2

Current and Voltage

Outline

Learning Outcomes

After completing this chapter, you will be able to

- describe the structure of atoms
- relate atomic structure to electric charge and force
- define electric charge in relation to electric force
- define potential difference in terms of work on charges
- explain potential difference and its relation to voltage
- explain electric current in relation to charge
- describe a number of dc sources, such as batteries, generators, and solar cells
- explain how atomic structure relates to insulators, conductors, and semiconductors
- describe how ammeters and voltmeters are used to measure circuit quantities

Key Terms

ammeter 31
ampere 22
battery 26
cell 26
conductor 30
conventional current flow 23
copper 21
coulomb 20
Coulomb's law 20
current 22
digital multimeter (DMM) 32
direct current (dc) 26
electron 19
electron current flow 23
electromotive force (emf) 26
free electron 21
insulator 30
neutron 19
nucleus 19
positive ion 21
potential 25
potential difference 24
potential energy 24
proton 19
semiconductor 31
volt (V) 24
voltage 24
voltage difference 26
voltmeter 31
volt-ohm-milliammeter (VOM) 32
work 24

2.1 ELECTRICITY

Electricity is a form of energy with a greater versatility than any other form. It can be produced by the transformation of many other forms of energy: chemical energy in batteries, mechanical energy in generators, or light energy in solar cells.

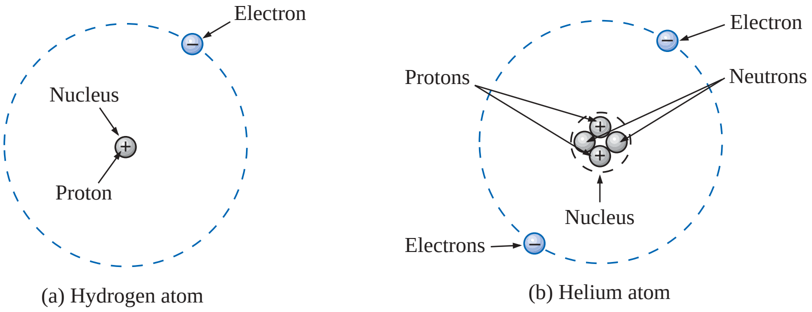
Electrical energy can be stored in batteries or transmitted great distances along transmission lines. When you have it where you want it, you can use electricity to run power tools, illuminate large buildings, operate complex machinery, communicate instantaneously around the world, and perform the many computations inside our computers.

To work in the electrical industry, you need an understanding of a number of concepts, quantities, and relations. In this chapter, we will examine the basic ideas of voltage and current, and their connections with the atomic structure of matter.

2.2 ATOMS AND THEIR STRUCTURE

A basic understanding of the fundamental concepts of current and voltage requires a degree of familiarity with the atom and its structure. The simplest of all atoms is the hydrogen atom, made up of two basic particles, the **proton** and the **electron**, in the relative positions shown in Fig. 2.1 (a). The **nucleus** of the hydrogen atom is the proton, a positively charged particle. *The orbiting electron carries a negative charge that is equal in magnitude to the positive charge of the proton.* In all other elements, the nucleus also contains **neutrons**, which are slightly heavier than protons and have no electrical charge. The helium atom, for example, has two neutrons in addition to two electrons and two protons, as shown in Fig. 2.1 (b). *In all neutral atoms the number of electrons is equal to the number of protons.* The mass of the electron is 9.09×10^{-28} g, and that of the proton is 1.673×10^{-24} g. The mass of the proton (or neutron) is therefore approximately 1837 times that of the electron. The radii of the proton, neutron, and electron are all of the order of magnitude of 2×10^{-15} m.

For the hydrogen atom, the radius of the smallest orbit followed by the electron is about 5×10^{-11} m. The radius of this orbit is approximately 25 000 times that of the radius of the electron, proton, or neutron. This is approximately equivalent to a sphere the size of a dime revolving about another sphere of the same size more than a quarter of a mile away.



(a) Hydrogen atom

(b) Helium atom

FIG. 2.1
The hydrogen and helium atoms.

Different atoms will have various numbers of electrons in the concentric shells about the nucleus. The first shell, which is closest to the nucleus, can contain only two electrons. If an atom should have three electrons, the third must go to the next shell. The second shell can contain a maximum of eight electrons; the third, 18; and the fourth, 32; as determined by the equation $2n^2$, where n is the shell number. These shells are often denoted by letters ($k, l, m, \ldots$).

Each shell is then broken down into subshells, where the first subshell can contain a maximum of 2 electrons; the second subshell, 6 electrons; the third, 10 electrons; and the fourth, 14; as shown in Fig. 2.2. The subshells are usually denoted by the letters *s*, *p*, *d*, and *f*, in that order, outward from the nucleus.

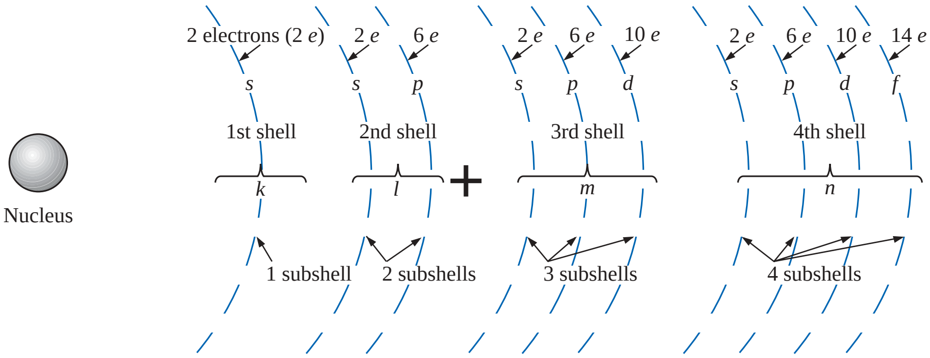


FIG. 2.2

Shells and subshells of the atomic structure.

The unit for charge is the **coulomb** (**C**), named after Charles Augustin de Coulomb (Fig. 2.3). Section 2.3 discusses the definitions for charge and current units. It has been determined by experimentation that *unlike charges attract, and like charges repel*. The force of attraction or repulsion between two charged bodies, Q_1 and Q_2, can be determined by **Coulomb's law**:

$$F \text{ (attraction or repulsion)} = \frac{kQ_1Q_2}{r^2} \qquad \text{(newtons, N)} \qquad (2.1)$$

where F is in newtons, k = a constant = $9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$, Q_1 and Q_2 are the charges in coulombs (in Section 2.3) and r is the distance in metres between the two charges. In particular, note the squared r term in the denominator, resulting in rapidly decreasing levels of F for increasing values of r. (See Fig. 2.3).

In the atom, therefore, electrons will repel each other, and protons and electrons will attract each other. Since the nucleus consists of many positive charges (protons), a strong attractive force exists for the electrons in orbits close to the nucleus [note the effects of a large charge Q and a small distance r in Eq. (2.1)]. As the distance between the nucleus and the orbital electrons increases, the binding force diminishes until it reaches its lowest level at the outermost subshell (largest r). Due to the weaker binding forces, less energy must be expended to remove an electron from an outer subshell than from an inner subshell. Also, it is generally true that electrons are more readily removed from atoms having outer subshells with few electrons. These properties of the atom that permit the removal of electrons under certain conditions are essential for electric current.

LUMINARIES

French (Angoulême, Paris)
Scientist and Inventor
Military Engineer in the West Indies

FIG. 2.3

Charles Augustin de Coulomb (1736–1806)

Coulomb attended the engineering school at Mezieres, the first such school of its kind. He formulated Coulomb's law, which defines the force between two electrical charges and is, in fact, one of the principal forces in atomic reactions. He also performed extensive research on the friction encountered in machinery and windmills, and the elasticity of metal and silk fibres.

Courtesy of the Smithsonian Institution, Photo No. 52,597

Copper is the most commonly used metal in the electrical/electronics industry. An examination of its atomic structure will help identify why it has such widespread applications. The copper atom (Fig. 2.4) has one more electron than needed to complete the first three shells. The incomplete outermost shell, possessing only one electron, and the distance between this electron and the nucleus cause the twenty-ninth electron to be loosely bound to the copper atom. If this twenty-ninth electron gains sufficient energy from the surrounding medium to leave its parent atom, it is called a **free electron**. In one cubic centimetre of copper at room temperature, there are approximately 8.5×10^{22} free electrons. Other metals that exhibit the same properties as copper, but to a different degree, are silver, gold, aluminum, and tungsten. Additional discussion of conductors and their characteristics can be found in Section 3.2.

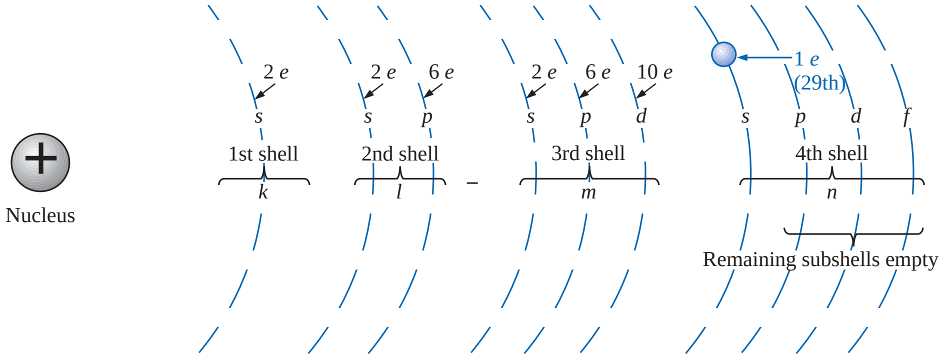


FIG. 2.4
The copper atom.

2.3 CURRENT

Consider a short length of copper wire cut with an imaginary perpendicular plane, producing the circular cross-section shown in Fig. 2.5. At room temperature with no external forces applied, there exists within the copper wire the random motion of free electrons created by the thermal energy that the electrons gain from the surrounding medium. When an atom loses its free electron, it acquires a net positive charge and is referred to as a **positive ion**. The free electron is able to move among these positive ions and leave the general area of the parent atom, while the positive ion can only oscillate in a mean fixed position. For this reason,

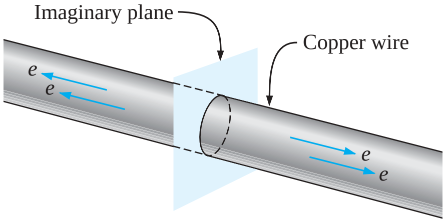


FIG. 2.5
Random motion of electrons in a copper wire with no external "pressure" (voltage) applied.

the free electron is the charge carrier in a copper wire or any other solid conductor of electricity.

An array of positive ions and free electrons is shown in Fig. 2.6. Within this array, the free electrons are continually gaining or losing energy by virtue of their changing direction and velocity. Some of the factors responsible for this random motion include (1) the collisions with positive ions and other electrons, (2) the attractive forces of the positive ions, and (3) the force of repulsion that exists between electrons. This random motion of free electrons is such that over a period of time, the number of electrons moving to the right across the circular cross-section of Fig. 2.5 is exactly equal to the number passing over to the left.

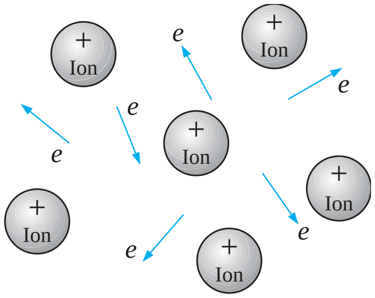


FIG. 2.6
Random motion of free electrons in an atomic structure.

With no external forces applied, the net flow of charge in a conductor in any one direction is zero.

Let us now connect copper wire between two battery terminals and a light bulb, as shown in Fig. 2.7, to create the simplest of electric circuits. The battery places a net positive charge at one terminal and a net negative charge on the other. The instant the final connection is made, the free electrons (of negative charge) will drift toward the positive terminal, while the positive ions left behind in the copper wire will simply oscillate in their mean fixed positions. The negative terminal is a "supply" of electrons to be drawn from when the electrons of the copper wire drift toward the positive terminal.

As shown in Fig. 2.7, the conventional direction for current is chosen to be away from the positive terminal of the battery and toward the negative terminal (that is, opposite to the direction of electron drift).

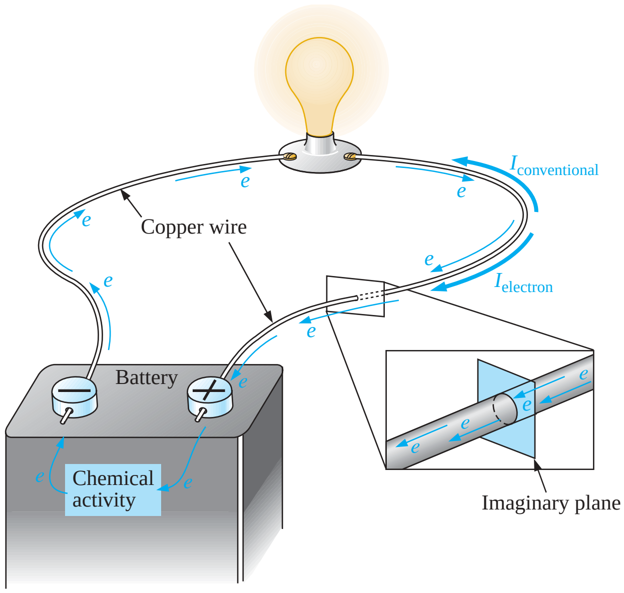


FIG. 2.7
Basic electric circuit.

The rate of flow of charge in a conductor is called the **current**. The unit of current is the **ampere** (**A**), named in honour of André Marie Ampère (Fig. 2.8). Current is defined by the rate of flow of charge in coulombs per second (C/s).

A current of 1 A produces a force of 2×10^{-7} N/m when flowing through two parallel conductors of infinite length and negligible diameter 1 m apart in a vacuum.

A coulomb is equal to an ampere-second, which corresponds to the charge on about 6.242×10^{18} electrons.

You can see that 1 A is the flow of 6.24×10^{18} electrons per second. The symbol I for current was chosen from the French word for current, *intensité*. In equation form, for charge (Q) in coulombs, and time (t) in seconds, the current is

$$I = \frac{Q}{t} \qquad \text{(amperes, A)} \qquad (2.2)$$

LUMINARIES

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FIG. 2.8
André Marie Ampère (1775–1836)

On September 18, 1820 Ampère introduced a new field of study, *electrodynamics*, devoted to the effect of electricity in motion, including the interaction between currents in adjoining conductors and the interplay of the surrounding magnetic fields. He constructed the first *solenoid* and demonstrated how it could behave like a magnet (the first *electromagnet*). He also suggested the name *galvanometer* for an instrument designed to measure current levels.

Courtesy of the Smithsonian Institution, Photo No. 76,524

Through algebraic manipulations, the other two quantities can be determined as follows:

$$\boxed{Q = It} \qquad \text{(coulombs, C)} \qquad (2.3)$$

and

$$\boxed{t = \frac{Q}{I}} \qquad \text{(seconds, s)} \qquad (2.4)$$

EXAMPLE 2.1

The charge flowing through the imaginary surface of Fig. 2.7 is 0.16 C every 64 ms. Determine the current in amperes.

Solution: Eq. (2.2):

$$I = \frac{Q}{t} = \frac{0.16\ \text{C}}{64 \times 10^{-3}\ \text{s}} = \frac{160 \times 10^{-3}\ \text{C}}{64 \times 10^{-3}\ \text{s}} = \mathbf{2.5\ A}$$

EXAMPLE 2.2

Determine the time required for 4.0×10^{16} electrons to pass through the imaginary surface of Fig. 2.7 if the current is 5.0 mA.

Solution: Determine Q:

$$4.0 \times 10^{16}\ \cancel{\text{electrons}} \left(\frac{1\ \text{C}}{6.242 \times 10^{18}\ \cancel{\text{electrons}}} \right) = 0.641 \times 10^{-2}\ \text{C}$$

$$= 6.41\ \text{mC}$$

Calculate t [Eq. (2.4)]:

$$t = \frac{Q}{I} = \frac{6.41 \times 10^{-3}\ \text{C}}{5.0 \times 10^{-3}\ \text{A}} = \mathbf{1.23\ s}$$

A second glance at Fig. 2.7 will reveal that two directions of charge flow have been indicated. One is called **conventional current flow**, and the other is called **electron current flow**. This text will deal only with conventional current flow for a variety of reasons, including the fact that it is the most widely used at educational institutions and in industry, it is employed in the design of all electronic device symbols, and it is the popular choice for all major computer software packages. The flow controversy is a result of an assumption made at the time electricity was discovered that the positive charge was the moving particle in metallic conductors. Be assured that the choice of conventional current flow will not create great difficulty and confusion in the chapters to follow. Once the direction of I is established, the issue is dropped and the analysis can continue without confusion.

Safety Considerations

It is important to realize that even small levels of current through the human body can cause serious, dangerous side effects. Experimental results reveal that the human body begins to react to currents of only a few milliamperes. Although most individuals can withstand currents up to perhaps 10 mA for very short periods of time without serious side effects, any current over 10 mA should be considered dangerous. In fact, currents of 50 mA can cause severe shock, and currents of over 100 mA can be fatal. In most cases the skin resistance of the body when dry is high enough to limit the current through the body to relatively safe levels for voltages typically found in the home. However, be aware that when the skin is wet due to perspiration, bathing, etc., or the skin barrier is broken due to an injury, the skin resistance drops dramatically and current levels could rise to dangerous levels for the same voltage shock. In general, therefore, simply remember that *water and electricity are a dangerous mixture.* Granted, there are safety devices in the home today that are designed specifically for use in wet areas such as the bathroom and kitchen, but accidents can happen. Treat electricity with respect—not fear.

2.4 VOLTAGE

An electric force produces electrical energy when it moves a charge through a distance. This process can be understood by comparison with the action of mechanical forces. Suppose an average force of $F = 50$ N is required to compress a spring by $d = 0.3$ m. The force does an amount of **work**

$$W = F\,d \qquad \text{(joules, J)} \qquad (2.5)$$

or 50 N (0.3 m) = 15 J. That work, or energy, is thereby stored in the spring as **potential energy**. The energy can be transferred to an object placed on the spring when it is released.

Compressing the spring by another distance will create a different amount of potential energy. There is a potential energy difference between the two distances of spring compression.

For electricity, consider the chemical energy found in the materials of a battery. Chemical action in the battery will create a surplus of electrons at the negative terminal, and a deficit of electrons at the positive terminal. These charge accumulations will exert electric forces on electrons in a wire connected between the two terminals (Fig. 2.7). You can say that there is an electric **potential difference** between the two terminals. Just as the spring can transfer energy to an object, the cell can transfer energy to electric charges. The potential difference between the two terminals is defined by the energy transferred per unit charge. The SI unit for potential difference is the **volt** (V).

A potential difference of 1 V exists between two points if 1 J of energy is transferred in moving 1 C of charge between the two points.

The volt is named for Alessandro Volta (Fig. 2.9) who developed the voltaic cell in 1800.

Consider a dry cell with a potential difference between its terminals of 1 V. Each coulomb of charge gains 1 J of energy in the cell and transfers 1 J of energy to the lamp. Each coulomb rises through a potential difference of 1 V in the cell (Fig. 2.10), and falls through a potential difference of 1 V in the lamp. The medium of electricity has transformed 1 J of chemical energy in the cell to 1 J of heat and light energy in the lamp. The potential difference is usually called **voltage**. Note in the above discussion that two points are always involved when

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Professor of Physics, Pavia, Italy

FIG. 2.9
Count Alessandro Volta (1745–1827)

Volta began electrical experiments at the age of 18 working with other European investigators. His major contribution was the development of an electrical energy source from chemical action in 1800. For the first time electrical energy was available on a continuous basis and could be used for practical purposes. Volta developed the first *condenser* known today as the *capacitor.* He was invited to Paris to demonstrate the *voltaic cell* to Napoleon. The International Electrical Congress meeting in Paris in 1881 honoured his efforts by choosing the *volt* as the unit of measure for electromotive force.

Courtesy of the Smithsonian Institution, Photo No. 55,393

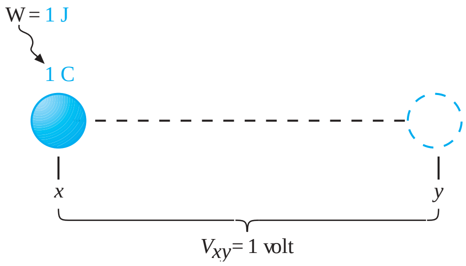


FIG. 2.10
Defining the unit of measurement for voltage.

talking about voltage or potential difference. In the future, therefore, it is very important to keep in mind that

a potential difference or voltage is always measured between two points in the system. Changing either point may change the potential difference between the two points under investigation.

In general, the potential difference between two points is determined by

$$\boxed{V = \frac{W}{Q}} \qquad \text{(volts, V)} \qquad (2.6)$$

Through algebraic manipulations, we have

$$\boxed{W = QV} \qquad \text{(joules, J)} \qquad (2.7)$$

and

$$\boxed{Q = \frac{W}{V}} \qquad \text{(coulombs, C)} \qquad (2.8)$$

EXAMPLE 2.3

Find the potential difference between two points in an electrical system if 60 J of energy are expended by a charge of 20 C between these two points.

Solution: Eq. (2.6):

$$V = \frac{W}{Q} = \frac{60\text{ J}}{20\text{ C}} = \mathbf{3.0\ V}$$

EXAMPLE 2.4

Determine the energy expended moving a charge of 50 μC through a potential difference of 0.6 V.

Solution: Eq. (2.7):

$$W = QV = (50 \times 10^{-6}\text{ C})(0.6\text{ V}) = 30 \times 10^{-6}\text{ J} = \mathbf{30\ \mu J}$$

To distinguish between sources of voltage (batteries and the like) and losses in potential across dissipative elements, the following notation will be used:

E for voltage sources (volts)
V for voltage drops (volts)

The normal usage for various terms associated with voltage can be seen in the following definitions:

Potential: *The voltage at a point with respect to another point in the electrical system. Typically the reference point is ground, which is at zero potential.*

Potential difference: *The algebraic difference in potential (or voltage) between two points of a network.*

***Voltage:** When isolated, like potential, the voltage at a point with respect to some reference such as ground (0 V).*

***Voltage difference:** The algebraic difference in voltage (or potential) between two points of the system. A voltage rise is positive and a voltage drop is negative.*

***Electromotive force (emf):** The force that establishes the flow of charge (or current) in a system due to the application of a difference in potential. This term is primarily associated with sources of energy.*

The applied potential difference (in volts) of a voltage source in an electric circuit is the "pressure" that causes the flow of charge through the circuit. A mechanical analogy for the applied voltage is the pressure applied to the water in a hose. The resulting flow of water through the system is comparable to the current through an electric circuit. Without the applied pressure from the spigot, the water will simply sit in the hose, just as the electrons of a copper wire do not have a general direction of drift without an applied voltage.

2.5 dc SUPPLIES

The term **dc** is an abbreviation for **direct current**, found in electrical systems having a *unidirectional* ("one direction") flow of charge.

dc Voltage Sources

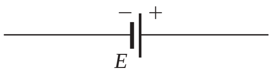


FIG. 2.11
Symbol for a dc voltage source.

The symbol used for all dc voltage supplies in this text appears in Fig. 2.11. The relative lengths of the bars indicate the terminals they represent.

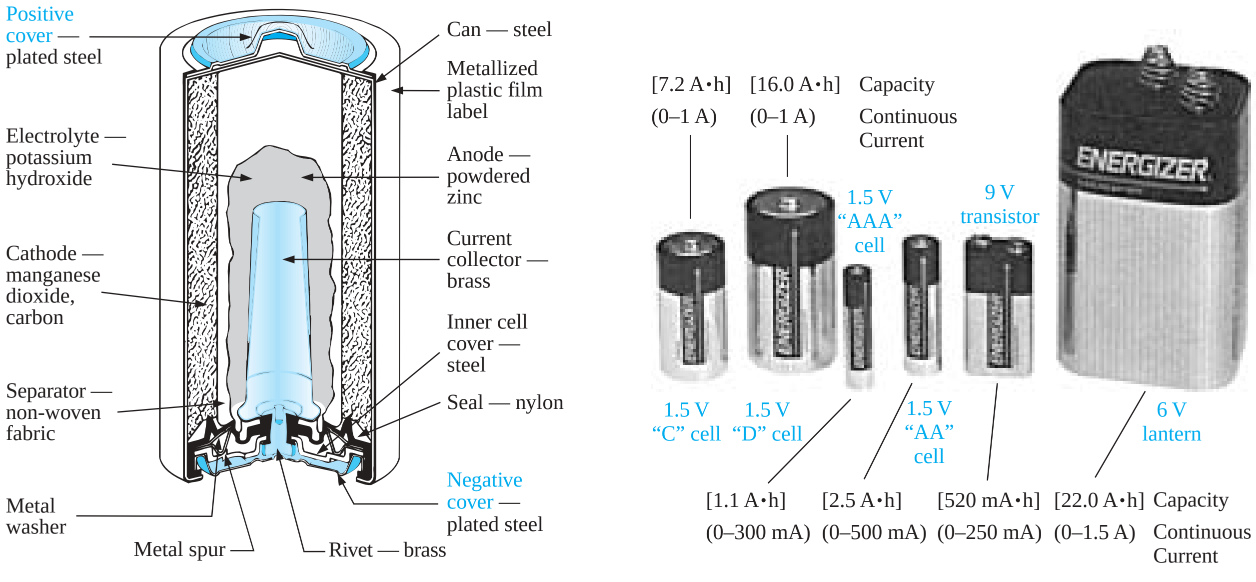
Sources of dc voltage can be divided into three broad categories: (1) batteries (chemical action), (2) generators (electromechanical), and (3) power supplies (rectification).

Batteries

GENERAL INFORMATION Batteries are the most common dc sources. A **battery** consists of a combination of two or more similar **cells.** A cell is the basic source of electrical energy produced by the conversion of chemical or solar energy. All cells can be divided into the *primary* or *secondary* types. The secondary is rechargeable; the primary is not. That is, the chemical reaction of the secondary cell can be reversed to restore its capacity. The two most common rechargeable batteries are the lead-acid unit (used primarily in automobiles) and the nickel-cadmium battery (used in calculators, tools, photoflash units, shavers, and so on). The obvious advantage of the rechargeable unit is the reduced cost associated with not having to continually replace discharged primary cells.

All the cells appearing in this chapter except the solar cell, which absorbs energy from incident light in the form of photons, establish a potential difference at the expense of chemical energy. In addition, each has a positive and a negative electrode and an electrolyte to complete the circuit between electrodes within the battery. The electrolyte is the contact element and the source of ions for conduction between the terminals.

ALKALINE AND LITHIUM–IODINE PRIMARY CELLS The popular alkaline primary battery uses a powdered zinc anode (+); a potassium (alkali metal) hydroxide electrolyte; and a manganese dioxide, carbon cathode (−) as shown in Fig. 2.12(a). In particular, note in Fig. 2.12(b) that the larger the cylindrical unit, the higher the current capacity. The lantern battery or cell is designed primarily for long-term use. Figure 2.13 shows two lithium–iodine primary units used in devices where frequent replacement is inconvenient.



(a) (b)

FIG. 2.12

(a) Cutaway of cylindrical Energizer alkaline cell; (b) Eveready Energizer primary cells. (Courtesy of Eveready Battery Company, Inc.)

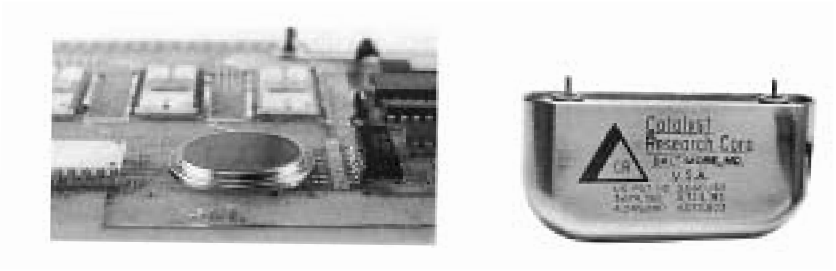
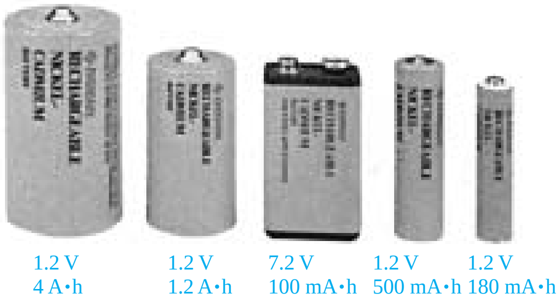


FIG. 2.13

Lithium–iodine primary cells. (Courtesy of Catalyst Research Corp.)

NICKEL–CADMIUM SECONDARY CELL The nickel–cadmium battery is a rechargeable battery that has been receiving enormous interest and development in recent years. For applications such as flashlights, shavers, portable televisions, power drills, and so on, the nickel–cadmium (Ni-Cad) battery of Fig. 2.14 is the secondary battery of choice. Although the current levels are lower, the period of continuous drain is usually longer. A typical nickel–cadmium battery can survive over 1000 charge/discharge cycles over a period of time that can last for years.



(a)

Eveready® BH 500 cell
1.2 V, 500 mA·h
App: Where vertical height is severe limitation

(b)

FIG. 2.14
Rechargeable nickel–cadmium batteries. (Courtesy of Eveready Batteries.)

40-W high-density solar module: 100-mm × 100-mm square cells are used to provide maximum power in a minimum of space. The 33 series-cell module provides a strong 12-V battery charging current for a wide range of temperatures (−40°C to 60°C).

FIG. 2.15
Solar module. (Courtesy of Motorola Semiconductor Products.)

SOLAR CELL A high-density, 40-W solar array appears in Fig. 2.15. Since the maximum available wattage in an average bright sunlit day is 100 mW/cm^2 and conversion efficiencies are currently between 10% and 14%, the maximum available power per square centimetre from most commercial units is between 10 mW and 14 mW. For a square metre, however, the return would be 100 W to 140 W. A more detailed description of the solar cell will appear in your electronics courses. For now it is important to realize that a fixed illumination of the solar cell will provide a fairly steady dc voltage for driving various loads, from watches to automobiles.

Generators

The dc generator is a device that converts mechanical energy to electrical energy (Fig. 2.16). When the shaft of the generator is rotating at the nameplate speed due to the applied torque of some external source of mechanical power, a voltage of rated value will appear across the external terminals. The terminal voltage and power-handling capabilities of the dc generator are typically higher than those of most batteries, and its lifetime is determined only by its construction. Commercially used dc generators are typically of the 120-V or 240-V variety. For the purposes of this text, no distinction will be made between the symbols for a battery and a generator.

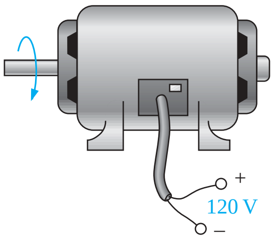


FIG. 2.16
dc generator.

Power Supplies

The dc supply encountered most often in the laboratory uses the *rectification* and *filtering* processes to obtain a steady dc voltage. Both processes will be covered in detail in your basic electronics courses. A dc laboratory supply of this type appears in Fig. 2.17.

FIG. 2.17

dc laboratory supply. (Courtesy of Leader Instruments Corporation.)

Most dc laboratory supplies have a regulated, adjustable voltage output with three available terminals, as indicated in Figs. 2.17 and 2.18(a). The symbol for ground or zero potential (the reference) is also shown in Fig. 2.18(a). If 10 V above ground potential are required, then the connections are made as shown in Fig. 2.18(b). If 15 V below ground potential are required, then the connections are made as shown in Fig. 2.18(c). If connections are as shown in Fig. 2.18(d), we say we have a “floating” voltage of 5 V since the reference level is not included. The configuration of Fig. 2.18(d) is not often used since it fails to protect the operator by providing a direct low-resistance path to ground and to establish a common ground for the system. In any case, the positive and negative terminals must be part of any circuit configuration.

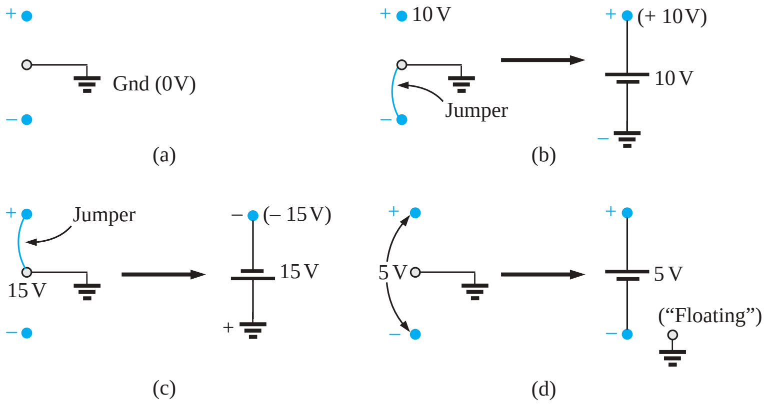


FIG. 2.18

dc laboratory supply: (a) available terminals; (b) positive voltage with respect to (w.r.t.) ground; (c) negative voltage w.r.t. ground; (d) floating supply.

dc Current Sources

The wide variety of types of, and applications for, the dc voltage source have made it a rather familiar device, the characteristics of which are understood, at least basically, by the layperson. For example, it is common knowledge that a 12-V car battery has a terminal voltage (at least approximately) of 12 V, even though the current drain by the automobile may vary under different operating conditions. In other words,

a dc voltage source will provide, ideally, a fixed terminal voltage, even though the current demand from the electrical/electronic system may vary,

as shown in Fig. 2.19(a). A dc current source

will supply, ideally, a fixed current to an electrical/electronic system, even though there may be variations in the terminal voltage as determined by the system,

as shown in Fig. 2.19(b).

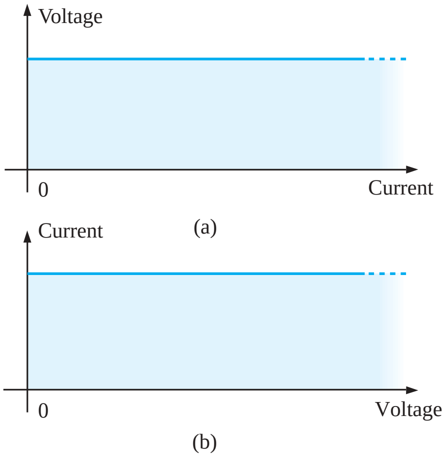


FIG. 2.19

Terminal characteristics: (a) ideal voltage source; (b) ideal current source.

2.6 CONDUCTORS AND INSULATORS

Different wires placed across the same two battery terminals will allow different amounts of charge to flow between the terminals. Many factors, such as the density, mobility, and stability characteristics of a material, account for these variations in charge flow. In general, however,

***conductors** are those materials that permit a generous flow of electrons with very little external force (voltage) applied.*

In addition,

The atoms of good conductors typically have only one electron in their outermost shell.

Since copper is used most often, it serves as the standard of comparison for the relative conductivity in Table 2.1. Note that aluminum, which has seen some commercial use, has only 61% of the conductivity level of copper, but keep in mind that this must be weighed against the cost and weight factors.

TABLE 2.1

Relative conductivity of various materials.

Metal	Relative Conductivity (%)
Silver	105
Copper	**100**
Gold	70.5
Aluminum	61
Tungsten	31.2
Nickel	22.1
Iron	14
Constantan	3.52
Nichrome	1.73
Calorite	1.44

***Insulators** are those materials that have very few free electrons and require a large applied potential (voltage) to establish a measurable current level.*

A common use of insulating material is for covering current-carrying wire that would be dangerous if not insulated. Power-line repair people wear rubber gloves and stand on rubber mats as safety measures when working on high-voltage transmission lines. A number of different types of insulators and their applications appear in Fig. 2.20.

FIG. 2.20

Different types of insulators. (Photo courtesy of Daburn Electronics & Cable Corp.)

It must be pointed out that even the best insulator will break down (permit charge to flow through it) if a sufficiently large potential is applied across it. The breakdown strengths of some common insulators are listed in Table 2.2. According to this table, for insulators with the same geometric shape, it would require 270/30 = 9 times as much potential to pass current through rubber as compared to air and approximately 67 times as much voltage to pass current through mica as through air.

TABLE 2.2

Breakdown strength of some common insulators.

Material	Average Breakdown Strength (kV/cm)
Air	30
Porcelain	70
Oils	140
Bakelite	150
Rubber	270
Paper (paraffin-coated)	500
Teflon	600
Glass	900
Mica	2000

2.7 SEMICONDUCTORS

A **semiconductor** has fewer free electrons than a conductor, but more than an insulator. Materials such as silicon and germanium are semiconductors that are used in diodes and transistors, which can control currents in circuits. Semiconductors are at the heart of the integrated circuits so important in computers and many control devices.

2.8 AMMETERS AND VOLTMETERS

It is important to be able to measure the current and voltage levels of an operating electrical system to check its operation, isolate malfunctions, and investigate effects impossible to predict on paper. As the names imply, **ammeters** are used to measure current levels, and **voltmeters**, the potential difference between two points. If the current levels are usually of the order of milliamperes, the instrument will typically be referred to as a milliammeter, and if the current levels are in the microampere range, as a microammeter. Similar statements can be made for voltage levels. Throughout the industry, voltage levels are measured more frequently than current levels primarily because voltmeters do not require that the network connections be disturbed.

The potential difference between two points can be measured by simply connecting the leads of the meter *across the two points*, as indicated in Fig. 2.21. An up-scale reading is obtained by placing the positive lead of the meter to the point of higher potential of the network and the common or negative lead to the point of lower potential. The reverse connection will result in a negative reading or a below-zero indication.

Ammeters are connected as shown in Fig. 2.22. Since ammeters measure the rate of flow of charge, the meter must be placed in the network so that the charge will flow through the meter. The only way this can be accomplished is to open the path in which the current is to be measured and place the meter between the two resulting terminals. For the configuration of Fig. 2.22, the voltage source lead (+) must be disconnected from the system and the ammeter inserted as shown. An up-scale reading will be obtained if the polarities on the terminals of the ammeter are such that the current of the system enters the positive terminal.

The introduction of any meter into an electrical/electronic system raises a concern about whether the meter will affect the behaviour of

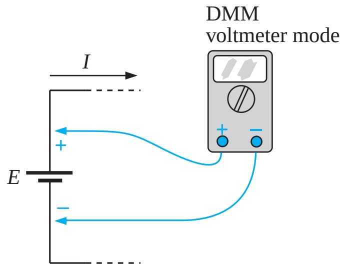


FIG. 2.21
Voltmeter connection for an up-scale (+) reading.

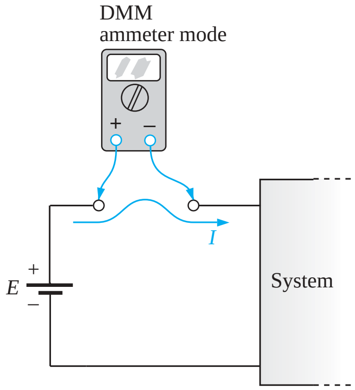


FIG. 2.22
Ammeter connection for an up-scale (+) reading.

the system. This question and others will be examined in Chapters 5 and 6 after additional terms and concepts have been introduced. For the moment, let it be said that since voltmeters and ammeters do not have internal sources, they will affect the network when introduced for measurement purposes. They are both designed, however, so that the impact is minimized.

There are instruments designed to measure just current or just voltage levels. However, the most common laboratory meters include the **volt-ohm-milliammeter** (VOM) of Fig. 2.23, and the **digital multimeter** (DMM) of Fig. 2.24. Both instruments will measure voltage and current and a third quantity, resistance, to be introduced in the next chapter. The VOM uses an analog scale, which requires interpreting the position of a pointer on a continuous scale, while the DMM provides a display of numbers with decimal point accuracy determined by the chosen scale. Comments on the characteristics and use of various meters will be made later in the text.

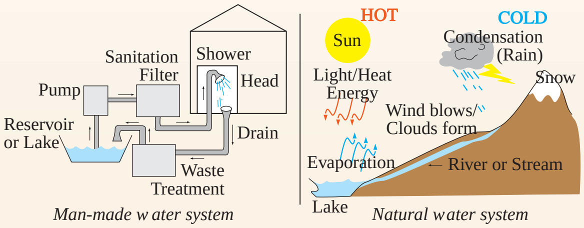
FIG. 2.23
Volt-ohm-milliammeter (VOM) analog meter. (Courtesy of Simpson Electric Co.)

FIG. 2.24
Digital multimeter (DMM). (Courtesy of John Fluke Mfg. Co. Inc.)

Practical Applications

Electric circuits and the water cycle

In circuit analysis we often talk of a closed path, whether we are talking about simple electric circuits such as a flashlight, some complex power system grid, or even a magnetic device such as a relay. People often have difficulty visualizing this concept of a closed path or process. The earth's water cycle is a good example of such a system. It also illustrates the basic properties of electric circuits: *voltage*, *current*, and *resistance*, as well as *kinetic* and *potential* energy. The man-made water systems used in our homes and businesses are also good illustrations of a closed cycle.

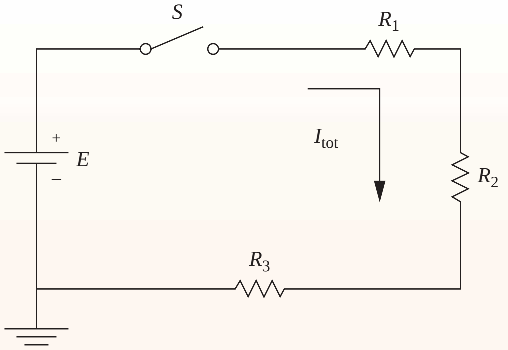


Man-made water system

Natural water system

Rain, which we all see and feel, is just one phase of earth's natural water cycle. This cycle begins with the evaporation of water from rivers, lakes, and oceans, up into the clouds. The *kinetic* energy for this process, and all other processes on earth, comes from the sun. So, when we are enjoying a sunny, warm day, the sun is also providing energy to water storage reservoirs and causing evaporation, which will eventually bring rain. The water that is stored in the clouds is comparable to the potential energy stored in a battery. When the clouds cool, and the water in them condenses sufficiently, this energy will come back to the earth in the form of rain, flowing into the streams and rivers to begin the process all over again. We see the effects of this *potential* energy from the clouds when it is unleashed as *kinetic* energy in floods and torrents.

In our man-made systems, we find elements such as swimming pools and water heaters acting as the reservoirs at the consumption end, with wells, rivers and lakes providing the original *source* of our water. To get the water from the source to the consumer, we must provide energy to pumps to fill our pools and water tanks. This corresponds to the evaporation process in nature. We use pipes to contain the water as it flows along under pressure from the pumps. The pipes present some resistance to the flow of the water, with smaller pipes providing more flow resistance than larger ones. Along the way, the water probably passes through some *filtration* process that removes unwanted components from it, and indeed may add components such as chlorine and fluorine to it for our safety and health.



Closed electric circuit.

The electrical analogy to this water cycle is an *electric circuit*. A source of stored energy (battery or electrical outlet) is connected through conductors (like pipes) to electrical components (maybe a toaster or electric razor) to perform some useful function. This passage of energy finds some opposition (called *resistance*) to its passage. In order that the energy may be converted from its electrical form to some other useful form, such as heat, light or motion, the electric charge that flows to make the *current* must have a closed circuit. If it did not, the process would be like pumping water into a closed container—once it is full, there can be no more flow unless the container bursts and permits the water to flow onto the floor and eventually back to some stream or river.

We can see the current in a river which results from the *flow* of the water; although we cannot see it, there is a flow of charges, which is also called *current*, past a given point in an electric circuit.

In the water system, there can be no flow unless there is some source of pressure or energy; similarly, there can be no electrical current without electrical pressure, called *voltage* or *electromotive force (emf)*. Water flow in a stream meets some resistance in the form of obstacles, and friction from the stream bed and sides. Water flowing in a pipe meets opposition, or resistance, as well. In an electrical circuit, all the components the current encounters present some resistance to this flow of electrical charge.

To get water to a pool or a bathtub, we must turn on a tap. In an electric circuit, we must close a switch to permit the flow of charge. The reservoirs of our cities and towns, our lakes and rivers, and even the oceans would eventually dry up without a closed system to return the water to its source. Similarly, we must have closed paths for our electric charges, or the sources of electrical energy would cease to function. To put it another way, if we send current in one direction, we must get it back in the other—we must have a closed path to have an electric *circuit*.

PROBLEMS

SECTION 2.2 Atoms and Their Structure

1. Calculate the force of repulsion between two adjacent protons in an atomic nucleus, with a distance between their centres of 1.0×10^{-15} m.

2. Find the force of attraction between a proton and an electron separated by a distance equal to the radius of the smallest orbit followed by an electron (5×10^{-11} m) in a hydrogen atom.

3. Plot the force of attraction in newtons between the charges Q_1 and Q_2 in Fig. 2.25 when r =

a. 1 m
b. 5 m
c. 8 m
d. 10 m

(Note how quickly the force drops with an increase in *r*.)

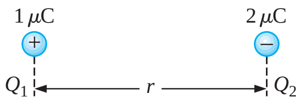


FIG. 2.25
Problem 3.

***4.** Plot the force of repulsion in newtons between Q_1 and Q_2 in Fig. 2.26 when r =

a. 1 m
b. 0.5 m
c. 0.25 m
d. 0.125 m

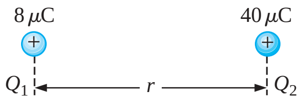


FIG. 2.26
Problem 4.

***5.** Plot the force of attraction (in newtons) versus separation (in metres) for two charges of 2 mC and −4 μC. Set *r* to 0.5 m and 1 m, followed by 1-m intervals to 10 m. Comment on the shape of the curve. Is it linear or nonlinear? What does it tell you about the force of attraction between charges as they are separated? What does it tell you about any function plotted against a squared term in the denominator?

6. Determine the distance between two charges of 30 μC if the force between the two charges is 3.6×10^4 N.

***7.** Two charged bodies, Q_1 and Q_2, when separated by a distance of 2 m, experience a force of repulsion equal to 1.8 N.

a. What will the force of repulsion be when they are 10 m apart?
b. If the ratio $Q_1/Q_2 = 1/2$, find Q_1 and Q_2 ($r = 10$ m).

SECTION 2.3 Current

8. Find the current in amperes if 650 C of charge pass through a wire in 50 s.

9. If 465 C of charge pass through a wire in 2.5 min, find the current in amperes.

10. If a current of 40 A exists for 1 min, how many coulombs of charge have passed through the wire?

11. How many coulombs of charge pass through a lamp in 30 min if the current is constant at 750 mA?

12. If the current in a conductor is constant at 2 A, how much time is required for 4600×10^{-6} C to pass through the conductor?

13. If $21.847 \times 10^{+18}$ electrons pass through a wire in 7 s, find the current.

14. How many electrons pass through a conductor in 30 s if the current is 1 A?

15. Will a fuse rated at 1 A "blow" if 86 C pass through it in 1.0 min?

***16.** If $0.784 \times 10^{+18}$ electrons pass through a wire in 643 ms, find the current.

***17.** Which would you prefer?

a. A penny for every electron that passes through a wire in 0.01 μs at a current of 2mA, or
b. A dollar for every electron that passes through a wire in 1.5 ns if the current is 100 μA.

SECTION 2.4 Voltage

18. What is the voltage between two points if 96 mJ of energy are required to move 50×10^{18} electrons between the two points?

19. If the potential difference between two points is 42 V, how much work is required to bring 6 C from one point to the other?

20. Find the charge *Q* that requires 1205 J of energy to be moved through a potential difference of 25 V.

21. How much charge passes through a battery of 22.5 V if the energy expended is 90 J?

22. If a conductor with a current of 200 mA passing through it converts 40 J of electrical energy into heat in 30 s, what is the potential drop across the conductor?

***23.** Charge is flowing through a conductor at the rate of 420 C/min. If the potential drop across the conductor is 3.53 V, how much energy is converted to heat in 30 s?

SECTION 2.5 dc Supplies

24. Discuss briefly the difference among the three types of dc voltage supplies (batteries, rectification, and generators).

25. Suggest an application where each of the three types of dc supply could be used to advantage.

26. Compare the characteristics of a dc current source with those of a dc voltage source. How are they similar and how are they different?

27. Explain the difference between a primary and a secondary cell.

SECTION 2.6 Conductors and Insulators

28. Discuss the properties of copper that have contributed to its role as a commonly used conductor.

29. Discuss the properties of the atomic structure of gold that make it a good conductor.

30. Name two materials not listed in Table 2.1 that are good conductors of electricity.

31. Explain the terms *insulator* and *breakdown strength.*

32. List three uses of insulators not mentioned in Section 2.6.

SECTION 2.7 Semiconductors

33. What is a semiconductor? How does it compare with a conductor and an insulator?

34. Consult a semiconductor electronics text and note the extensive use of germanium and silicon semiconductor materials. Report the main characteristics of each material.

SECTION 2.8 Ammeters and Voltmeters

35. What are the significant differences in the way ammeters and voltmeters are connected?

36. Explain why a voltmeter must be connected across two points in an electric circuit in order to obtain a correct reading.

37. Explain why an ammeter must be connected across a break in a conductor.

38. If an ammeter reads 2.5 A for a period of 2 min, determine the charge that has passed through the meter.

39. Between two points in an electric circuit, a voltmeter reads 12.5 V for a period of 20 s. If the current measured by an ammeter is 10 A, determine the energy expended and the charge that flowed between the two points.