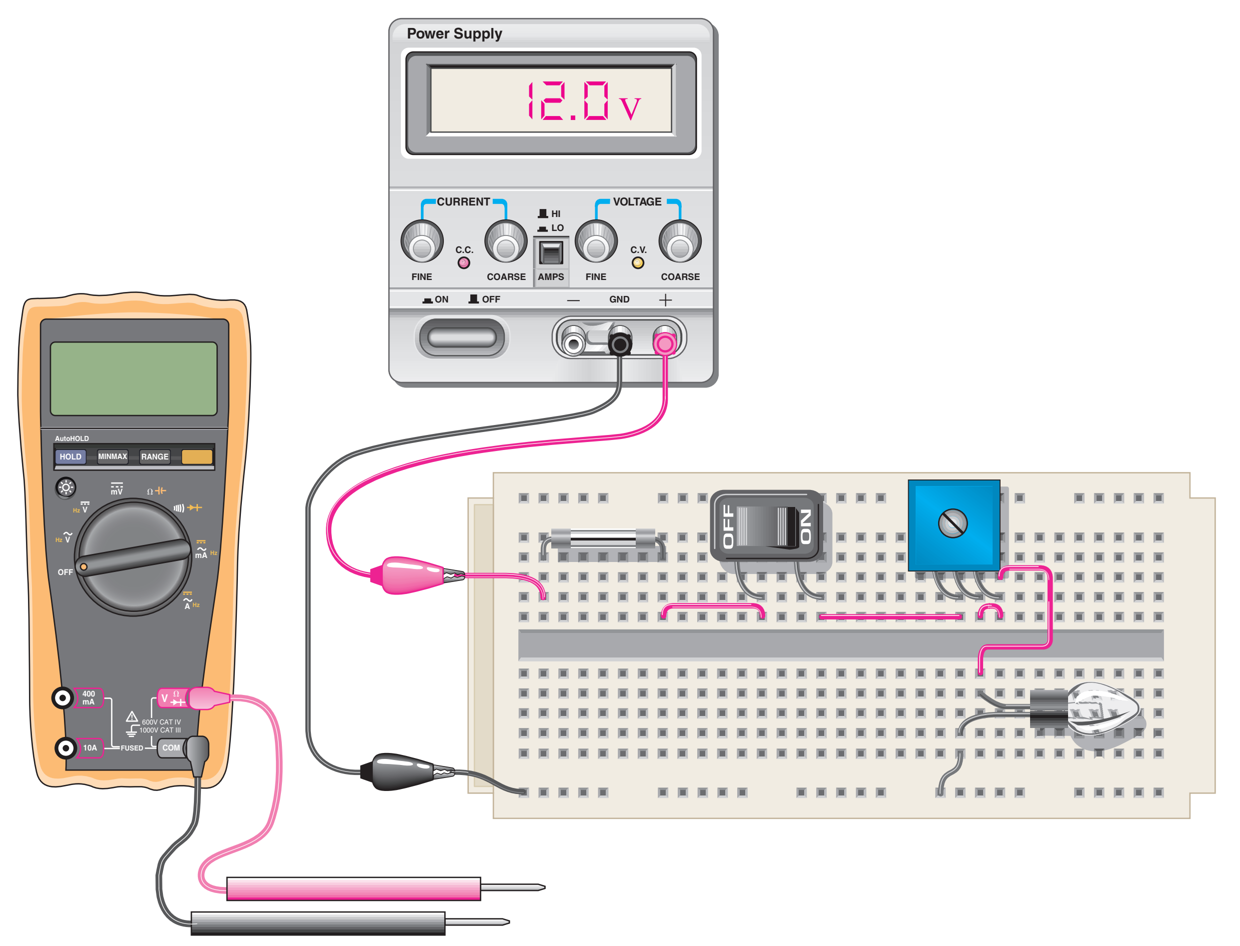


FIGURE 2–59

Basic panel illumination circuit schematic.



▲ **FIGURE 2–60**

Test bench setup for simulating the panel illumination circuit.

The Test Bench

Figure 2–60 shows the breadboarded circuit, a dc power supply, and a digital multimeter. The power supply is connected to provide 12 V to the circuit. The multimeter is used to measure current, voltage, and resistance in the circuit.

1. Identify each component in the circuit and check the breadboarded circuit in Figure 2–60 to make sure it is connected as the schematic in Figure 2–59 indicates.

2. Explain the purpose of each component in the circuit.

As shown in Figure 2–61, the typical protoboard consists of rows of small sockets into which component leads and wires are inserted. In this particular configuration, all five sockets in each row are connected together and are effectively one electrical point as shown in the bottom view. All sockets arranged on the outer edges of the board are typically connected together as shown.

Measuring Current with the Multimeter

Set the DMM to the ammeter function to measure current. You must break the circuit in order to connect the ammeter in series to measure current. Refer to Figure 2–62.

3. Redraw the schematic in Figure 2–59 to include the ammeter.

4. For which measurement (A, B, or C) is the lamp brightest? Explain.

5. List the change(s) in the circuit that can cause the ammeter reading to go from A to B.

6. List the circuit condition(s) that will produce the ammeter reading in C.

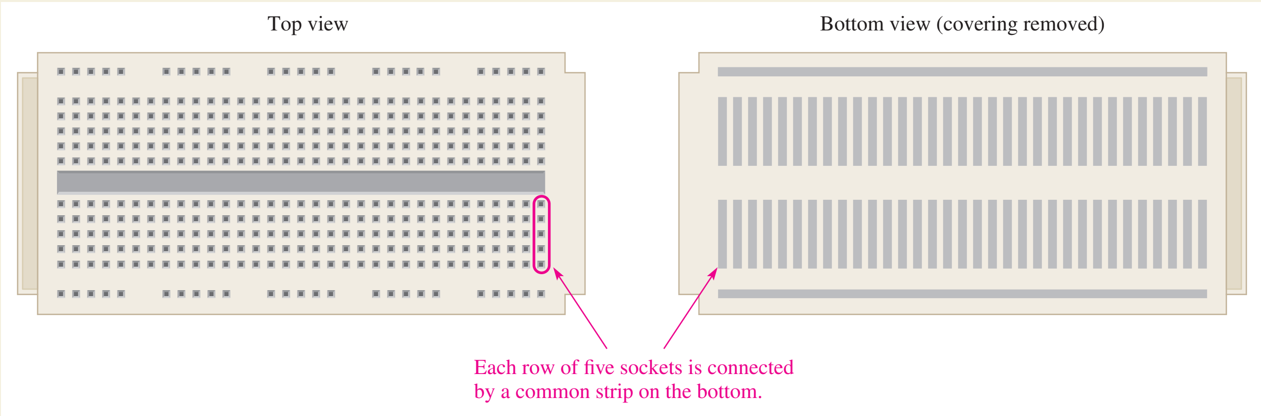


FIGURE 2–61

A typical protoboard used for breadboarding.

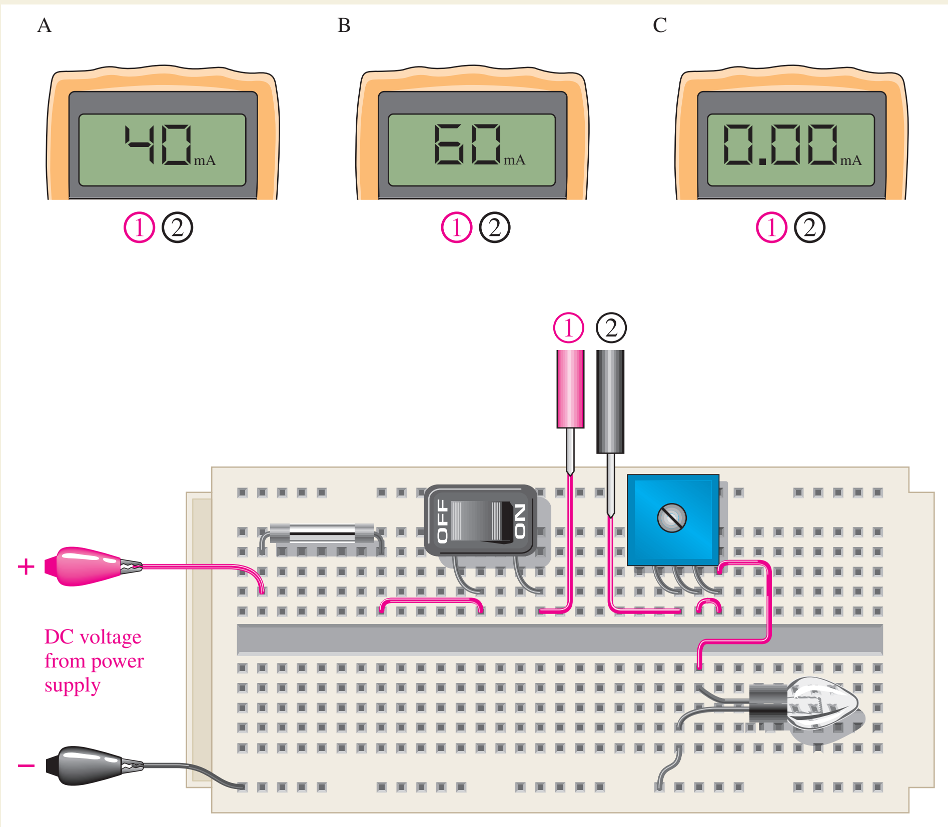


FIGURE 2–62

Current measurements. Only the meter displays are shown.

Measuring Voltage with the Multimeter

Set the DMM to the voltmeter function to measure voltage. You must connect the voltmeter to the two points across which you are measuring the voltage. Refer to Figure 2–63.

7. Across which component is the voltage measured?
8. Redraw the schematic in Figure 2–59 to include the voltmeter.
9. For which measurement (A or B) is the lamp brighter? Explain.
10. List the change(s) in the circuit that can cause the voltmeter reading to go from A to B.

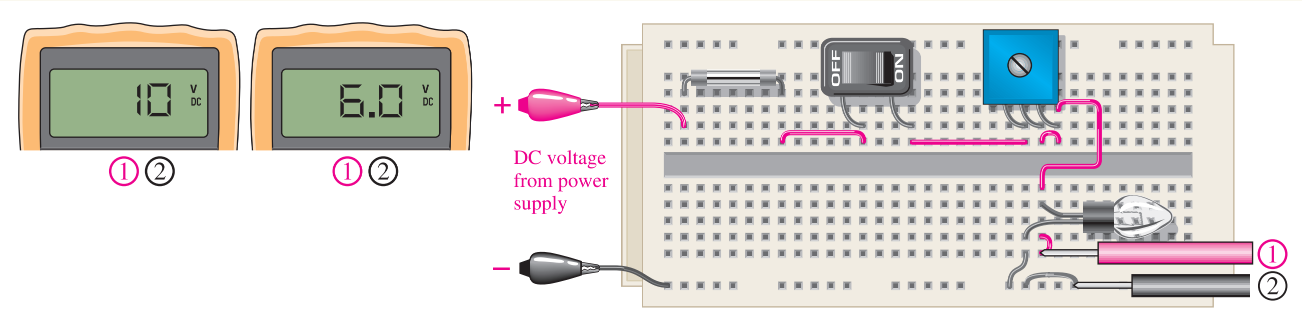


FIGURE 2–63

Voltage measurements.

Measuring Resistance with the Multimeter

Set the DMM to the ohmmeter function to measure resistance. Before you connect the ohmmeter, you must disconnect the resistance to be measured from the circuit. Before you disconnect any component, first turn the power supply off. Refer to Figure 2–64.

11. For which component is the resistance measured?
12. For which measurement (A or B) will the lamp be brighter when the circuit is reconnected and the power turned on? Explain.

Review

13. If the dc supply voltage in the panel illumination circuit is reduced, how is the amount of light produced by the lamp affected? Explain.
14. Should the potentiometer be adjusted to a higher or lower resistance for the circuit to produce more light?

Multisim Analysis

Open multisim and create the instrument panel illumination circuit. Run the simulation; operate the switch and rheostat to observe operation.

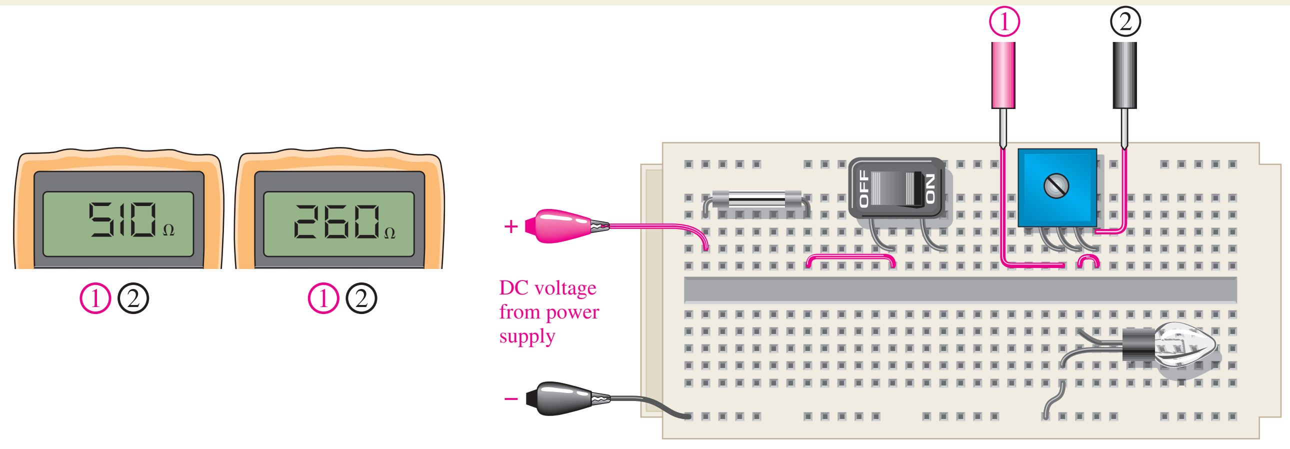


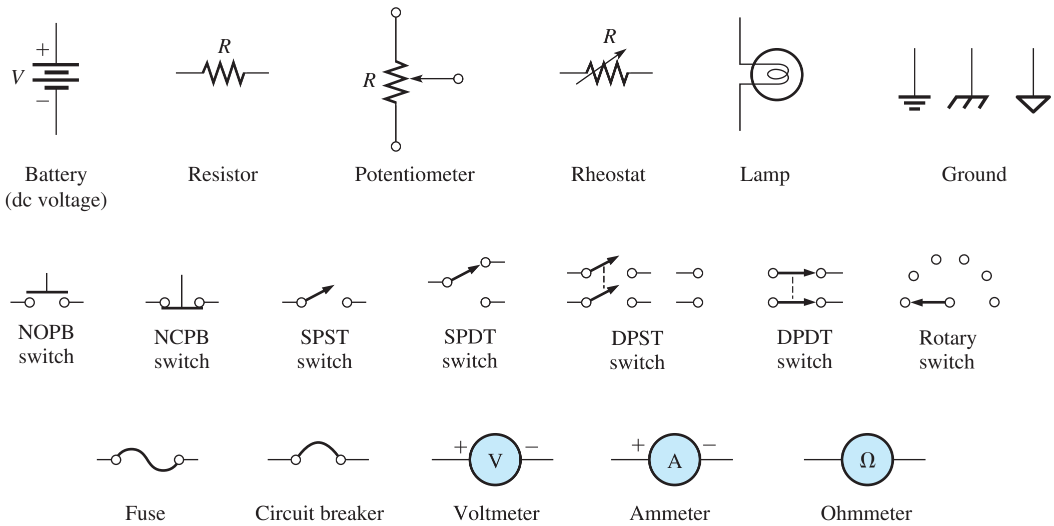
FIGURE 2–64

Resistance measurements.

SUMMARY

- An atom is the smallest particle of an element that retains the characteristics of that element.
- When electrons in the outer orbit of an atom (valence electrons) break away, they become free electrons.
- Free electrons make current possible.
- Like charges repel each other, and opposite charges attract each other.

- Voltage must be applied to a circuit to produce current.
- Resistance limits the current.
- Basically, an electric circuit consists of a source, a load, and a current path.
- An open circuit is one in which the current path is broken.
- A closed circuit is one which has a complete current path.
- An ammeter is connected in line with the current path.
- A voltmeter is connected across the current path.
- An ohmmeter is connected across a resistor (resistor must be disconnected from circuit).
- One coulomb is the charge of 6.25×10^{18} electrons.
- One volt is the potential difference (voltage) between two points when one joule of energy is required to move one coulomb of charge from one point to the other.
- One ampere is the amount of current that exists when one coulomb of charge moves through a given cross-sectional area of a material in one second.
- One ohm is the resistance when there is one ampere of current in a material with one volt applied across the material.
- Figure 2–65 shows the electrical symbols introduced in this chapter.
- Standard connections to electrical outlets include a hot wire, a neutral, and a safety ground.
- GFCI breakers sense the currents in the hot wire and neutral wire and trip the breaker if the currents are different, indicating a ground fault.



▲ **FIGURE 2–65**

Schematic symbols.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Ammeter An electrical instrument used to measure current.

Ampere (A) The unit of electrical current.

Atom The smallest particle of an element possessing the unique characteristics of that element.

AWG American wire gauge; a standardization based on wire diameter.

Charge An electrical property of matter that exists because of an excess or a deficiency of electrons. Charge can be either positive or negative.

Circuit An interconnection of electrical components designed to produce a desired result. A basic circuit consists of a source, a load, and an interconnecting current path.

Closed circuit A circuit with a complete current path.

Conductance The ability of a circuit to allow current. The unit is siemens (S).

Conductor A material in which electric current is easily established. An example is copper.

Coulomb (C) The unit of electrical charge; the total charge possessed by 6.25×10^{18} electrons.

Coulomb's law A law that states a force exists between two charged bodies that is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.

Current The rate of flow of charge. In metallic conductors, the charge is carried by electrons. Charge can also be carried by ions in an electrolyte or in an ionized gas.

Current source A device that produces a constant current for a varying load.

DMM Digital multimeter; an electronic instrument that combines functions for measurement of voltage, current, and resistance.

Electrical shock The physical sensation resulting from electrical current through the body.

Electron A basic particle of electrical charge in matter. The electron possesses negative charge.

Free electron A valence electron that has broken away from its parent atom and is free to move under the influence of an electric or magnetic field.

Ground The common or reference point in a circuit.

Insulator A material that does not allow current under normal conditions.

Load An element connected across the output terminals of a circuit that draws current from the source and upon which work is done.

Ohm (Ω) The unit of resistance.

Ohmmeter An instrument for measuring resistance.

Open circuit A circuit in which there is not a complete current path.

Potentiometer A three-terminal variable resistor.

Pole With reference to a switch, it is the movable arm; the number of poles determines the number of independent circuits the switch can control. Thus a DP switch can control 2 independent circuits.

Power supply An electronic device that converts ac voltage to dc voltage.

Reference ground A common point in a circuit from which voltages are typically measured.

Resistance Opposition to current. The unit is the ohm (Ω).

Resistor An electrical component specifically designed to have a certain amount of resistance.

Rheostat A two-terminal variable resistor.

Semiconductor A material that has a conductance value between that of a conductor and an insulator. Silicon and germanium are examples.

Siemens (S) The unit of conductance.

Strain gauge A sensor in which the resistance varies with the applied force. They are widely used in scales and in various transducers (accelerometers, displacement and force) and for expansion and contraction.

Throw With reference to a switch, it is the number of contacts (positions) that are affected by a single switch action. Thus a single throw (ST) switch close a circuit in only one position. A double-throw (DT) switch has two positions.

Volt The unit of voltage or electromotive force.

Voltage The amount of energy per charge available to move electrons from one point to another in an electric circuit.

Voltage source A device that produces a constant voltage for a varying load.

Voltmeter An instrument used to measure voltage.

FORMULAS

2–1	$Q = \dfrac{\text{Number of electrons}}{6.25 \times 10^{18}\ \text{electrons/C}}$	Charge
2–2	$V = \dfrac{W}{Q}$	Voltage equals energy divided by charge.
2–3	$I = \dfrac{Q}{t}$	Current equals charge divided by time.
2–4	$G = \dfrac{1}{R}$	Conductance is the reciprocal of resistance.
2–5	$A = d^2$	Cross-sectional area (in CM) equals the diameter squared.
2–6	$R = \dfrac{\rho l}{A}$	Resistance is resistivity times length divided by cross-sectional area.

TRUE/FALSE QUIZ

Answers are at the end of the chapter.

1. The number of protons in the nucleus is the atomic number of that element.
2. The outermost shell of an atom contains the valence electrons.
3. Silicon and germanium are classed as insulators.
4. The unit of charge is ampere.
5. Like charges repel.
6. Coulomb's law shows the relationship of the energy between two charges.
7. A battery stores charge.
8. An ideal voltage source can provide a constant voltage for any current required by a circuit.
9. A volt can be defined in terms of energy per charge.
10. A fuel cell combines a fuel with an oxidizer to produce electricity.
11. The unit of current is coulomb.
12. In a 5-band precision resistor, the fourth band is the tolerance band.
13. A resistor with a single black band represents zero ohms.
14. A resistor labeled 0R1 is 1 ohm.
15. A rheostat performs the same function as a potentiometer.
16. A strain gauge changes resistance in response to an applied force.
17. All circuits must have a complete path for current.
18. A circular mil is a unit of area.
19. The three basic measurements that can be done by a DMM are voltage, current, and power.
20. If a GFCI breaker detects a difference in the hot line and neutral, the breaker should trip.

SELF-TEST

Answers are at the end of the chapter.

1. A neutral atom with an atomic number of three has how many electrons?
   (a) 1 **(b)** 3 **(c)** none **(d)** depends on the type of atom
2. Electron orbits are called
   (a) shells **(b)** nuclei **(c)** waves **(d)** valences
3. Materials in which there is no current when voltage is applied are called
   (a) filters **(b)** conductors **(c)** insulators **(d)** semiconductors
4. When placed close together, a positively charged material and a negatively charged material will
   (a) repel **(b)** become neutral **(c)** attract **(d)** exchange charges
5. The charge on a single electron is
   (a) 6.25×10^{-18} C **(b)** 1.6×10^{-19} C
   (c) 1.6×10^{-19} J **(d)** 3.14×10^{-6} C
6. *Potential difference* is another term for
   (a) energy **(b)** voltage
   (c) distance of an electron from the nucleus **(d)** charge
7. The unit of energy is the
   (a) watt **(b)** coulomb **(c)** joule **(d)** volt
8. Which one of the following is not a type of energy source?
   (a) battery **(b)** solar cell **(c)** generator **(d)** potentiometer
9. Which one of the following is not a possible condition in an electric circuit?
   (a) voltage and no current **(b)** current and no voltage
   (c) voltage and current **(d)** no voltage and no current

10. Electrical current is defined as

(a) the reciprocal of resistance **(b)** the rate of flow of charge

(c) the energy required to move charge **(d)** the charge on free electrons

11. There is no current in a circuit when

(a) a switch is closed **(b)** a switch is open **(c)** there is no voltage

(d) answers (a) and (c) **(e)** answers (b) and (c)

12. The primary purpose of a resistor is to

(a) increase current **(b)** limit current

(c) produce heat **(d)** resist current change

13. Wire resistance depends on the

(a) type of material **(b)** length of wire

(c) cross-sectional area **(d)** all of these

14. Potentiometers and rheostats are types of

(a) voltage sources **(b)** variable resistors

(c) fixed resistors **(d)** circuit breakers

15. The current in a given circuit is not to exceed 22 A. Which value of fuse is best?

(a) 10 A **(b)** 25 A **(c)** 20 A **(d)** a fuse is not necessary

16. The neutral line in a ac utility should

(a) have zero current

(b) have current equal to the ground current

(c) share the current equally with the ground line

(d) have current equal to the hot current

PROBLEMS AND QUESTIONS?

Answers to odd-numbered problems are at the end of the book.

SECTION 2–2 Electrical Charge

1. What is the charge in coulombs of the nucleus of a copper atom?

2. What is the charge in coulombs of the nucleus of a chlorine atom?

3. How many coulombs of charge do 50×10^{31} electrons possess?

4. How many electrons does it take to make 80 μC (microcoulombs) of charge?

SECTION 2–3 Voltage

5. Determine the voltage in each of the following cases:

(a) 10 J/C **(d)** 5 J/2 C **(c)** 100 J/25 C

6. Five hundred joules of energy are used to move 100 C of charge through a resistor. What is the voltage across the resistor?

7. What is the voltage of a battery that uses 24 J of energy to move 2.0 C of charge through a resistor?

8. How much energy does a 12 V battery use to move 2.5 C through a circuit?

9. If a resistor with a current of 20 mA through it converts 12 J of electrical energy into heat energy in 60 s, what is the voltage across the resistor?

10. List four common sources of voltage.

11. Upon what principle is electrical generators based?

12. How does and electronic power supply differ from the other sources of voltage?

SECTION 2–4 Current

13. A certain current source provides 100 mA to a 1 kΩ load. If the resistance is decreased to 500 Ω, what is the current in the load?

14. Determine the current in each of the following cases:
    (a) 75 C in 1 s **(b)** 10 C in 0.5 s **(c)** 5 C in 2 s
15. Six-tenths coulomb passes a point in 3 s. What is the current in amperes?
16. How long does it take 10 C to flow past a point if the current is 5 A?
17. How many coulombs pass a point in 0.1 s when the current is 1.5 A?
18. 5.74×10^{17} electrons flow through a wire in 250 ms. What is the current in amperes?

SECTION 2–5 Resistance

19. Find the conductance for each of the following resistance values:
    (a) 5 Ω **(b)** 25 Ω **(c)** 100 Ω
20. Find the resistance corresponding to the following conductances:
    (a) 0.1 S **(b)** 0.5 S **(c)** 0.02 S
21. Determine the resistance values and tolerance for the following 4-band resistors:
    (a) red, violet, orange, gold **(b)** brown, gray, red, silver
    (c) brown, red, brown, gold **(d)** orange, blue, red, silver
22. Find the minimum and the maximum resistance within the tolerance limits for each resistor in Problem 21.
23. Determine the color bands for each of the following 4-band, 5% values: 330 Ω, 2.2 kΩ, 56 kΩ, 100 kΩ, and 39 kΩ.
24. Determine the resistance and tolerance of each of the following 4-band resistors:
    (a) brown, black, black, gold
    (b) green, brown, green, silver
    (c) blue, gray, black, gold
25. Determine the resistance and percent tolerance for each of the resistors in Figure 2–66.

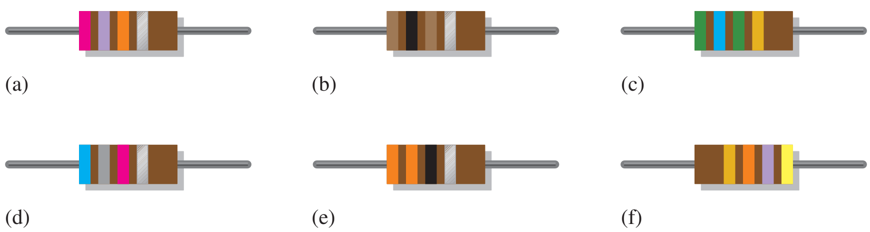


FIGURE 2–66

26. From the selection of resistors in Figure 2–67, select the following values: 330 Ω, 2.2 kΩ, 56 kΩ, 100 kΩ, and 39 kΩ.

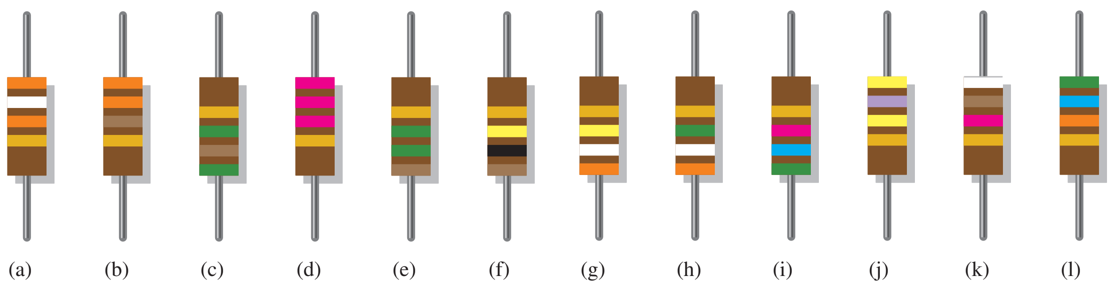


FIGURE 2–67

27. Determine the color bands for each of the following 4-band resistors. Assume each has 5% tolerance.

(a) 0.47 Ω **(b)** 270 kΩ **(c)** 5.1 MΩ

28. Determine the resistance and tolerance of each of the following 5-band resistors:

(a) red, gray, violet, red, brown

(b) blue, black, yellow, gold, brown

(c) white, orange, brown, brown, brown

29. Determine the color bands for each of the following 5-band resistors. Assume each has 1% tolerance.

(a) 14.7 kΩ **(b)** 39.2 Ω **(c)** 9.76 kΩ

30. The adjustable contact of a linear potentiometer is set at the mechanical center of its adjustment. If the total resistance is 1,000 Ω, what is the resistance between each end terminal and the adjustable contact?

31. What resistance is indicated by 4K7?

32. Determine the resistance and tolerance of each resistor labeled as follows:

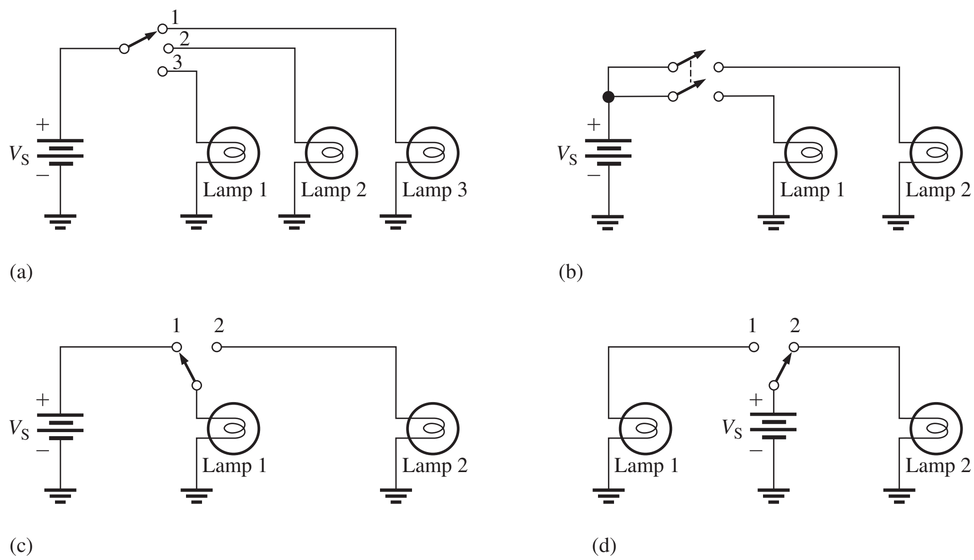
(a) 27RJ **(b)** 5602M **(c)** 1501F **(d)** 0R5

SECTION 2–6 The Electric Circuit

33. Trace the current path in Figure 2–68(a) with the switch in position 2.

34. With the switch in either position, redraw the circuit in Figure 2–68(d) with a fuse connected to protect the circuit against excessive current.

FIGURE 2–68



35. There is only one circuit in Figure 2–68 in which it is possible to have all lamps on at the same time. Determine which circuit it is.

36. In Figure 2–68, determine which (if any) circuits have an SPDT switch.

37. In Figure 2–68, determine which (if any) circuits have a DPST switch.

38. Through which resistor in Figure 2–69 is there always current, regardless of the position of the switches?

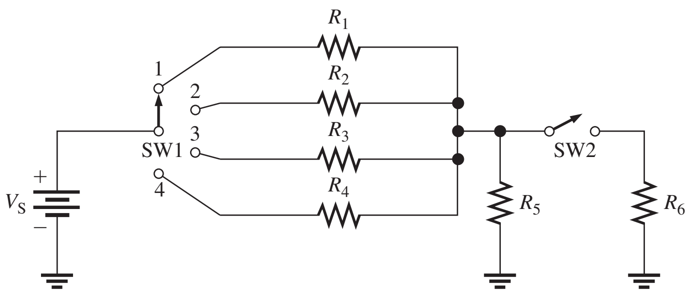
39. Devise a switch arrangement whereby two voltage sources (V_{S1} and V_{S2}) can be connected simultaneously to either of two resistors (R_1 and R_2) as follows:

V_{S1} connected to R_1 and V_{S2} connected to R_2

or V_{S1} connected to R_2 and V_{S2} connected to R_1

40. Show how a single switch can be used to connect a CD (compact disk) player, an AM tuner, or an FM tuner to an amplifier by a single knob control. Only one unit can be connected to the amplifier at any time.

▶ FIGURE 2–69

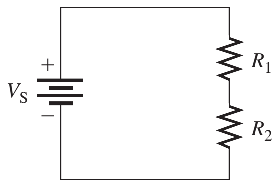


SECTION 2–7 Basic Circuit Measurements

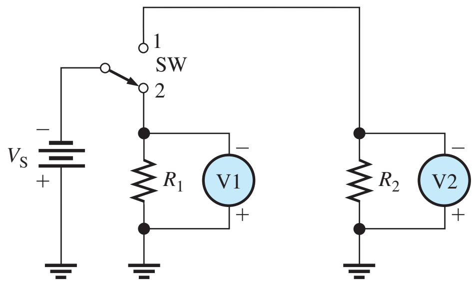
41. Show the placement of an ammeter and a voltmeter to measure the current and the source voltage in Figure 2–70.

42. Explain how you would measure the resistance of R_2 in Figure 2–70.

43. In Figure 2–71, how much voltage does each meter indicate when the switch is in position 1? In position 2?



▲ FIGURE 2–70



▲ FIGURE 2–71

44. In Figure 2–71, indicate how to connect an ammeter to measure the current from the voltage source regardless of the switch position.

45. In Figure 2–69, show the proper placement of ammeters to measure the current through each resistor and the current out of the battery.

46. Show the proper placement of voltmeters to measure the voltage across each resistor in Figure 2–69.

47. What is the voltage reading of the meter in Figure 2–72(a)?

48. How much resistance is the ohmmeter in Figure 2–72(b) measuring?

49. Determine the resistance indicated by each of the following ohmmeter readings and range settings:

(a) pointer at 2, range setting at $\times 10$

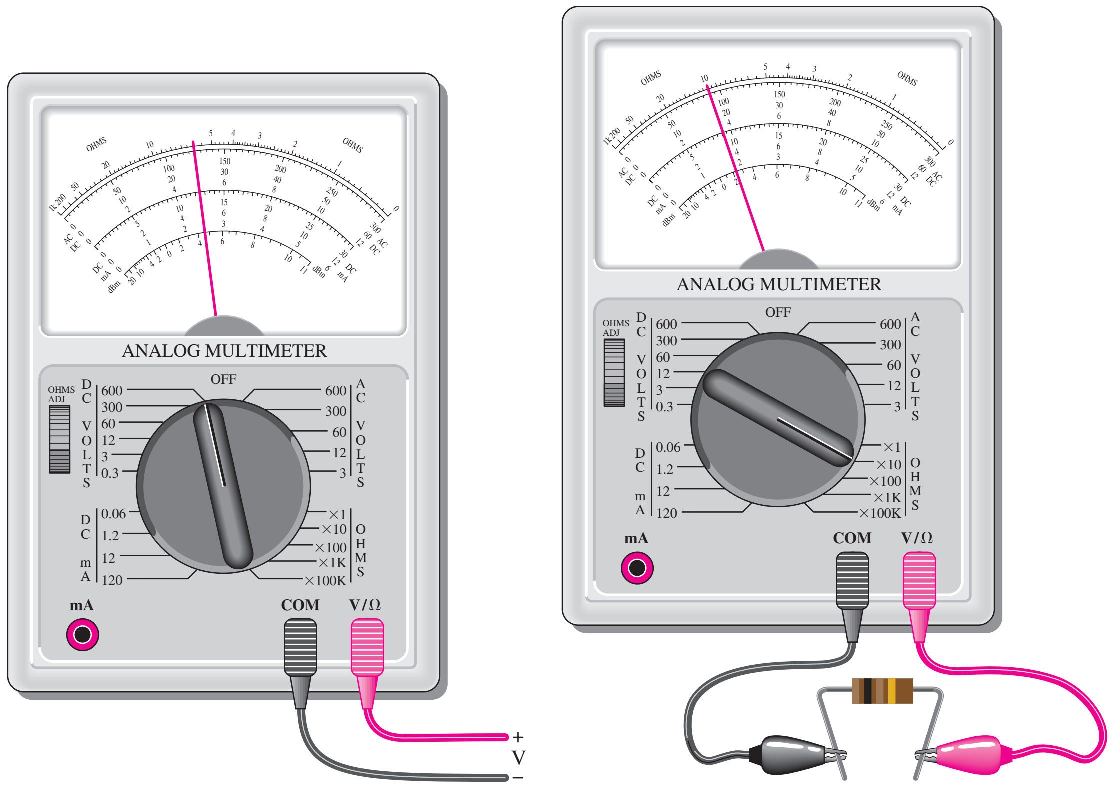
(b) pointer at 15, range setting at $\times 100{,}000$

(c) pointer at 45, range setting at $\times 100$

50. What is the maximum resolution of a 4½-digit DMM?

51. Indicate how you would connect the multimeter in Figure 2–72(b) to the circuit in Figure 2–73 to measure each of the following quantities. In each case, indicate the appropriate function and range.

(a) I_1 **(b)** V_1 **(c)** R_1

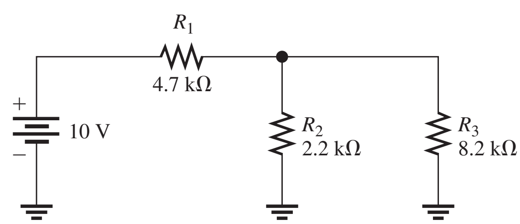


(a)

(b)

▲ **FIGURE 2–72**

► **FIGURE 2–73**



ANSWERS

SECTION CHECKUPS

SECTION 2–1 Atomic Structure

1. The electron is the basic particle of negative charge.
2. An atom is the smallest particle of an element that retains the unique characteristics of the element.
3. An atom is a positively charged nucleus surrounded by orbiting electrons.
4. Atomic number is the number of protons in a nucleus.
5. No, each element has a different type of atom.
6. A free electron is an outer-shell electron that has drifted away from the parent atom.
7. Shells are energy bands in which electrons orbit the nucleus of an atom.
8. Copper and silver

SECTION 2–2 Electrical Charge

1. Q = charge
2. The unit of charge is coulomb; C
3. Positive or negative charge is caused by the loss or acquisition respectively of an outer-shell (valence) electron.
4. $Q = \dfrac{10 \times 10^{12} \text{ electrons}}{6.25 \times 10^{18} \text{ electrons/C}} = 1.6 \times 10^{-6}\text{ C} = 1.6\ \mu\text{C}$

SECTION 2–3 Voltage

1. Voltage is energy per unit charge.
2. Volt is the unit of voltage.
3. $V = W/Q = 24\text{ J}/10\text{ C} = 2.4\text{ V}$
4. Battery, fuel cell, solar cell, generator, power supply, thermocouple
5. Oxidation-reduction

SECTION 2–4 Current

1. Current is the rate of flow of electrons; its unit is ampere (A).
2. electrons/coulomb $= 6.25 \times 10^{18}$
3. $I = Q/t = 20\text{ C}/4\text{ s} = 5\text{ A}$
4. A constant current for any load.

SECTION 2–5 Resistance

1. Resistance is opposition to current and its unit is ohm.
2. Two resistor categories are fixed and variable. The value of a fixed resistor cannot be changed, but that of a variable resistor can.
3. *First band:* first digit of resistance value. *Second band:* second digit of resistance value. *Third band:* multiplier (number of zeros following the second digit). *Fourth band:* % tolerance.
4. **(a)** 4,700 Ω ± 5% **(b)** 62 kΩ ± 10%
   (c) 18 Ω ± 10% **(d)** 22.6 kΩ ± 0.5%
5. **(a)** 33R = 33 Ω **(b)** 5K6 = 5.6 kΩ
   (c) 900 = 900 Ω **(d)** 6M8 = 6.8 MΩ
6. A rheostat has two terminals; a potentiometer has three terminals.
7. Thermistor: temperature
   photoconductive cell: light
   strain gauge: mechanical force

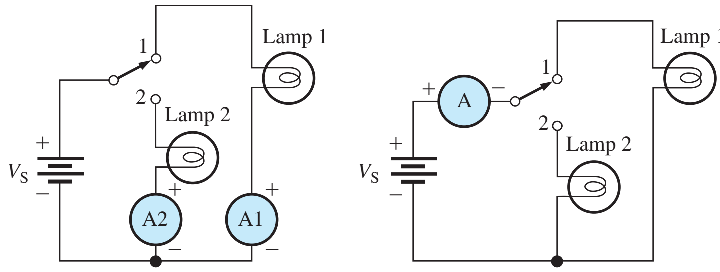
SECTION 2–6 The Electric Circuit

1. An electric circuit consists of a source, load, and current path between source and load.
2. An open circuit is one that has no path for current.
3. A closed circuit is one that has a complete path for current.
4. A fuse is not resettable, a circuit breaker is.
5. AWG 3 is larger.
6. Ground is the common or reference point.

SECTION 2–7 Basic Circuit Measurements

1. **(a)** An ammeter measures current.
   (b) A voltmeter measures voltage.
   (c) An ohmmeter measures resistance.
2. See Figure 2–74.

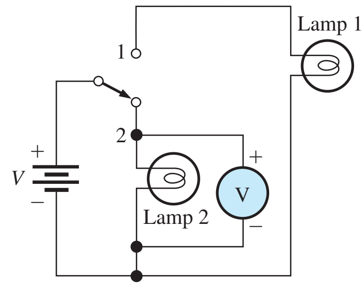
► FIGURE 2–74



(a) Two ammeters (b) One ammeter

3. See Figure 2–75.

► FIGURE 2–75



4. Two types of DMM displays are liquid-crystal display (LCD) and light-emitting display (LED). The LCD requires little current, but it is difficult to see in low light and is slow to respond. The LED can be seen in the dark, and it responds quickly. However, it requires much more current than does the LCD.
5. Resolution is the smallest increment of a quantity that the meter can measure.
6. 1.5 V

SECTION 2–8 Electrical Safety

1. Current 2. F 3. F 4. F 5. T
6. GFCI: ground fault circuit interrupter

RELATED PROBLEMS FOR EXAMPLES

2–1 1.88×10^{19} electrons

2–2 600 J

2–3 3.0 C

2–4 4700 $\Omega \pm 5\%$

2–5 47.5 $\Omega \pm 2\%$

2–6 1.25 kΩ

2–7 2.25 CM

2–8 1.280 Ω; same as calculated result

2–9 The needle will move left to the "100" mark.

TRUE/FALSE QUIZ

1. T	**2.** T	**3.** F	**4.** F	**5.** T	**6.** F	**7.** F	**8.** T
9. T	**10.** T	**11.** F	**12.** F	**13.** T	**14.** F	**15.** F	**16.** T
17. T	**18.** T	**19.** F	**20.** T				

SELF-TEST

1. (b)	**2.** (a)	**3.** (c)	**4.** (c)	**5.** (b)	**6.** (b)	**7.** (c)
8. (d)	**9.** (b)	**10.** (b)	**11.** (e)	**12.** (b)	**13.** (d)	**14.** (b)
15. (c)	**16.** (d)					