2 Voltage, Current, and Resistance

Chapter Outline

2–1 Atomic Structure
2–2 Electrical Charge
2–3 Voltage, Current, and Resistance
2–4 Voltage and Current Sources
2–5 Resistors
2–6 The Electric Circuit
2–7 Basic Circuit Measurements
2–8 Electrical Safety
A Circuit Application

Chapter Objectives

- Describe the basic structure of atoms
- Explain the concept of electrical charge
- Define *voltage, current,* and *resistance* and discuss the characteristics of each
- Discuss a voltage source and a current source
- Recognize and discuss various types and values of resistors
- 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
- Voltage
- Volt
- Current
- Ampere
- Resistance
- Ohm
- Conductance
- Siemens
- Voltage source
- Current source
- Resistor
- Potentiometer
- Rheostat
- Circuit
- Load
- Closed circuit
- Open circuit
- AWG
- Ground
- Voltmeter
- Ammeter
- Ohmmeter
- DMM
- Electrical shock

A Circuit Application Preview

In the circuit application, you will see how the theory presented in this chapter is applied to a practical circuit that simulates part of a car's 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 light bulbs to the battery, which provides the voltage and produces current through each bulb. The current causes the bulbs to emit light. The light bulbs themselves have resistance that limits the amount of current. The instrument panel light in most cars can be adjusted for brightness. By turning a knob, you actually change the resistance in the circuit, thereby causing the current to change. The amount of current through the light bulb determines its brightness.

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Introduction

The useful application of electronics technology to practical situations requires that you first understand the theory that is the basis of a given application. Once you have mastered the theory, you can learn to apply it in practice. In this chapter and throughout the rest of the book, you will learn to put technology theory into practice in circuit applications.

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.

You will be introduced to the types of devices that generate voltage and current. In addition, 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 that are commonly used in electric circuits are introduced. Also, you will learn how to control and measure voltage, current, and resistance using measuring 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*

An **atom** is the smallest particle of an **element** that retains the characteristics of that element. Each of the known 109 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**.

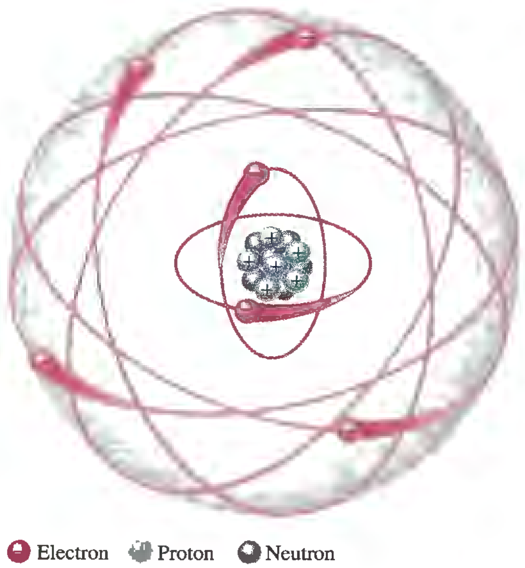
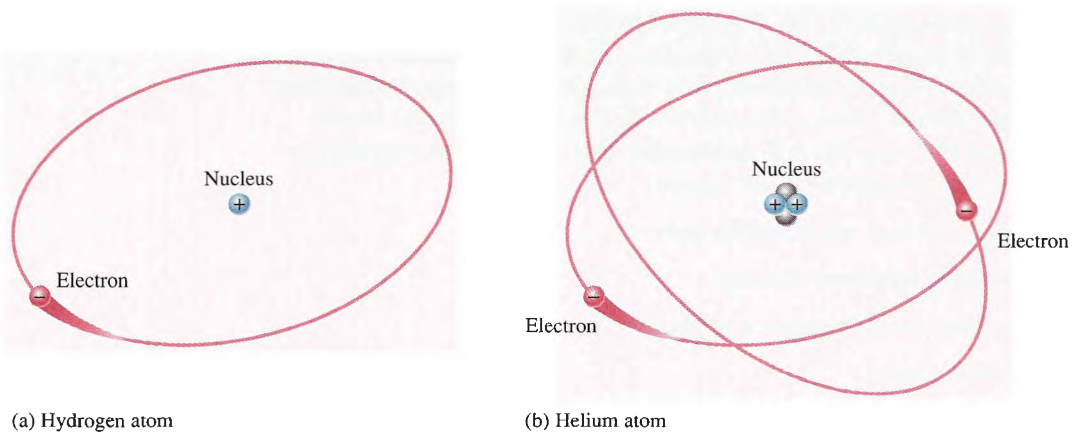


FIGURE 2–1

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

Each type of atom has a certain number of electrons and 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.

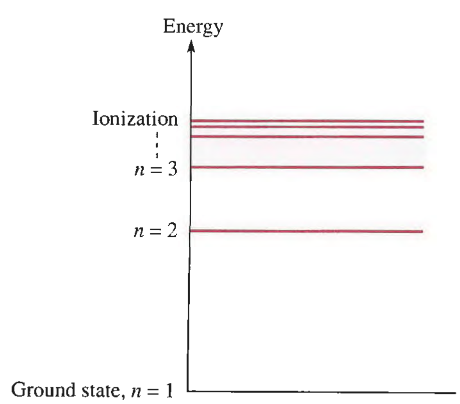
Shells, Orbits, and Energy Levels

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 hydrogen

► FIGURE 2–3

Energy levels in 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, Erin 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.

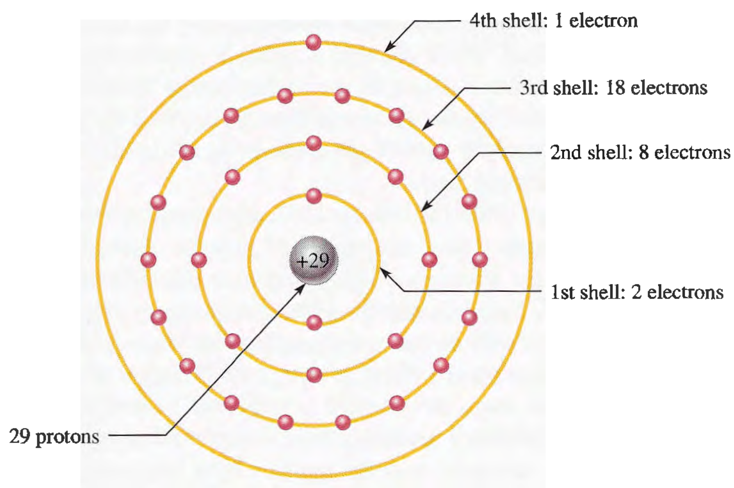
Energy Levels and Ionization Energy

If an electron absorbs a photon with sufficient energy, it escapes from the atom and becomes a **free electron**. 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 some cases, an atom or group of atoms can acquire an electron, 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 2 electrons, the second shell up to 8 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 1 valence electron. When the valence electron in the outer shell of the copper atom gains sufficient thermal energy, it can break away from the parent atom



▶ **FIGURE 2–4**

The copper 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 materials that are poor conductors of electric current. In fact, insulators are used to prevent current where it is not wanted. Compared to conductive materials, insulators have very few free electrons and are characterized by more than four valence electrons in their atomic structures.

SECTION 2–1 REVIEW

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. Electrical **charge**, an electrical property of matter that exists because of an excess or deficiency of electrons, is symbolized by 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.

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. This force, called an *electric field,* consists of invisible lines of force, as represented in Figure 2–6.

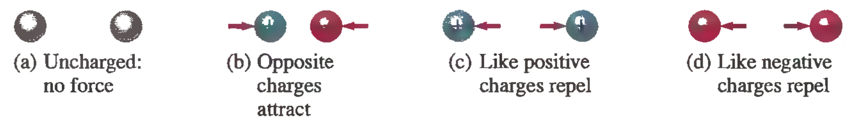


FIGURE 2–5

Attraction and repulsion of electrical charges.

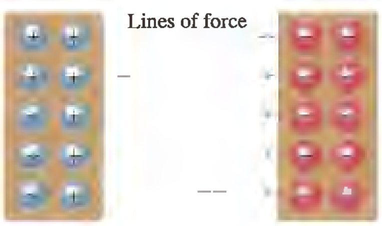
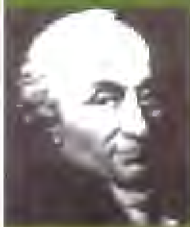


FIGURE 2–6

Electric field between two oppositely charged surfaces.

BIOGRAPHY



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: Courtesy of the Smithsonian Institution. Photo number 52,597.)

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 single electron has a charge of 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

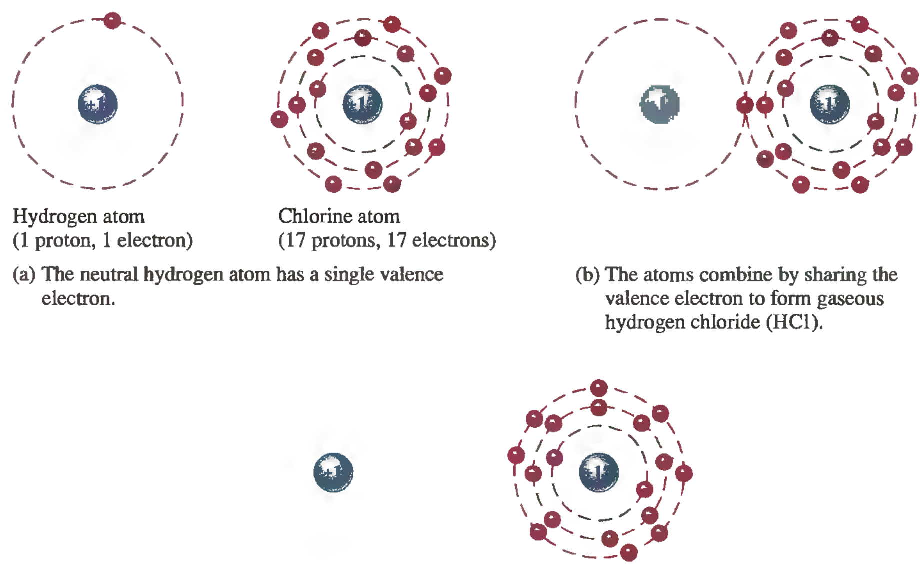
Positive and Negative Charge

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 release 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 REVIEW

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, CURRENT, AND RESISTANCE

Voltage, current, and resistance are the basic quantities present in all electrical circuits. Voltage is necessary to produce current, and resistance limits the amount of current in a circuit. The relationship of these three quantities is described by Ohm's law in Chapter 3.

After completing this section, you should be able to

- **Define *voltage, current,* and *resistance* and discuss the characteristics of each**
    - State the formula for voltage and name its unit
    - State the formula for current and name its unit
    - Explain the movement of electrons
    - Name the unit of resistance

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 in electric circuits and is what establishes current.

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.

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

$$V = \frac{W}{Q}$$

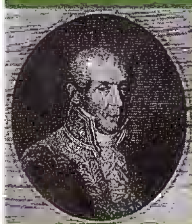
Equation 2–2

where: V = voltage in volts (V)
W = energy in joules (J)
Q = charge in coulombs (C)

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.

BIOGRAPHY



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.)

EXAMPLE 2–2 If 50 J of energy are available for every 10 C of charge, what is the voltage?

Solution

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

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

Current

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

As you have learned, free electrons are available in all conductive and semiconductive materials. These electrons drift randomly in all directions, from atom to atom, within the structure of the material, as indicated in Figure 2–8.

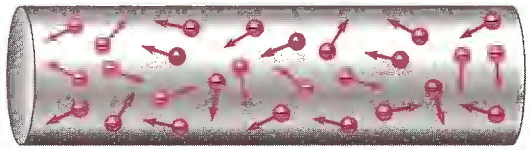


FIGURE 2–8

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 2–9. 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 2–9.

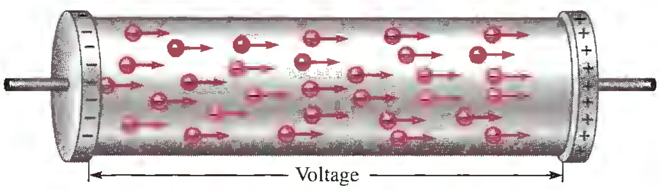


FIGURE 2–9

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

Equation 2–3

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

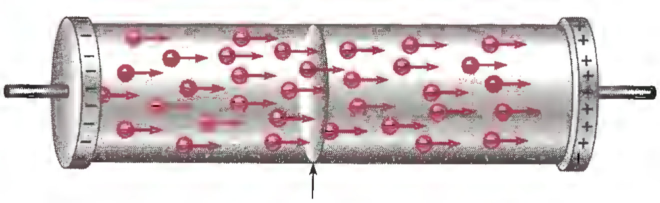
where: I = current in amperes (A)

Q = charge in coulombs (C)

t = 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 2–10. 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 2–10

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

BIOGRAPHY

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

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

Related Problem If there are 8 A of current through the filament of a lamp, how many coulombs of charge move through the filament in 1.5 s?

Resistance

When there is current through a material, the free electrons move through the material and occasionally collide with atoms. These collisions cause the electrons to 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 2–11.

FIGURE 2–11

Resistance symbol.

B I O G R A P H Y

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, LC-USZ62-40943.)

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

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

Equation 2–4

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.

SECTION 2–3 REVIEW

1. Define *voltage*.
2. What is the unit of voltage?
3. How much is the voltage when there are 24 joules of energy for 10 coulombs of charge?
4. Define *current* and state its unit.
5. How many electrons make up one coulomb of charge?
6. What is the current in amperes when 20 C flow past a point in a wire in 4 s?
7. Define *resistance*.
8. Name the unit of resistance.
9. Define one ohm.

2–4 VOLTAGE AND CURRENT SOURCES

A **voltage source** provides electrical energy or electromotive force (emf), more commonly known as voltage. Voltage is produced by means of chemical energy, light energy, and magnetic energy combined with mechanical motion. A current source provides a constant current to a load.

After completing this section, you should be able to

- **Discuss a voltage source and a current source**
  - List six categories of voltage sources
  - Describe the basic operation of a battery
  - Explain how a solar cell creates voltage
  - Discuss the principle of a generator
  - Describe what an electronic power supply does

BIOGRAPHY

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.)

The Voltage Source

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. We will assume ideal unless otherwise specified.

Voltage sources can be either dc or ac. A common symbol for a dc voltage source is shown in Figure 2–12(a) and one for an ac voltage source is shown in part (b). AC voltage sources will be used later in the book.

FIGURE 2–12

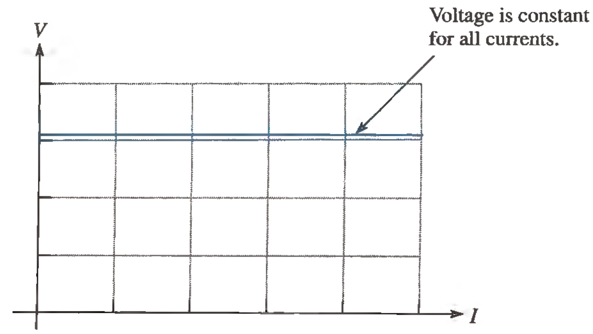
Symbols for voltage sources.

(a) DC voltage source (b) AC voltage source

A graph showing voltage versus current for an ideal dc voltage source is called the *VI* characteristic and is illustrated in Figure 2–13. 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. Current is always drawn from a voltage source when a load such as a resistance is connected to it.

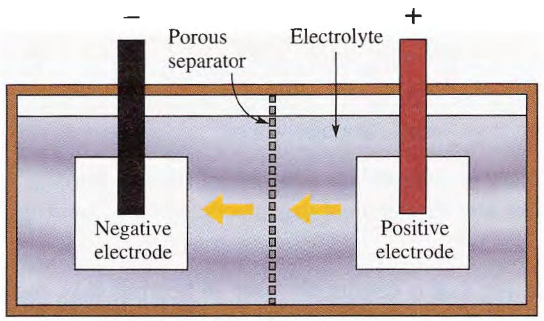
FIGURE 2–13

VI characteristic of an ideal voltage source.



Types of DC Voltage Sources

Batteries A **battery** is a type of voltage source that converts chemical energy into electrical energy. A battery consists of one or more electro-chemical cells that are electrically connected. A cell consists of four basic components: a positive electrode, a negative electrode, an electrolyte, and a porous separator. The *positive electrode* has a deficiency of electrons due to chemical reaction, the *negative electrode* has a surplus of electrons due to chemical reaction, the *electrolyte* provides a mechanism for charge flow between positive and negative electrodes, and the *separator* electrically isolates the positive and negative electrodes. A basic diagram of a battery cell is shown in Figure 2–14.



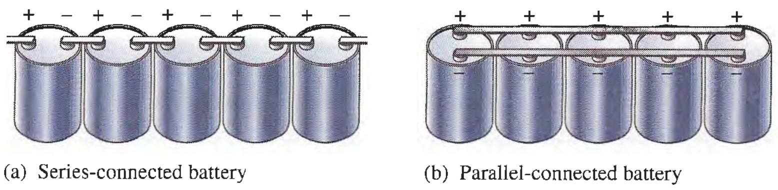
◀ FIGURE 2–14

Diagram of a battery cell.

The materials used in a battery cell determine the voltage that it produces. The chemical reaction at each of the electrodes produces a fixed potential at each electrode. For example, in a lead-acid cell, a potential of −1.685 V is produced at the positive electrode and a potential of +0.365 V is produced at the negative electrode. This means that the voltage between the two electrodes of a cell is 2.05 V, which is the standard lead-acid electrode potential. Factors such as acid concentration will affect this value to some degree so that the typical voltage of a commercial lead-acid cell is 2.15 V. The voltage of any battery 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.

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 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 2–15(a), the battery voltage is the sum of the individual cell voltages. This is called a series connection. To increase battery capacity, the positive electrodes of several cells are connected together and all the negative electrodes are connected together, as illustrated in Figure 2–15(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.



▲ FIGURE 2–15

Cells connected to form batteries.

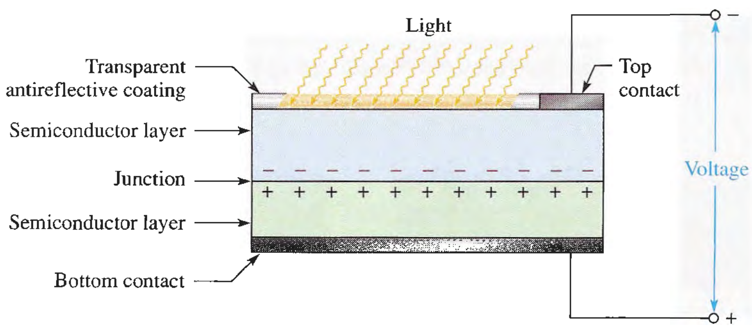
Batteries are divided into two major classes, primary and secondary. Primary batteries are used once and discarded because their chemical reactions are irreversible. Secondary batteries can be recharged and reused many times because they are characterized by reversible chemical reactions.

There are many types, shapes, and sizes of batteries. Some of the sizes that you are most familiar with are AAA, AA, C, D, and 9 V. There is also a less common size called AAAA, which is smaller than the AAA. Batteries for hearing aids, watches, and other miniature applications are usually in a flat round configuration and are often called button batteries or coin batteries. Large multicell batteries are used in lanterns and industrial applications and, of course, there is the familiar automotive battery.

In addition to the many sizes and shapes, batteries are usually classified according to their chemical makeup as follows. Each of these classifications are typically available in several physical configurations.

- *Alkaline-MnO_2* This is a primary battery that is commonly used in palm-type computers, photographic equipment, toys, radios, and recorders.
- *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.
- *Zinc air* This is a primary battery that is commonly used in hearing aids, medical monitoring instruments, pagers, and other frequency-use applications.
- *Silver oxide* This is a primary battery that is commonly used in watches, photographic equipment, hearing aids, and electronics requiring high-capacity batteries.
- *Nickel-metal hydride* This is a secondary (rechargable) battery that is commonly used in portable computers, cell phones, camcorders, and other portable consumer electronics.
- *Lead-acid* This is a secondary (rechargable) battery that is commonly used in automotive, marine, and other similar applications.

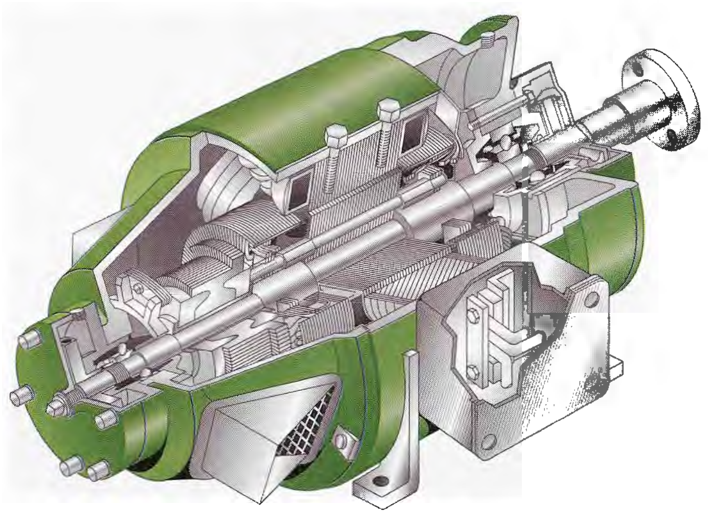
Solar Cells The operation of solar cells is based on the **photovoltaic effect**, which is the process whereby light energy is converted directly into electrical energy. A basic solar cell consists of two layers of different types of semiconductive materials joined together to form a junction. When one layer is exposed to light, many electrons acquire enough energy to break away from their parent atoms and cross the junction. This process forms negative ions on one side of the junction and positive ions on the other, and thus a potential difference (voltage) is developed. Figure 2–16 shows the construction of a basic solar cell.



▲ FIGURE 2–16

Construction of a basic solar cell.

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 2–17.



▲ FIGURE 2–17

Cutaway view of a dc voltage generator.

The Electronic Power Supply **Electronic power supplies** convert the ac voltage from a wall outlet to a constant (dc) voltage that is available across two terminals, as indicated in Figure 2–18(a). Typical commercial power supplies are shown in Figure 2–18(b).

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.

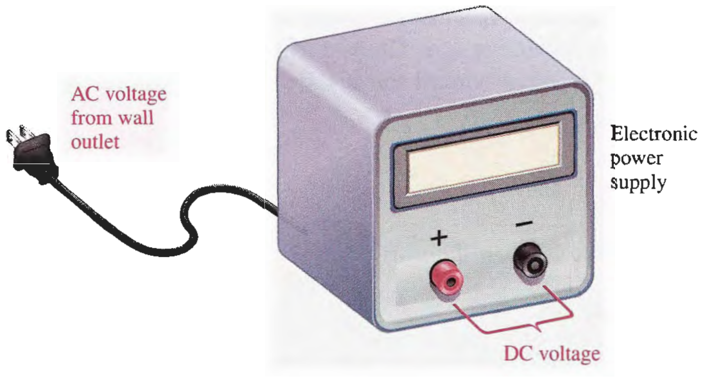
Standard types of thermocouple are characterized by the specific metals used. These standard thermocouples produce predictable output voltages for a range of temperatures. The most common is type K, made of chromel and alumel. Other types are also designated by letters as E, J, N, B, R, and S. Most thermocouples 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.

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 *IV* characteristic for an ideal current source is a horizontal line as illustrated in Figure 2–19(b). Notice that the current is constant for any voltage across the current source.

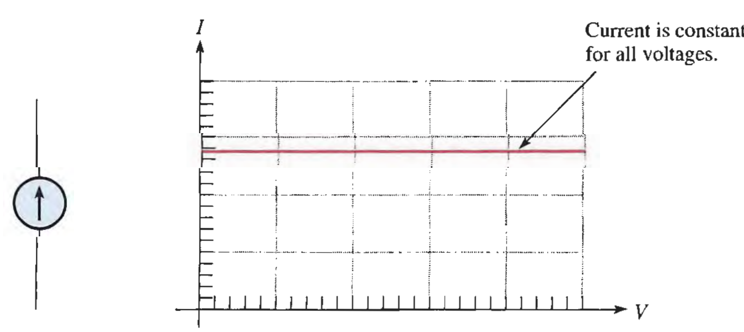


(a)

(b)

▲ FIGURE 2–18

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

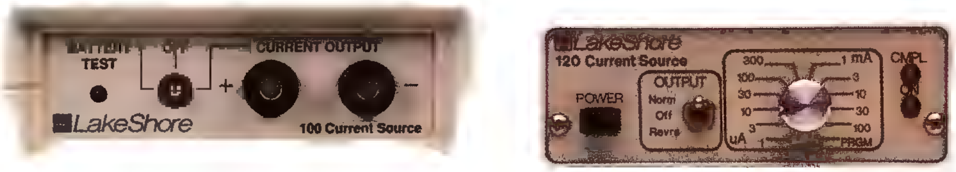


(a) Symbol (b) *IV* characteristic

▲ FIGURE 2–19

The current source.

Actual Current Sources Power supplies are normally thought of as voltage sources because they are the most common source in the laboratory. However, current sources can also be considered a type of power supply. Typical commercial constant-current sources are illustrated in Figure 2–20.

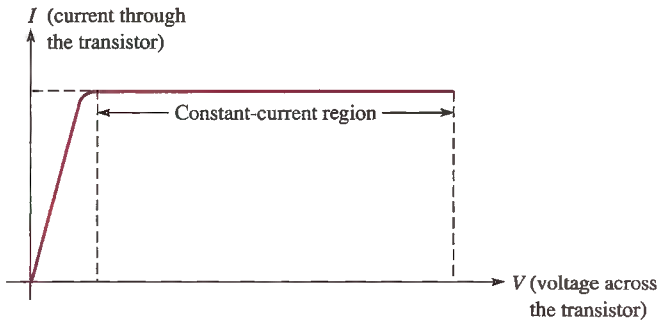


(a) (b)

◀ **FIGURE 2–20**

Typical commercial current sources. (Courtesy of Lake Shore Cryotronics)

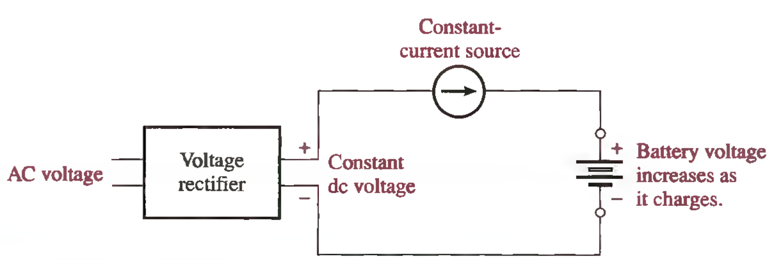
In most transistor circuits, the transistor acts as a current source because part of the *IV* characteristic curve is a horizontal line as shown by the transistor characteristic in Figure 2–21. The flat part of the graph indicates where the transistor current is constant over a range of voltages. The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



◀ **FIGURE 2–21**

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

One common application of a constant-current source is in constant-current battery chargers, as illustrated in a simplified way in Figure 2–22. The rectifier is a circuit that acts as a dc voltage source by converting the ac voltage from a standard wall outlet to a constant dc voltage. This voltage is effectively applied in parallel with a battery that is to be charged and in series with a constant-current source. The battery voltage is initially low but increases over time due to the constant charging current. The total voltage across the current source is the voltage from the rectifier minus the voltage of the battery, which increases as the battery charges.



◀ **FIGURE 2–22**

Battery charger as an example of a current source application.

SECTION 2–4 REVIEW

1. Define a voltage source.
2. Explain how a battery produces voltage.
3. Describe how a solar cell produces voltage.
4. Discuss how an electrical generator creates voltage.

5. Explain what an electronic power supply does.
6. Define a current source.
7. Name an electronic component that is used as a current source.

2–5 RESISTORS

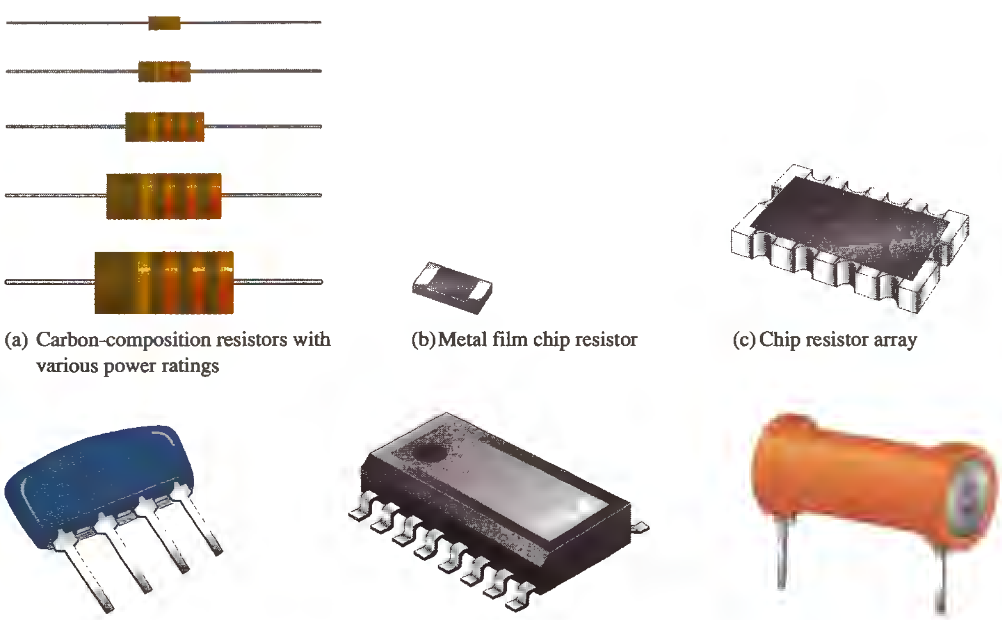
A component that is specifically designed to have a certain amount of resistance is called a **resistor**. The principal applications of resistors are to limit current in a circuit, to divide voltage, and, in certain cases, to generate heat. Although resistors come in many shapes and sizes, they can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

After completing this section, you should be able to

- **Recognize and discuss various types and values of resistors**
    - Distinguish between fixed resistors and variable resistors
    - Know how the physical size of a resistor determines its ability to dissipate power
    - Read a color code or other designation to determine the resistance value
    - Describe how certain resistors are constructed

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.

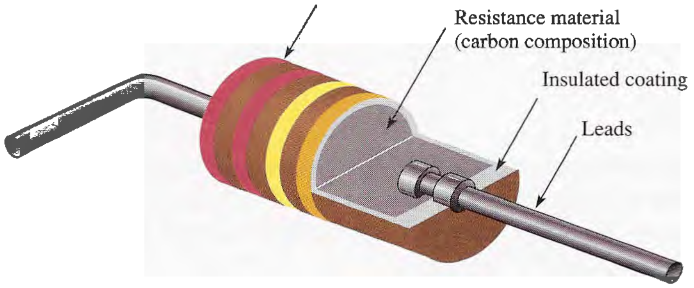


(a) Carbon-composition resistors with various power ratings
(b) Metal film chip resistor
(c) Chip resistor array
(d) Resistor network (simm)
(e) Resistor network (surface mount)
(f) Radial-lead for PC board insertion

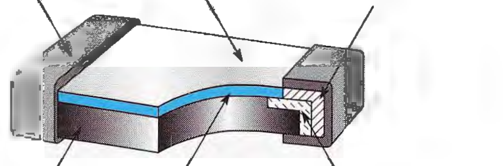
FIGURE 2–23

Typical fixed resistors.

One common fixed resistor is the carbon-composition type, which is made 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. Figure 2–24(a) shows the construction of a typical carbon-composition resistor.



(a) Cutaway view of a carbon-composition resistor



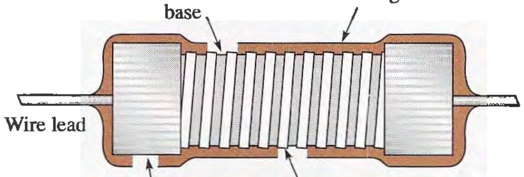
(b) Cutaway view of a tiny chip resistor

▲ FIGURE 2–24

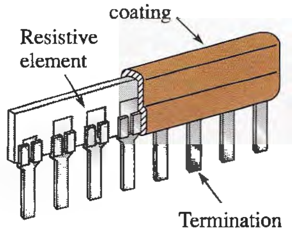
Two types of fixed resistors (not to scale).

The chip resistor is another type of fixed resistor and is in the category of SMT (surface mount technology) components. It has the advantage of a very small size for compact assemblies. Figure 2–24(b) shows the construction of a chip resistor.

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 they are constructed with a coil of wire, wirewound resistors have significant inductance and are not used at higher frequencies. Some typical wirewound resistors are shown in Figure 2–26.

▲ FIGURE 2–26

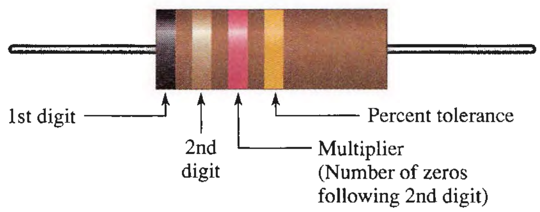
Typical wirewound power resistors.

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.

▶ 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

2. The second band is the second digit of the resistance value.
3. The third band is the number of zeros following the second digit, or the multiplier.
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.

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

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

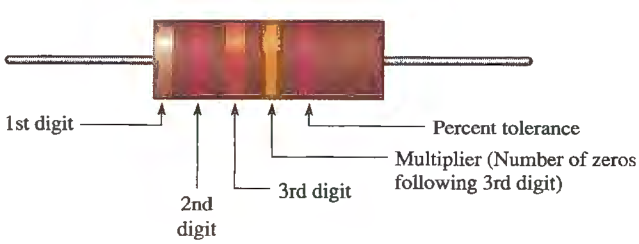
$$R = 100\ \Omega \pm 10\%$$

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

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

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

Resistor Reliability Band An extra band on some color-coded resistors indicates the resistor's reliability in percent of failures per 1000 hours (1000 h) of use. The reliability color code is listed in Table 2–3. For example, a brown fifth band on a 4-band color-coded resistor means that if a group of like resistors is operated under standard conditions for 1000 h, 1% of the resistors in that group will fail.

Resistors, as well as other components, should be operated substantially below their rated values to enhance their reliability.

TABLE 2–3

Reliability color code.

COLOR	FAILURES DURING 1000 h OF OPERATION
Brown	1.0%
Red	0.1%
Orange	0.01%
Yellow	0.001%

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 = ×0.1, fifth band is red = ±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 = ±1% tolerance.

$$R = 402\ \Omega \pm 1\%$$

(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 = ±0.5% tolerance.

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

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.

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 This type of marking 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.

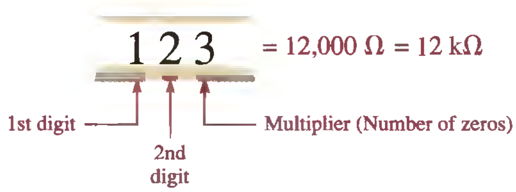


FIGURE 2–31

Example of three-digit labeling for a resistor.

Alphanumeric Labeling Another common type of marking is a three- or four-character label that uses both digits and letters. This type of 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 1000 (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. Figure 2–32 shows three examples of this type of resistor label.

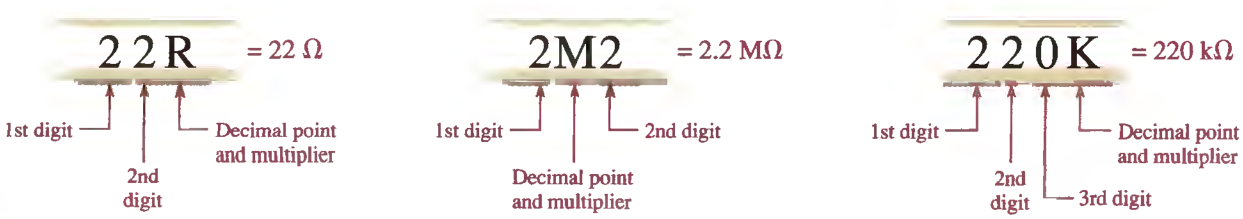


FIGURE 2–32

Examples of the alphanumeric resistor label.

EXAMPLE 2–6

Interpret the following alphanumeric resistor labels:

(a) 470 (b) 5R6 (c) 68K (d) 10M (e) 3M3

Solution (a) 470 = **470 Ω** (b) 5R6 = **5.6 Ω** (c) 68K = **68 kΩ**
(d) 10M = **10 MΩ** (e) 3M3 = **3.3 MΩ**

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 = ±1% G = ±2% J = ±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.

Variable Resistors

Variable resistors are designed so that their resistance values can be changed easily with a manual or an automatic adjustment.

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 up or down.

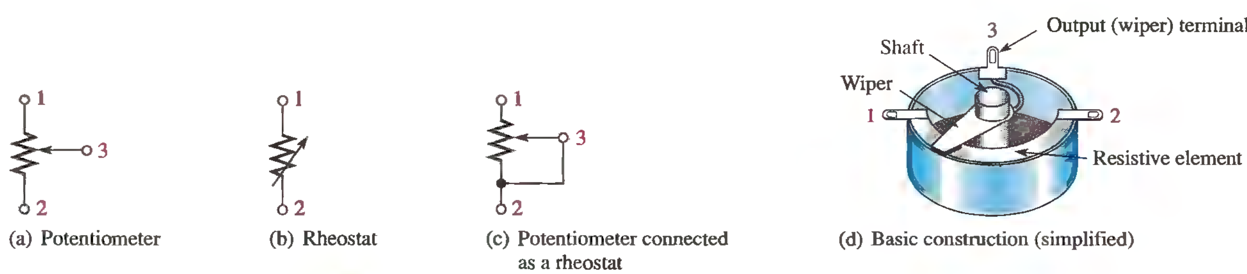


FIGURE 2–33

Potentiometer and rheostat symbols and basic construction of one type of potentiometer.

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. Part (d) shows a simplified construction diagram of a potentiometer (which can also be configured as a rheostat). Some typical potentiometers are pictured in Figure 2–34.

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.

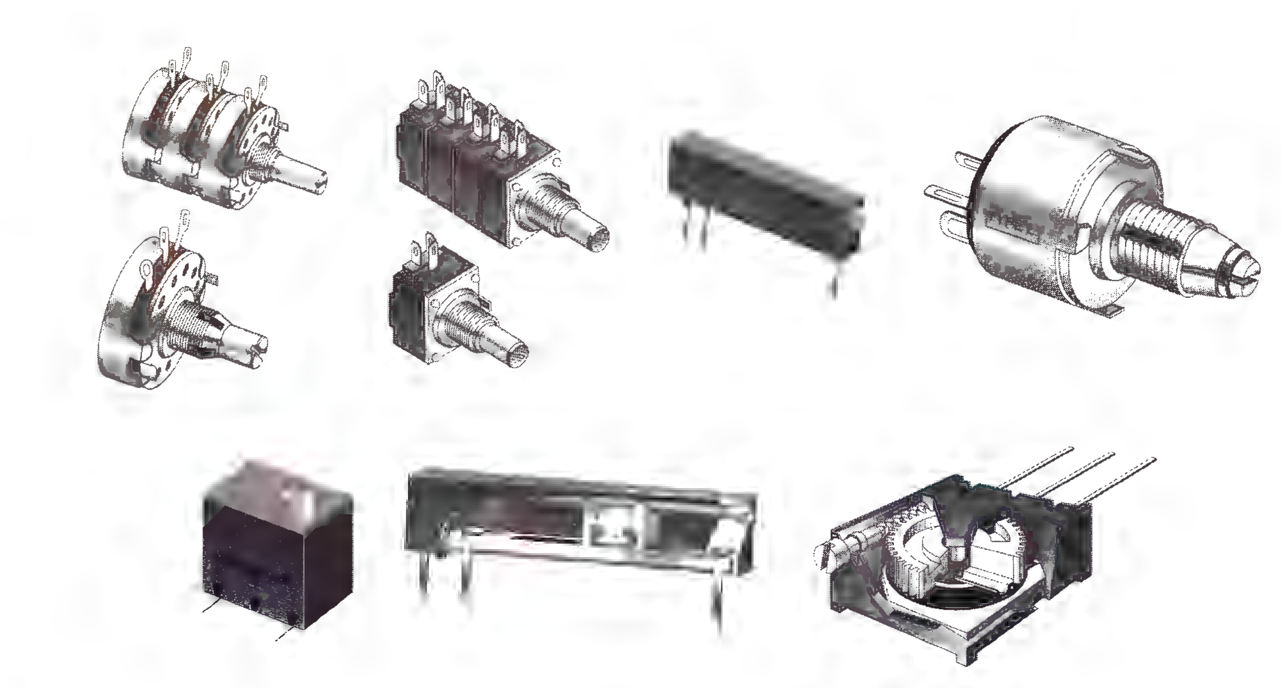


FIGURE 2–34

Typical potentiometers and two construction views.

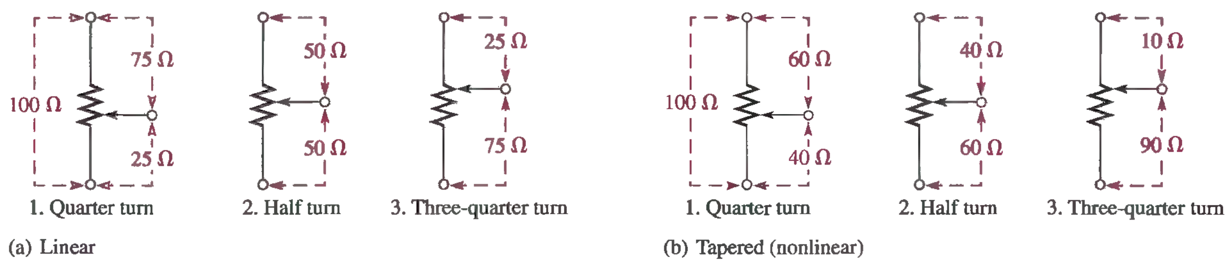


FIGURE 2–35

Examples of linear and tapered potentiometers.

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.

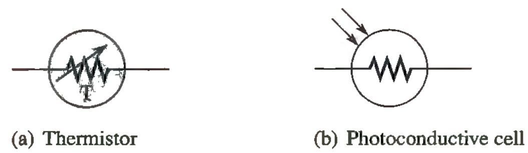
The potentiometer is used as a voltage-control device because when a fixed voltage is applied across the end terminals, a variable voltage is obtained at the wiper contact with respect to either end terminal. The rheostat is used as a current-control device because the current can be changed by changing the wiper position.

Two Types of Automatically Variable Resistors A **thermistor** is a type of variable resistor that is temperature sensitive. When its temperature coefficient is negative, the resistance changes inversely with temperature. When its temperature coefficient is positive, the resistance changes directly with temperature.

The resistance of a **photoconductive cell** changes with a change in light intensity. This cell also has a negative temperature coefficient. Symbols for both of these devices are shown in Figure 2–36. Sometimes the Greek letter lambda (λ) is used in conjunction with the photoconductive cell symbol.

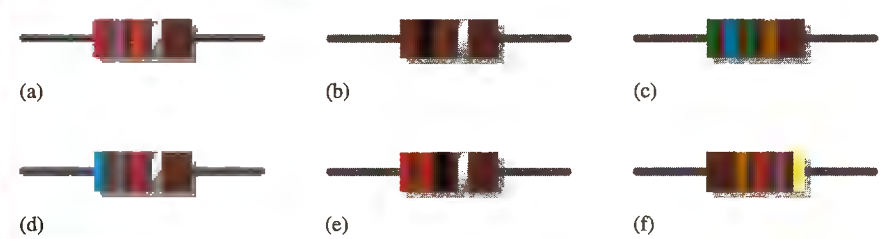
FIGURE 2–36

Symbols for resistive devices with sensitivities to temperature and light.



SECTION 2–5 REVIEW

1. What are the two main categories of resistors? Briefly explain the difference between them.
2. In the 4-band resistor color code, what does each band represent?
3. Determine the resistance and percent tolerance for each of the resistors in Figure 2–37.



4. From the selection of resistors in Figure 2–38, select the following values: 330 Ω, 2.2 kΩ, 56 kΩ, 100 kΩ, and 39 kΩ.

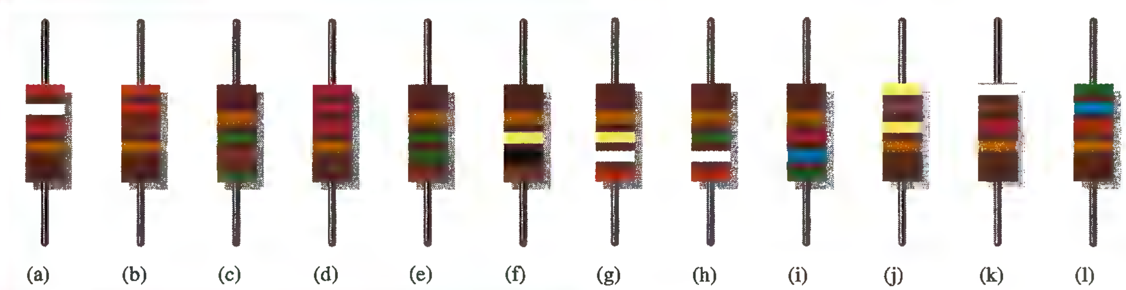


FIGURE 2–38

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. What is a thermistor?

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*

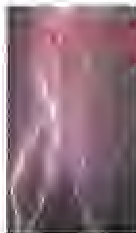
Direction of Current

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. An alternate version of this text that uses electron flow direction is also available.

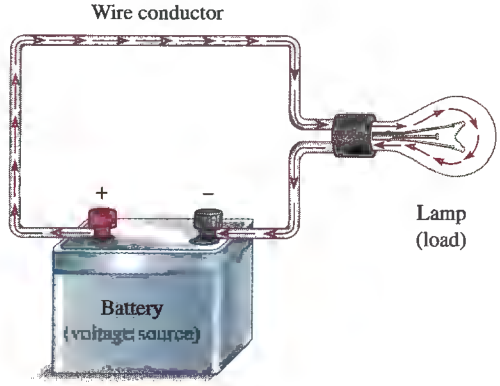


NOTE

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.

The Basic Circuit

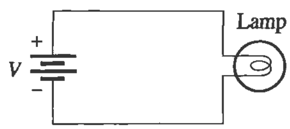
Basically, an electric **circuit** consists of a voltage source, a load, and a path for current between the source and the load. Figure 2–39 shows in pictorial form an example of a simple electric circuit: a battery connected to a lamp with two conductors (wires). The battery is the voltage source, the 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 2–39**

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.



▲ FIGURE 2–40

Schematic for the circuit in Figure 2–39.

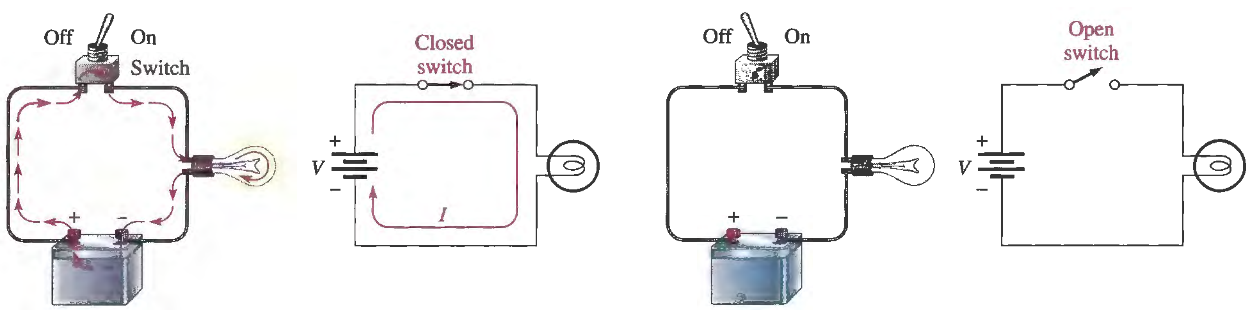
The Electric Circuit Schematic An electric circuit can be represented by a **schematic** using standard symbols for each element, as shown in Figure 2–40 for the simple circuit in Figure 2–39. A schematic, in an organized manner, shows how the various components in a given circuit are interconnected so that the operation of the circuit can be determined.

Circuit Current Control and Protection

The example circuit in Figure 2–39 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 2–41. 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, and 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).

Figure 2–42 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

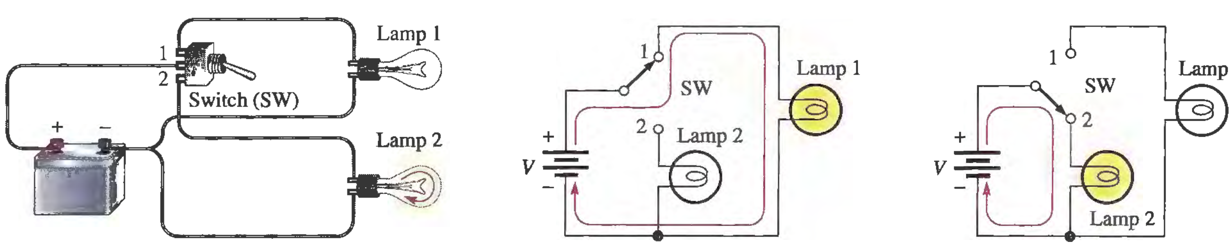


(a) There is current in a *closed* circuit because there is a complete current path (switch is ON or in the *closed* position). Current is almost always indicated by a red arrow in this text.

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

▲ FIGURE 2–41

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



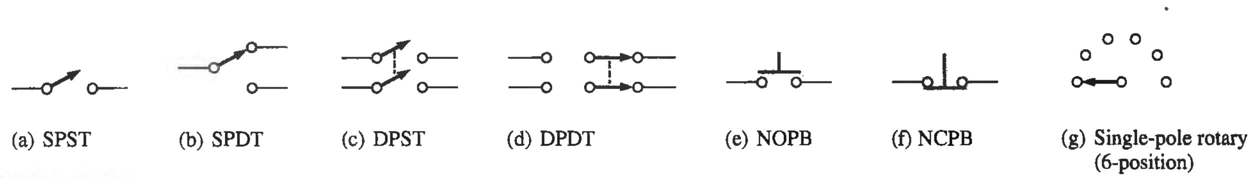
(a) Pictorial

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

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

▲ FIGURE 2–42

An example of an SPDT switch controlling two lamps.



▲ FIGURE 2–43

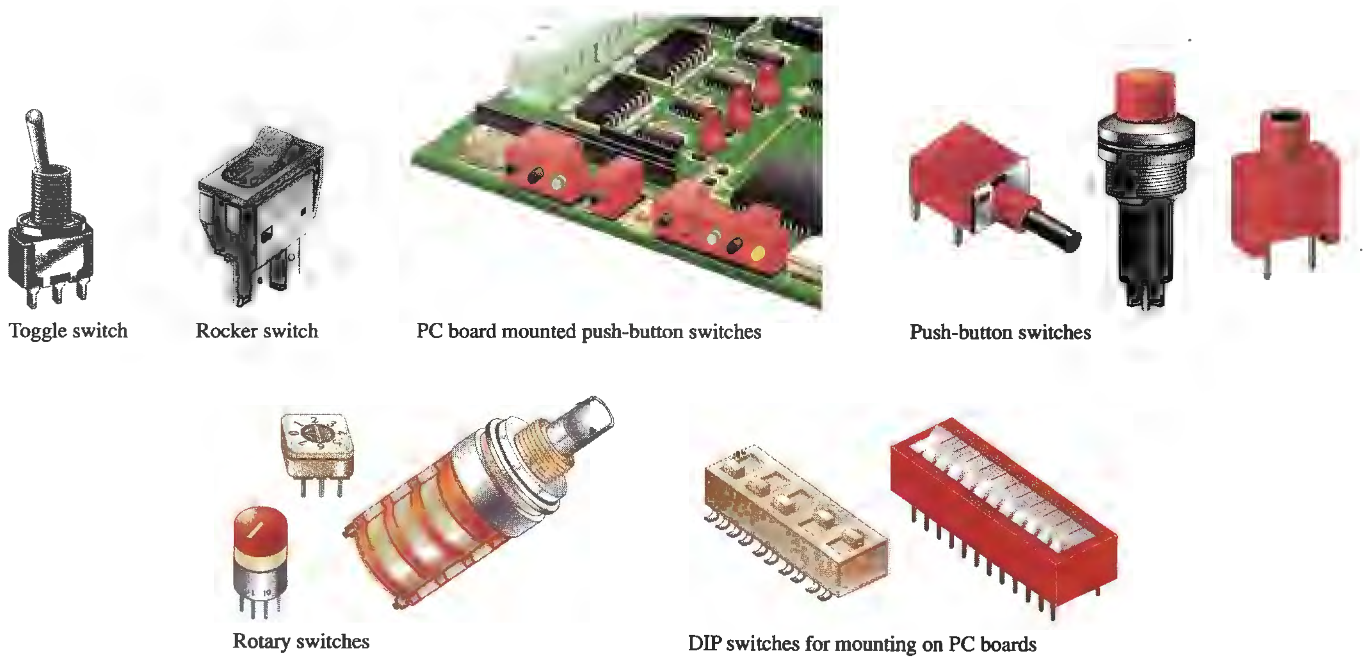
Switch symbols.

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.

In addition to the SPST and the SPDT switches (symbols are shown in Figure 2–43(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 2–43(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 2–43(d).
- *Push-button (PB)* In the normally open push-button switch (NOPB), shown in Figure 2–43(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 2–43(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 2–43(g).

Figure 2–44 shows several varieties of mechanical switches, and Figure 2–45 shows the construction view of a typical toggle switch.

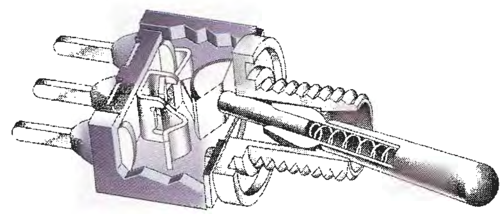


▲ FIGURE 2–44

Typical mechanical switches.

▶ FIGURE 2–45

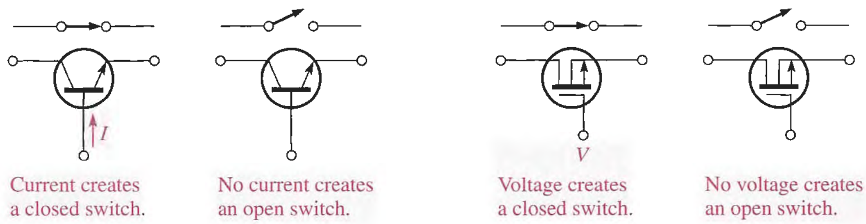
Construction view of a typical toggle switch.



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 2–46 with their mechanical switch equivalents.

▶ FIGURE 2–46

Transistor switches.



(a) Bipolar transistor (b) Field-effect transistor

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 2–46(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 2–47.

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 2–47(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, most fuses are subjected to intermittent current surges the 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 2–47(c).

Typical circuit breakers are shown in Figure 2–47(d) and the symbol is shown in part (e). Generally, a circuit breaker detects excess current either by the heating effect of the current

(a) Cartridge fuses

(b) Plug fuse

(c) Fuse symbol

(d) Circuit breakers

(e) Circuit breaker symbol

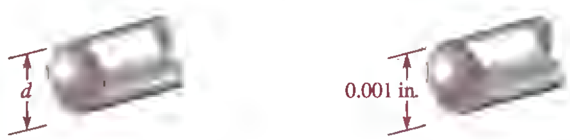
▲ FIGURE 2–47

Typical fuses and circuit breakers and their symbols.

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 2–48. 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



Cross-sectional area, A

$A = 1$ CM

FIGURE 2–48

Cross-sectional area of a wire.

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 2–4 lists the AWG sizes with their corresponding cross-sectional area and resistance in ohms per 1000 ft at 20°C.

▼ **TABLE 2–4**

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. 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

$$R = \frac{\rho l}{A}$$

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 2–4 to determine the resistance of 100 ft of copper wire with a cross-sectional area of 810.1 CM. Compare with the calculated result.

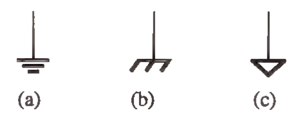
As mentioned, Table 2–4 lists the resistance of the various standard wire sizes in ohms per 1000 feet at 20°C. For example, a 1000 ft length of 14 gauge copper wire has a resistance of 2.525 Ω. A 1000 ft length of 22 gauge wire has a resistance of 16.14 Ω. For a given length, the smaller wire has more 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*. 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. 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.

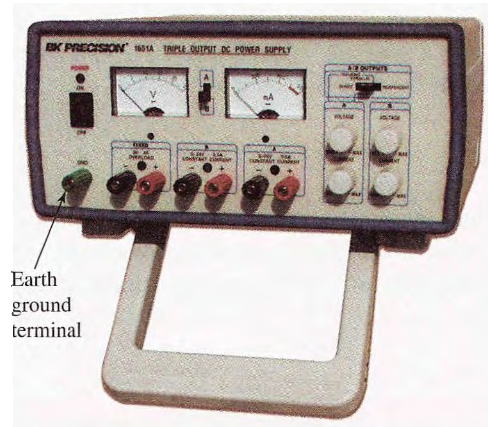
Three ground symbols are shown in Figure 2–49. Unfortunately, there is not a separate symbol to distinguish between earth ground and reference ground. The symbol in (a) represents either an earth ground or a reference ground, (b) shows a chassis ground, and (c) is an alternate reference symbol typically 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 2–49

Commonly used ground symbols.

An instrument such as a laboratory power supply may have a green terminal that is labeled as earth ground. Figure 2–50 shows a triple output power supply. Each of the three

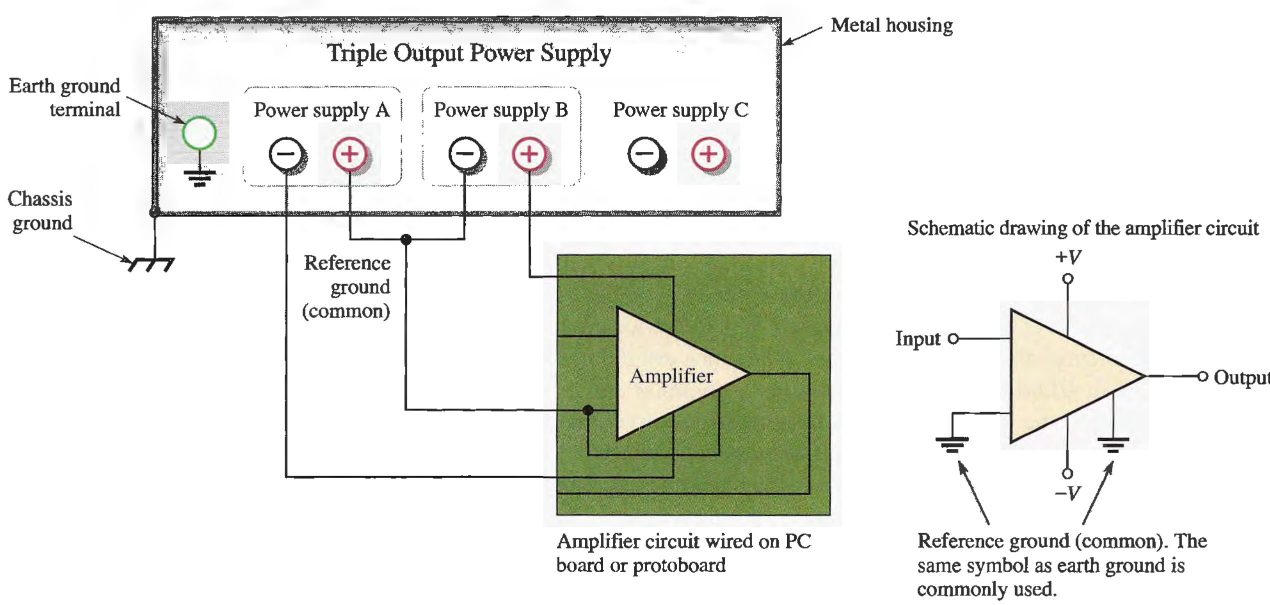


▶ FIGURE 2–50

A triple output power supply. (Courtesy of B+K Precision)

power supplies in the same chassis is isolated from the earth ground. An earth ground connection is brought out to the front panel on the separate green connector on the left side, for cases when earth ground is required. Internally, this is tied to the center (round) pin on the ac plug.

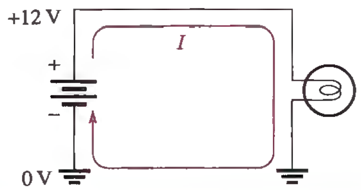
If you want to connect a positive supply to a circuit, the earth ground is not used and the ground reference (common) for the circuit is the (−) terminal of the supply. If you require a negative voltage, the (+) terminal is the ground reference. Many circuits require both positive and negative supplies, so in this case the (+) terminal of one supply can be connected to the negative terminal of the other supply which becomes the reference. Figure 2–51 illustrates this type of connection. The earth ground is not used for this application. Notice that for the example circuit board, the amplifier circuit requires a common connection between two points which is connected to the power supply reference ground or common. As illustrated in the figure, a schematic drawing can show the common reference with a ground symbol or symbols. When a ground symbol is not shown on a circuit schematic, the common or reference point is generally assumed to be either the negative side or the positive of the voltage source, depending on the circuit configuration.



▲ FIGURE 2–51

Example of using grounds in a circuit application.

Figure 2–52 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.



◀ **FIGURE 2–52**

A simple circuit with ground connections.

SECTION 2–6 REVIEW

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

An electronics technician cannot function without knowing how to measure voltage, current, and resistance.

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 2–53. You may see any of four types of symbols for voltmeters, ammeters, or ohmmeters, depending on which symbol most effectively conveys the information

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

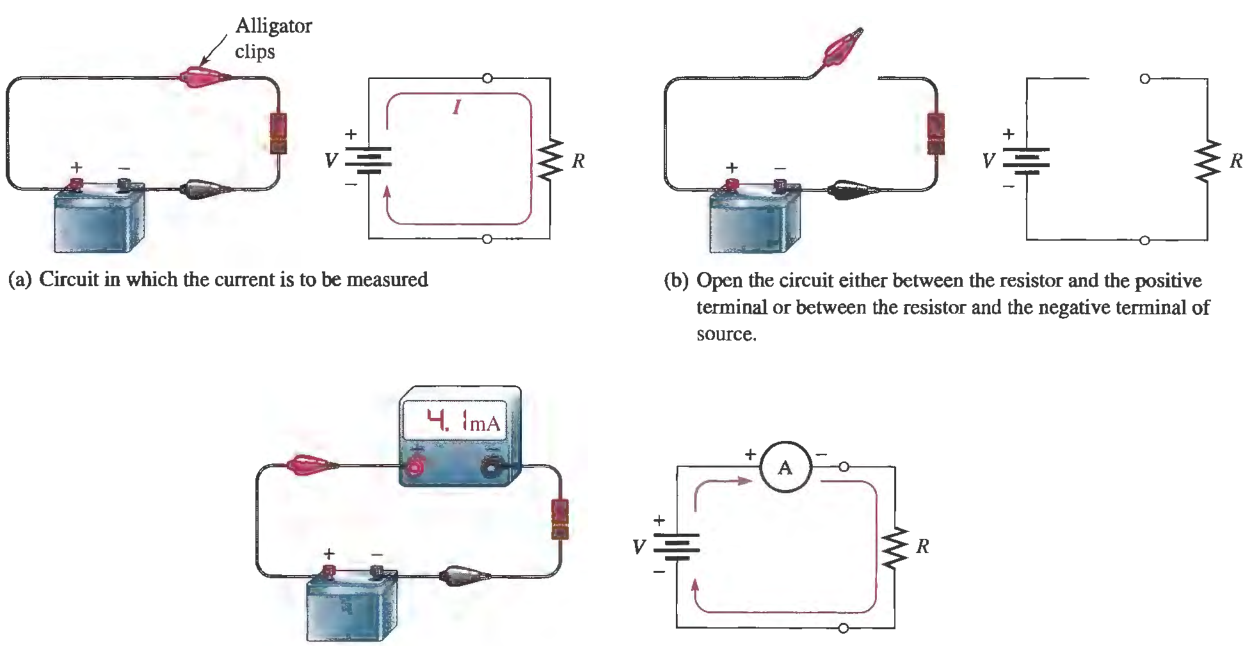
▲ FIGURE 2–53

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).

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.

Measuring Current

Figure 2–54 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.

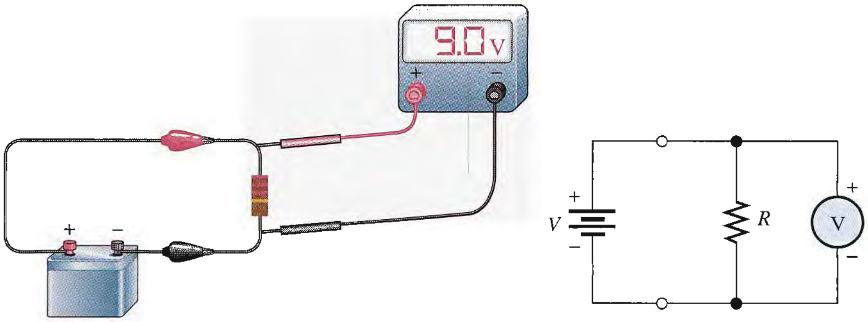
(c) Install the ammeter in the current path with polarity as shown (negative to negative, positive to positive).

FIGURE 2–54

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

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 2–55 shows a voltmeter connected to measure the voltage across the resistor.



▲ FIGURE 2–55

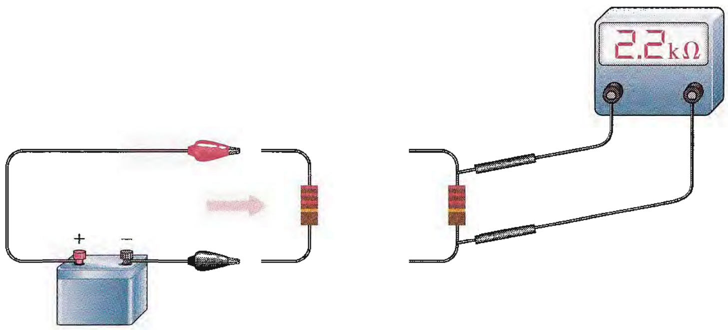
Example of a voltmeter connection in a simple circuit to measure voltage.

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.

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 2–56.



(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 2–56

Example of using an ohmmeter to measure resistance.

Digital Multimeters

A **DMM** (digital multimeter) is an electronic instrument that combines meters for the measurement of 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 2–57 shows typical DMMs.

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

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

Some DMMs provide special functions such as transistor or diode tests, power measurement, and decibel measurement for audio amplifier tests. Some meters require manual

▶ FIGURE 2–57

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

(a) (b)

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) or LED (light-emitting diode) readouts. 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 2000 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. LEDs, on the other hand, can be seen in the dark and respond quickly to changes in measured values. LED displays require much more current than LCDs, and, therefore, battery life is shortened when LEDs are used in portable equipment.

Both LCD and LED DMM displays are in a 7-segment format. Each digit in a display consists of seven separate segments as shown in Figure 2–58(a). Each of the ten decimal digits is formed by the activation of appropriate segments, as illustrated in Figure 2–58(b). In addition to the seven segments, there is also a decimal point.

▶ FIGURE 2–58

Seven-segment display.

(a) (b)

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 2–59(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 2–59(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

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

FIGURE 2–59

A 3½-digit DMM illustrates how the resolution changes with the number of digits in use.

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%.

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 2–60. This particular instrument can be used to measure both direct current (dc) and alternating current (ac) quantities as well as resistance values. It has four selectable

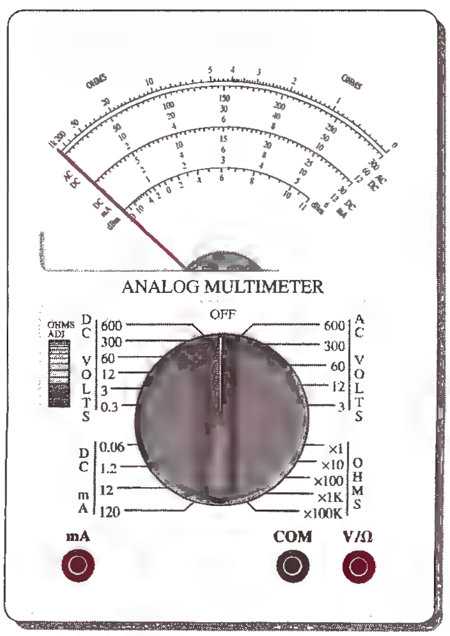


FIGURE 2–60

A typical analog multimeter.

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, ×1000, and ×100,000.

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 2–60, 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 $20 \times 100 = 2000\ \Omega$.

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. 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.

EXAMPLE 2–9

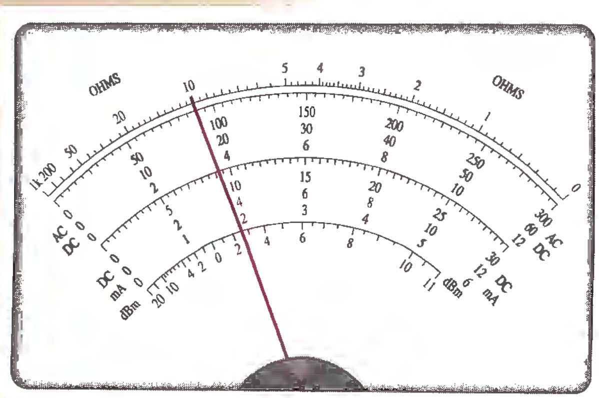
Determine the quantity (voltage, current, or resistance) that is being measured and its value for each specified switch setting on the meter in Figure 2–61.

(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.

FIGURE 2–61



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 2–61 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?

SECTION 2–7 REVIEW

1. Name the meters for measurement of (a) current, (b) voltage, and (c) resistance.
2. Place two ammeters in the circuit of Figure 2–42 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 2–42.
4. List two common types of DMM displays, and discuss the advantages and disadvantages of each.
5. Define *resolution* in a DMM.
6. The multimeter in Figure 2–60 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?
7. How do you set up the meter in Figure 2–60 to measure 275 V dc, and on what scale do you read the voltage?
8. If you expect to measure a resistance in excess of 20 kΩ, where do you set the switch?

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 2–5 shows the effects for various values of current in milliamperes.

TABLE 2–5

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

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 the amount of voltage required to produce each of the effects listed in Table 2–5. 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.

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.
- Use equipment with three-wire power cords (three-prong plug).
- 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 with your hands.

- 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.
- Never handle instruments when your hands are wet.
- Never assume that a circuit is off. Double-check it with a reliable meter before handling.
- Set the limiter on electronic power supplies to prevent currents larger than necessary to supply the circuit under test.
- Some devices such as capacitors can store a lethal charge for long periods after power is removed. They must be properly discharged before you work with them.
- 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.
- Report any unsafe condition.
- 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.

SECTION 2–8 REVIEW

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)

A Circuit Application

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

The instrument panel illumination circuit in an automobile operates from the 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 2–62 shows the schematic for the illumination circuit. Figure 2–63 shows a breadboarded circuit which simulates the illumination circuit by using components that are functionally equivalent but not physically the same as those in a car. A laboratory dc power supply is used in the place of an actual automobile battery. The protoboard in Figure 2–63 is a type that is commonly used for constructing circuits on the test bench.

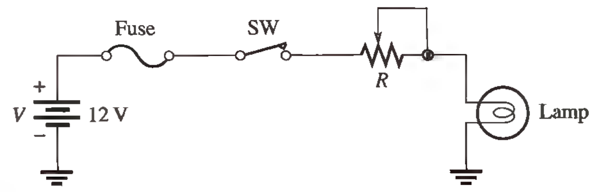


FIGURE 2–62

Basic panel illumination circuit schematic.

The Test Bench

Figure 2–63 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.

- Identify each component in the circuit and check the breadboarded circuit in Figure 2–63 to make sure it is connected as the schematic in Figure 2–62 indicates.
- Explain the purpose of each component in the circuit.

As shown in Figure 2–64, 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 2–65.

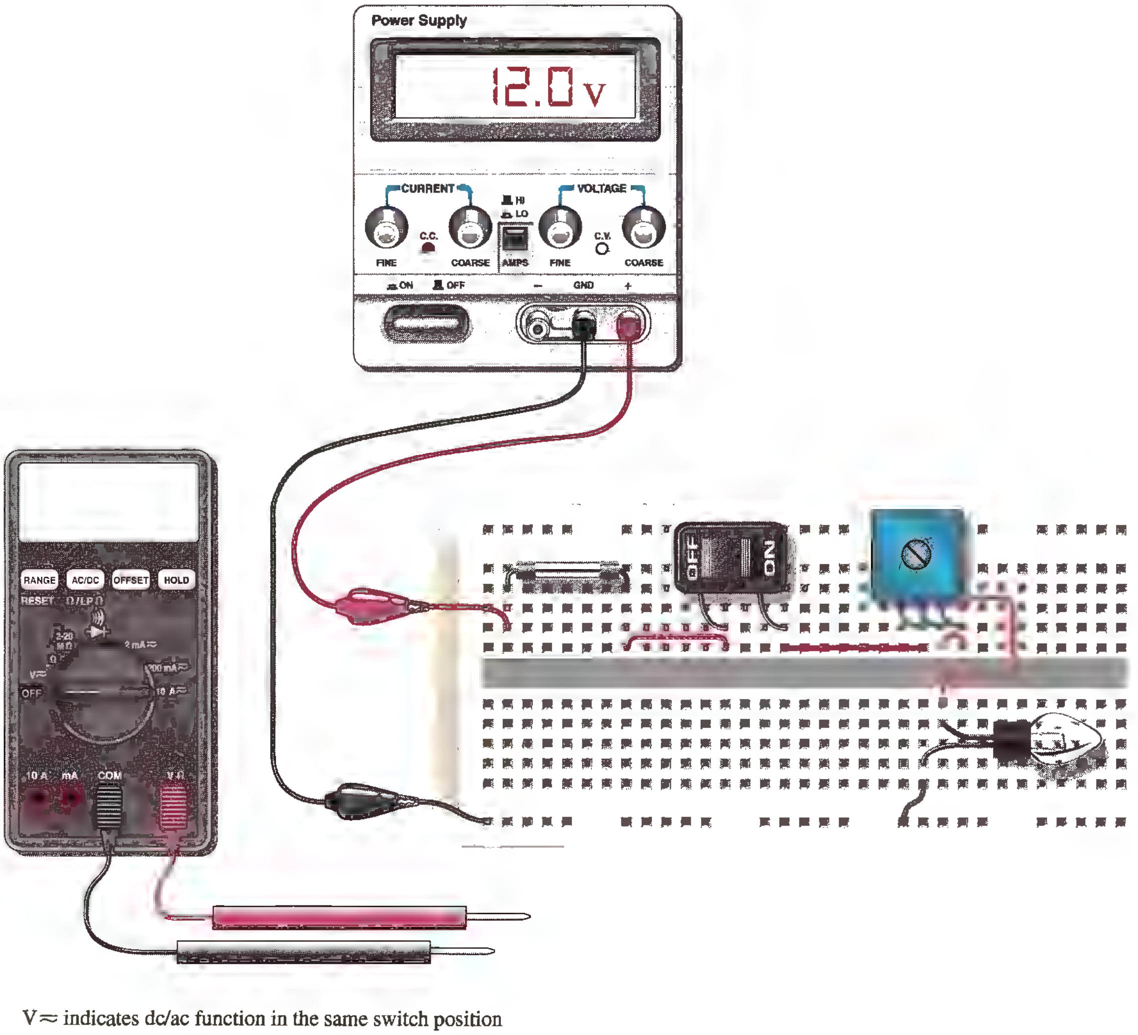
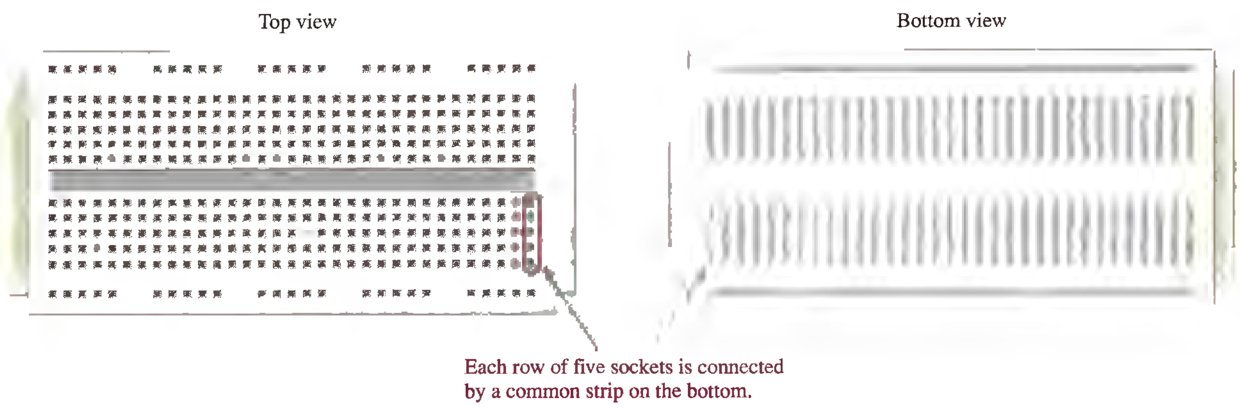


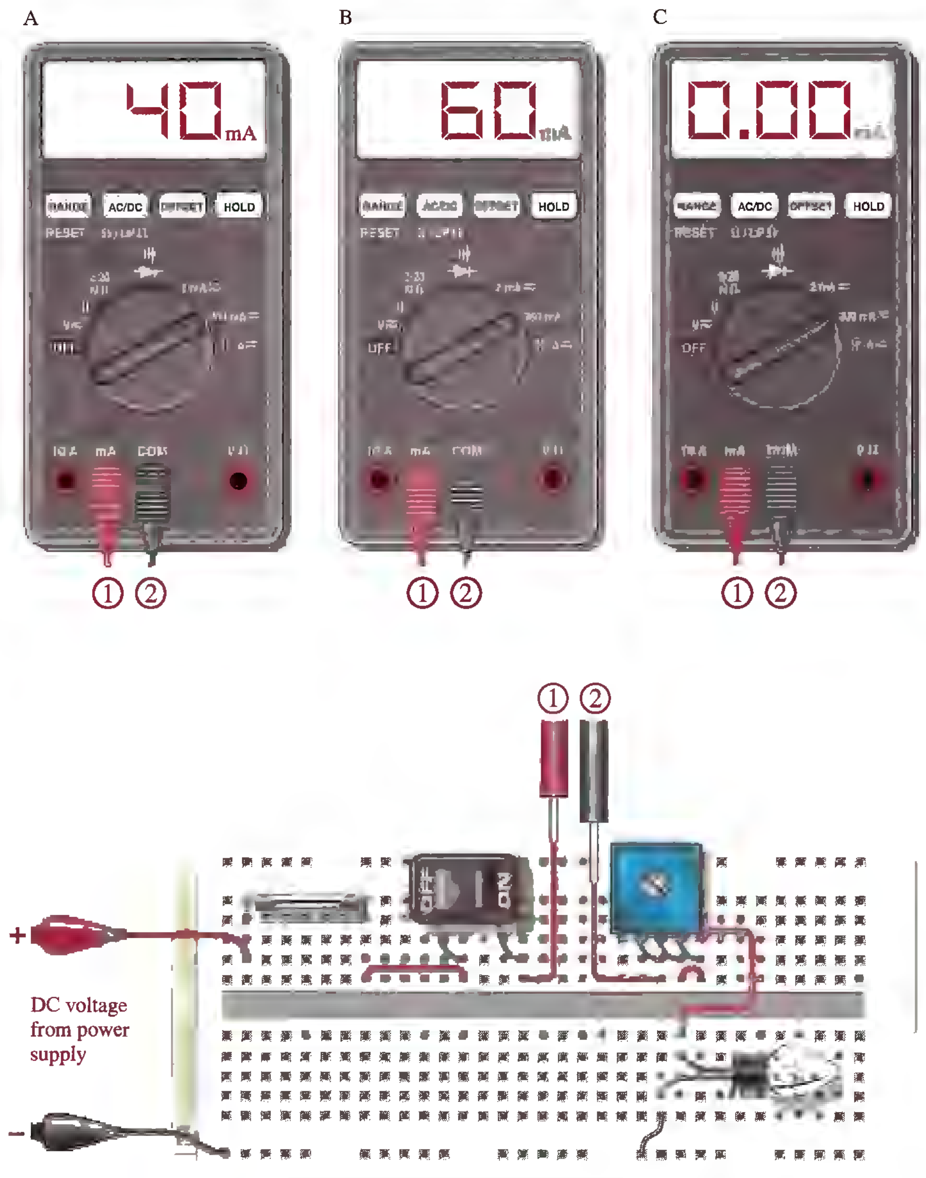
FIGURE 2–63

Test bench setup for simulating the panel illumination circuit.



▲ **FIGURE 2–64**

A typical protoboard used for breadboarding.



◀ **FIGURE 2–65**

Current measurements. The circled numbers indicate the meter-to-circuit connections.

- Redraw the schematic in Figure 2–62 to include the ammeter.
- For which measurement (A, B, or C) is the lamp brightest? Explain.
- List the change(s) in the circuit that can cause the ammeter reading to go from A to B.
- List the circuit condition(s) that will produce the ammeter reading in C.

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 2–66.

- Across which component is the voltage measured?
- Redraw the schematic in Figure 2–62 to include the voltmeter.
- For which measurement (A or B) is the lamp brighter? Explain.
- List the change(s) in the circuit that can cause the voltmeter reading to go from A to B.

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 2–67.

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

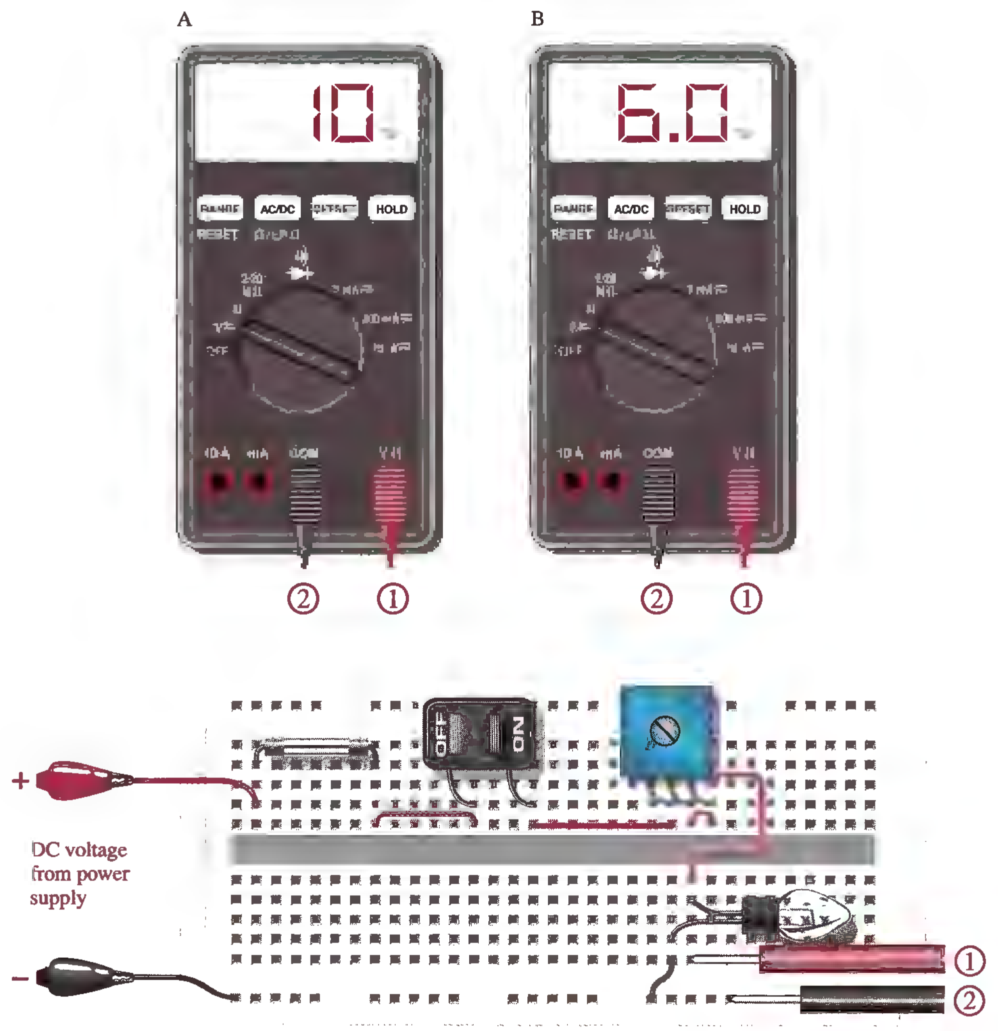


FIGURE 2–66

Voltage measurements.

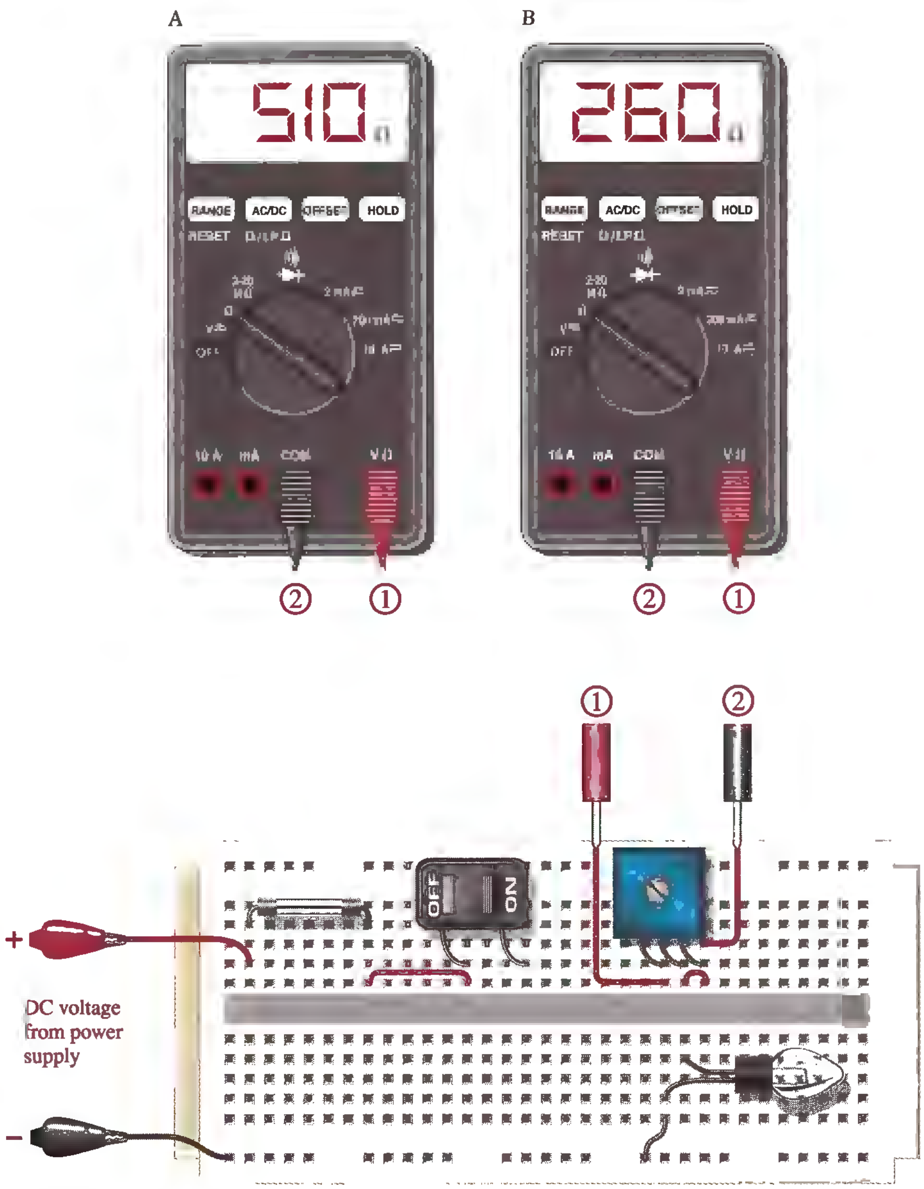


FIGURE 2–67

Resistance measurements.

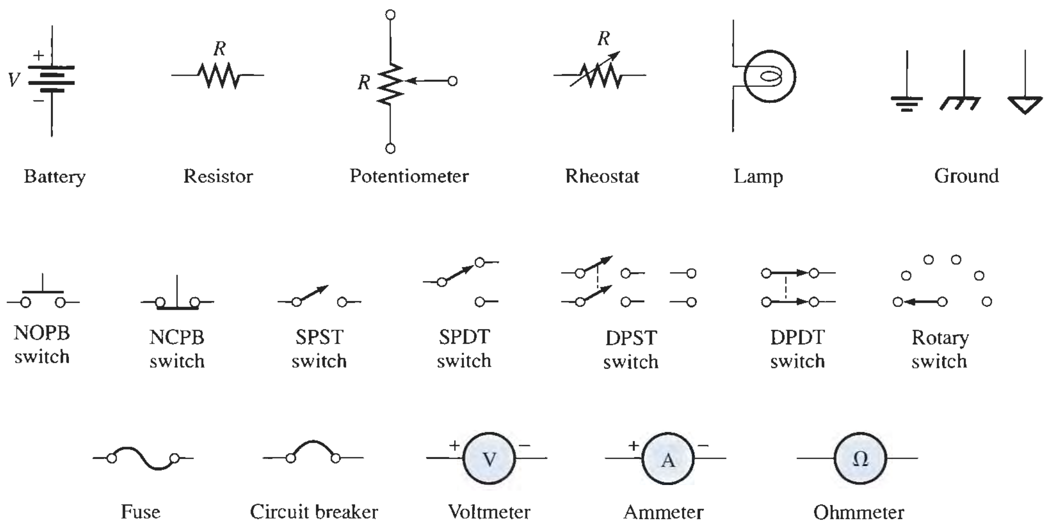
Review

1. If the dc supply voltage in the panel illumination circuit is reduced, how is the amount of light produced by the lamp affected? Explain.

2. Should the potentiometer be adjusted to a higher or lower resistance for the circuit to produce more light?

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 used to move one coulomb 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 2–68 shows the electrical symbols introduced in this chapter.



▲ **FIGURE 2–68**

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 the 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.

Current The rate of flow of charge (electrons).

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

DMM Digital multimeter; an electronic instrument that combines meters 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 from atom to atom within the atomic structure of a material.

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.

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.

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	$Q = \dfrac{\textbf{number of electrons}}{\mathbf{6.25 \times 10^{18}}\ \textbf{electrons/C}}$	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 equals the diameter squared.
2–6	$R = \dfrac{\rho l}{A}$	Resistance is resistivity times length divided by cross-sectional area.

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) free electrons
    (b) the rate of flow of free electrons
    (c) the energy required to move electrons
    (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. Potentiometers and rheostats are types of
    (a) voltage sources (b) variable resistors
    (c) fixed resistors (d) circuit breakers
14. 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

PROBLEMS

More difficult problems are indicated by an asterisk (*).
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, Current, and Resistance

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

(a) 10 J/C **(b)** 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 800 J of energy to move 40 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 2 A through it converts 1000 J of electrical energy into heat energy in 15 s, what is the voltage across the resistor?

10. 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

11. Six-tenths coulomb passes a point in 3 s. What is the current in amperes?

12. How long does it take 10 C to flow past a point if the current is 5 A?

13. How many coulombs pass a point in 0.1 s when the current is 1.5 A?

14. 5.74×10^{17} electrons flow through a wire in 250 ms. What is the current in amperes?

15. Find the conductance for each of the following resistance values:

(a) 5 Ω **(b)** 25 Ω **(c)** 100 Ω

16. Find the resistance corresponding to the following conductances:

(a) 0.1 S **(b)** 0.5 S **(c)** 0.02 S

SECTION 2–4 Voltage and Current Sources

17. List four common sources of voltage.

18. Upon what principle is electrical generators based?

19. How does an electronic power supply differ from the other sources of voltage?

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

SECTION 2–5 Resistors

21. Determine the resistance values and tolerance for the following 4-band resistors:

(a) red, violet, orange, gold **(b)** brown, gray, 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 color bands for each of the following 4-band resistors. Assume each has a 5% tolerance.

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

26. 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

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

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

28. The adjustable contact of a linear potentiometer is set at the mechanical center of its adjustment. If the total resistance is 1000 Ω, what is the resistance between each end terminal and the adjustable contact?

29. What resistance is indicated by 4K7?

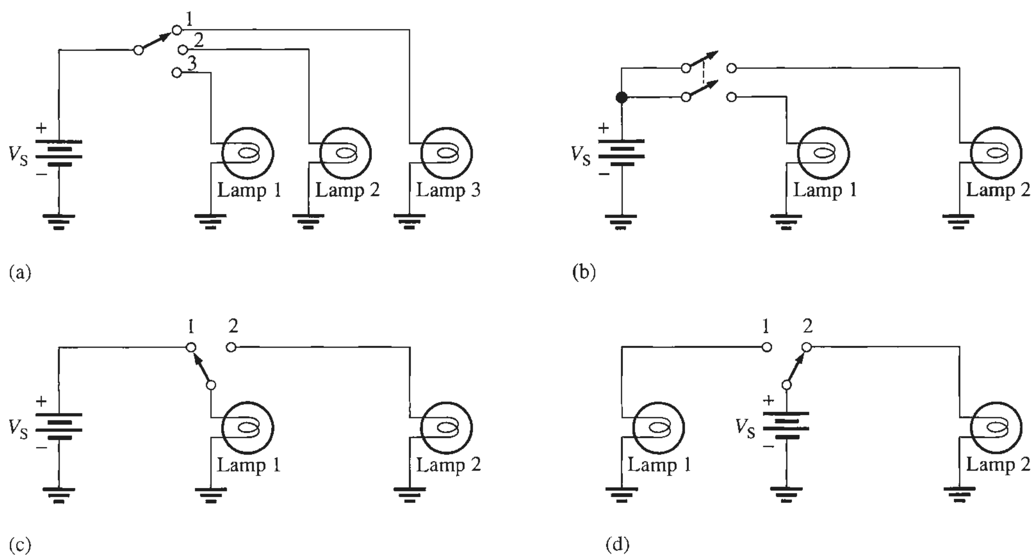
30. Determine the resistance and tolerance of each resistor labeled as follows:

(a) 4R7J **(b)** 5602M **(c)** 1501F

SECTION 2–6 The Electric Circuit

31. Trace the current path in Figure 2–69(a) with the switch in position 2.

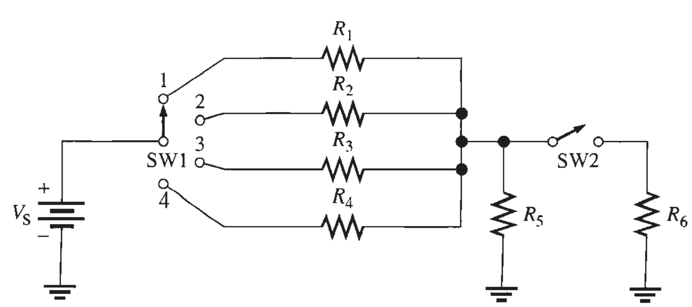
32. With the switch in either position, redraw the circuit in Figure 2–69(d) with a fuse connected to protect the circuit against excessive current.



▲ FIGURE 2–69

33. There is only one circuit in Figure 2–69 in which it is possible to have all lamps on at the same time. Determine which circuit it is.

34. Through which resistor in Figure 2–70 is there always current, regardless of the position of the switches?



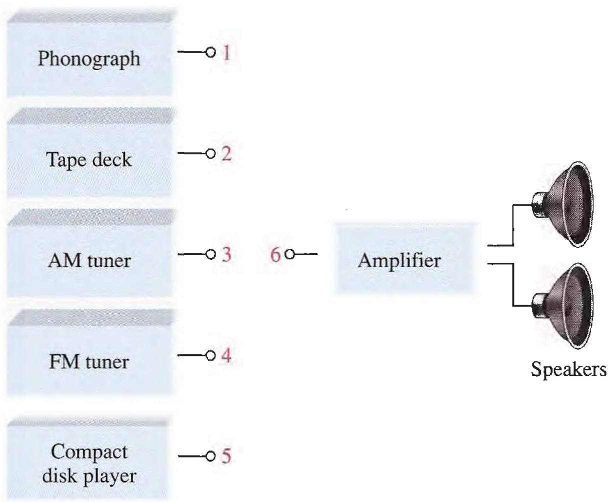
▲ FIGURE 2–70

*35. 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

36. The different sections of a stereo system are represented by the blocks in Figure 2–71. Show how a single switch can be used to connect the phonograph, the CD (compact disk) player, the tape deck, the AM tuner, or the FM tuner to the amplifier by a single knob control. Only one section can be connected to the amplifier at any time.

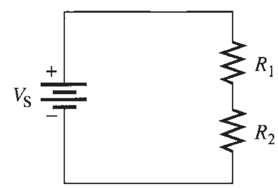


▲ FIGURE 2–71

SECTION 2–7 Basic Circuit Measurements

37. Show the placement of an ammeter and a voltmeter to measure the current and the source voltage in Figure 2–72.

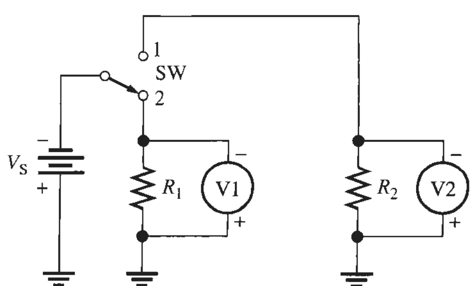
► FIGURE 2–72



38. Explain how you would measure the resistance of R_2 in Figure 2–72.

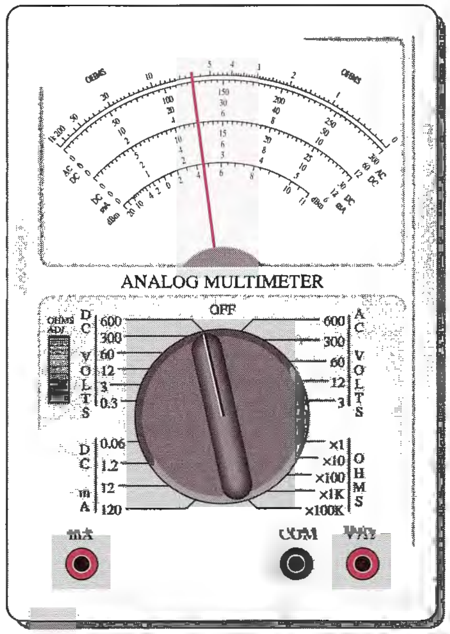
39. In Figure 2–73, how much voltage does each meter indicate when the switch is in position 1? In position 2?

► FIGURE 2–73



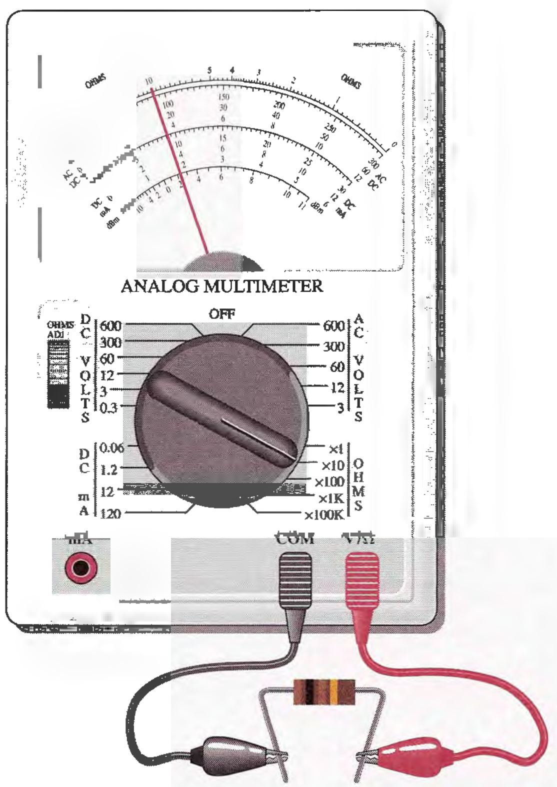
40. In Figure 2–73, indicate how to connect an ammeter to measure the current from the voltage source regardless of the switch position.
41. In Figure 2–70, show the proper placement of ammeters to measure the current through each resistor and the current out of the battery.
42. Show the proper placement of voltmeters to measure the voltage across each resistor in Figure 2–70.
43. What is the voltage reading of the meter in Figure 2–74?

▶ FIGURE 2–74



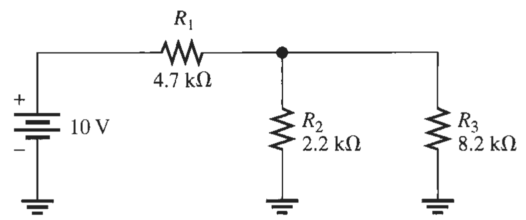
44. How much resistance is the ohmmeter in Figure 2–75 measuring?

▶ FIGURE 2–75



45. Determine the resistance indicated by each of the following ohmmeter readings and range settings:
    (a) pointer at 2, range setting at ×10
    (b) pointer at 15, range setting at ×100,000
    (c) pointer at 45, range setting at ×100
46. What is the maximum resolution of a 4½-digit DMM?
47. Indicate how you would connect the multimeter in Figure 2–75 to the circuit in Figure 2–76 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

▶ FIGURE 2–76



ANSWERS

SECTION REVIEWS

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. Unit of charge is the 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, Current, and Resistance

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. Current is the rate of flow of electrons; its unit is the ampere (A).
5. electrons/coulomb $= 6.25 \times 10^{18}$
6. $I = Q/t = 20\text{ C}/4\text{ s} = 5\text{ A}$
7. Resistance is opposition to current.
8. The unit of resistance is the ohm (Ω).
9. One ohm exists when 1 V produces 1 A.

SECTION 2–4 Voltage and Current Sources

1. A voltage source is a device that produces a constant voltage for a varying load.
2. A battery converts chemical energy to electrical energy.
3. A solar cell uses the photovoltaic effect to convert light energy to electrical energy.
4. A generator produces voltage by rotating a conductor through a magnetic field based on the principle of electromagnetic induction.
5. An electronic power supply converts the commercially available ac voltage to dc voltage.
6. A current source is a device that produces a constant current for a varying load.
7. Transistor

SECTION 2–5 Resistors

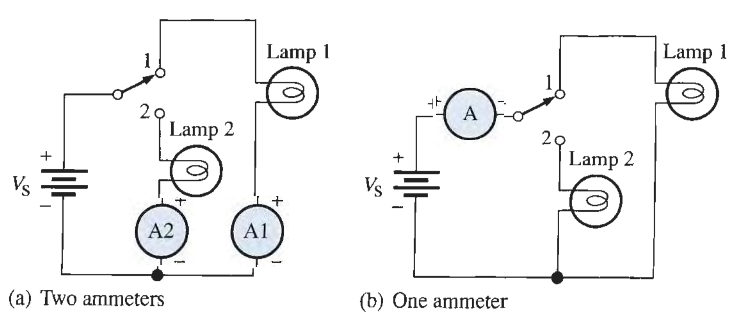
1. Two resistor categories are fixed and variable. The value of a fixed resistor cannot be changed, but that of a variable resistor can.
2. *First band:* first digit of resistance value. *Second band:* second digit of resistance value. *Third band:* multiplier (number of zeros following the second digit). *Fourth band:* % tolerance.
3. **(a)** 27 kΩ ± 10% **(b)** 100 Ω ± 10%
   (c) 5.6 MΩ ± 5% **(d)** 6.8 kΩ ± 10%
   (e) 33 Ω ± 10% **(f)** 47 kΩ ± 5%
4. 330 Ω: (b); 2.2 kΩ: (d); 56 kΩ: (e); 100 kΩ: (f); 39 kΩ: (a)
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. A thermistor is a temperature-sensitive resistor.

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

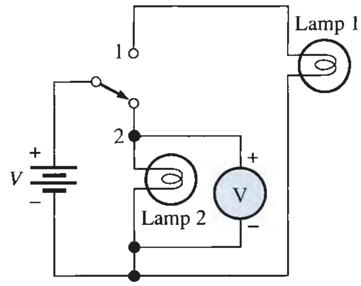
1. **(a)** An ammeter measures current.
   (b) A voltmeter measures voltage.
   (c) An ohmmeter measures resistance.
2. See Figure 2–77.



▲ FIGURE 2–77

3. See Figure 2–78.

▶ **FIGURE 2–78**



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

7. Set the range switch to 300 and read on the upper ac-dc scale.

8. $\times$1000 range

SECTION 2–8 Electrical Safety

1. Current

2. F

3. F

4. F

5. T

A Circuit Application

1. Less voltage causes less light because the current is reduced.

2. A lower resistance will result in more light.

RELATED PROBLEMS FOR EXAMPLES

2–1 1.88×10^{19} electrons

2–2 600 J

2–3 12 C

2–4 4700 Ω ± 5%

2–5 47.5 Ω ± 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.

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.** (b)	**14.** (c)		