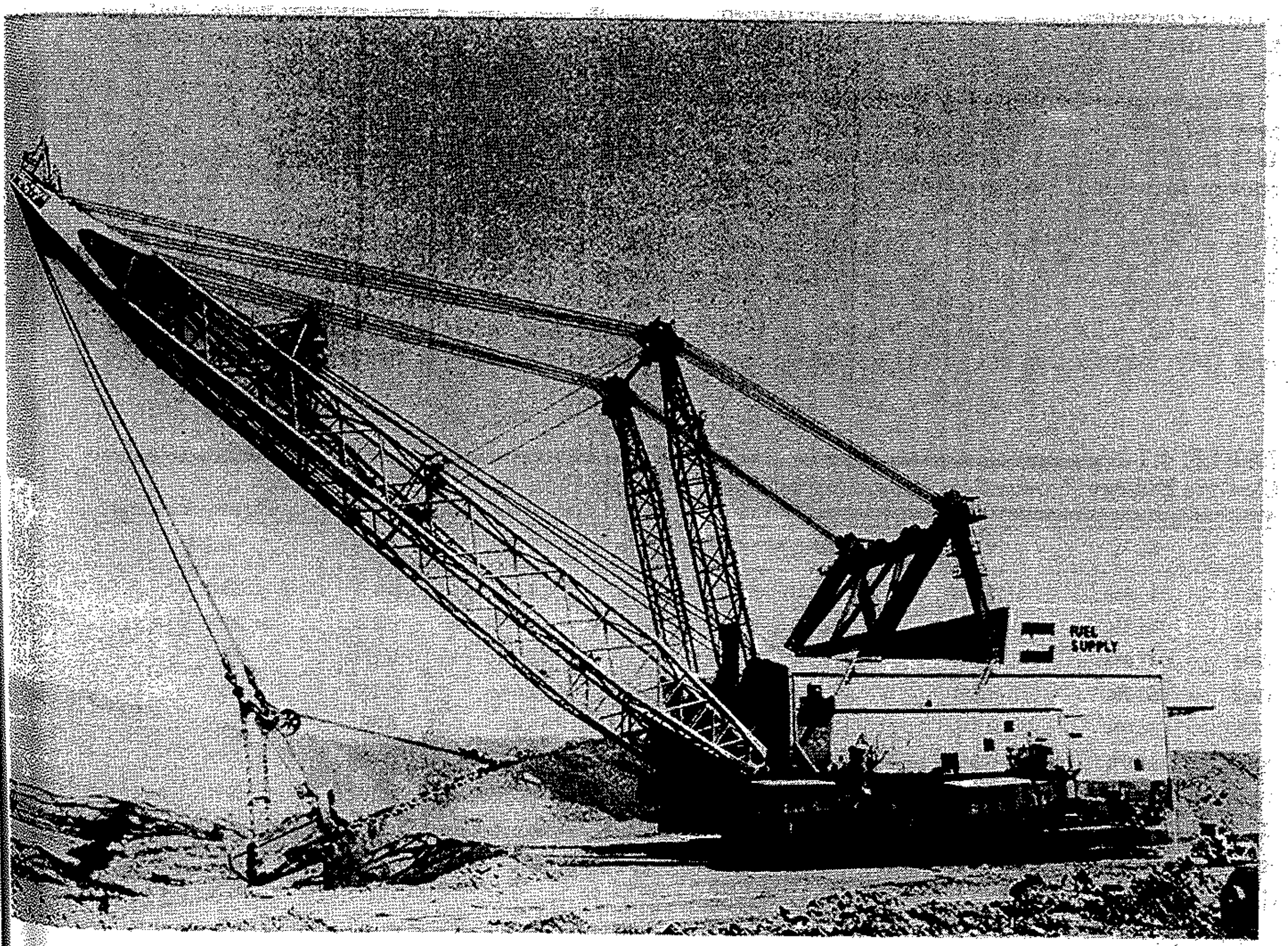
4

Electric Energy

4.1 Motivation

Visitors to Niagara Falls marvel at the sight of water lazily approaching the falls and then plummeting downward under the influence of the gravitational force. Above the falls another impressive event attracts few sightseers. There, water is quietly shuttled into a large pipe under the city of Niagara and thence to water turbines downstream from the falls. The water turbines spin electric generators, and electricity is channeled through wires to consumers. When you watch a river, you sense the motion of water and its kinetic energy. You see nothing in motion and no evidence of energy when you view wires leading from electric generators. Make no mistake, energy is there. Were it not, motors would not function and light bulbs would not light when plugged into electrical outlets. In the electrical wires, submicroscopic electrons move in response to electric forces exerted on them. Electric energy acquired by electrons is converted to a wide variety of other types of energy including heat, light, sound, and motion. The versatility and relative ease of the production and transmission of electric energy makes it a precious commodity.

Input energy to electric power plants accounted for 36% of the gross energy consumption in 1989. About two-thirds of this input energy was lost in the



The magnitude of the appetite of electric power plants for energy is portrayed by the giant shovel "Big Muskie" stripping the overburden from layers of coal. (Photograph courtesy of American Electric Power Service Corporation.)

conversion to electric energy and in the transmission to consumers. This means about three units of energy are converted to deliver one unit of electric energy to a consumer. An important energy conservation message surfaces here: Every unit of electric energy saved by a consumer means that three units of energy need not be converted.

Table 4.1 itemizes electric energy production according to type of energy converted. The decline in the use of petroleum is notable. Electric utilities turned increasingly to clean-burning oil in the early 1970s. As oil became more expensive in the latter part of the 1970s, restrictions were placed on burning oil in newly developed systems. Electric utilities turned to coal and uranium (Table 4.1) as a substitute for oil.

Electric energy generated by hydroelectric power plants remained essentially constant in the period 1973 to 1989. Because the total amount of electric energy increased, the percentage produced by hydroelectric plants declined from 14.6% to 9.5%. Hydroelectric energy has several attractive features, but expansion is hampered by a lack of suitable sites and by environmental restrictions.

Electricity sales grew by about 33% between 1973 and 1989. Distribution of electricity changed very little in this period. The residential, commercial, and industrial sectors purchased 34%, 27%, and 35%, respectively, of the electric energy sold in 1987.

Sometime or other all of us have to purchase light bulbs, as well as many other electrically operated devices, and many of us have to pay for their operation. On a light bulb you can read notations such as 120 volts and 100 watts. On the utility bill you see kilowatt-hours or maybe an abbreviation kWh. In newspapers you may read of electric energy shortages during heavy usage periods on hot summer days. You might also read of an accidental electrocution. The purpose of this chapter is to provide you with an insight into volts, watts, kilowatt-hours, and the generation of electricity so you may become a more informed citizen.

TABLE 4.1
Electric Energy Production According to Type of Energy Converted

	COAL	PETROLEUM	GAS	NUCLEAR	HYDRO	OTHER	TOTAL
1973	45.6%	16.9%	18.3%	4.5%	14.6%	0.1%	1861
1976	46.3%	15.7%	14.5%	9.4%	13.9%	0.2%	2038
1979	47.8%	13.5%	14.7%	11.4%	12.4%	0.2%	2247
1982	53.2%	6.5%	13.6%	12.6%	13.8%	0.2%	2241
1985	56.8%	4.1%	11.8%	15.5%	11.4%	0.4%	2470
1988	56.9%	5.5%	9.4%	19.5%	8.3%	0.4%	2701
1989	55.8%	5.7%	9.5%	19.0%	9.5%	0.4%	2781

Production is expressed as a percentage of the total electric energy produced, which is given in billions of kilowatt-hours. The data are from the Energy Information Administration, United States Department of Energy.

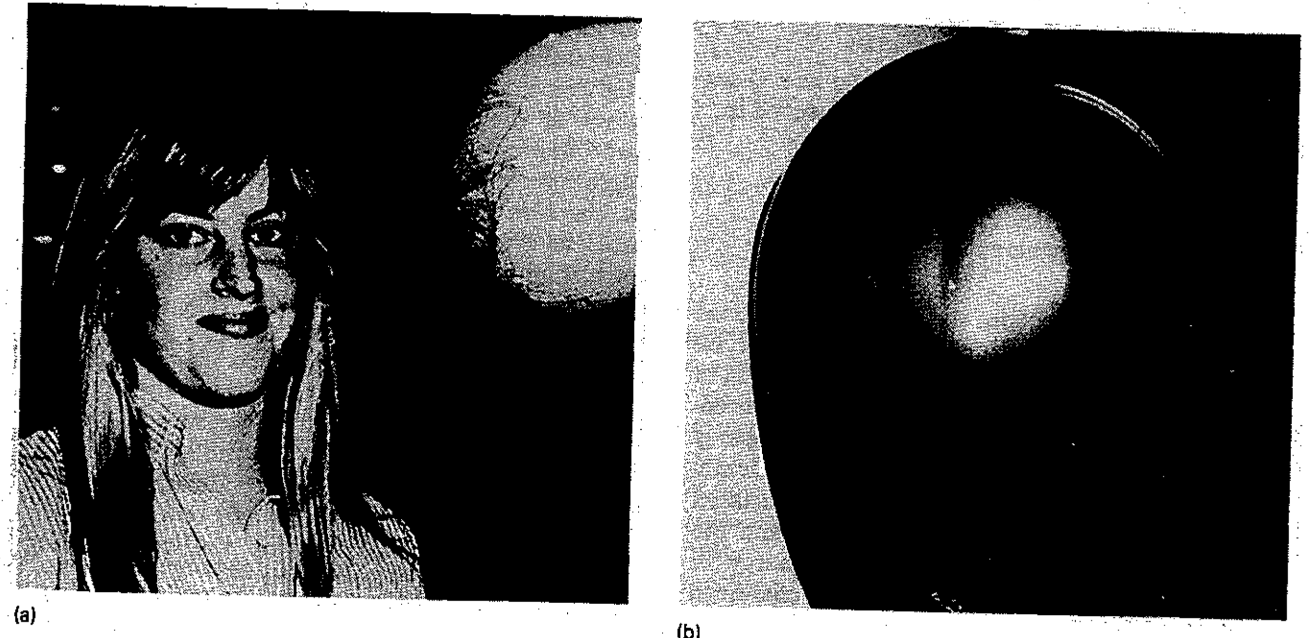
4.2 Electric Force and Electric Charge

If you were to see a child's balloon resting on a floor, you could analyze its motionless condition by saying: The earth pulls downward on the balloon with a gravitational force. Responding to a downward force by the balloon, the floor pushes upward with an equal but oppositely directed force. The net force is zero; therefore the balloon is in equilibrium. You might pick up the balloon, rub it on your hair, touch it to the wall and see the balloon cling peacefully to the wall (Fig. 4.1). Now a different explanation is required. Certainly, the net force on the balloon is zero; otherwise it would fall. The earth still pulls downward with a gravitational force. Something must pull upward with an equal but oppositely directed force. But what? Had you not rubbed the balloon on your hair, the balloon would not adhere to the wall. The upward force must be associated with the rubbing.

This force on the balloon needs investigation, and balloons are our tools. Take two inflated balloons and with threads suspend them an inch or so apart. Unless you rubbed the balloons on something, the threads should be vertical. Rub both balloons on your hair and remove your hands. You see the space between the balloons increase, indicating mutual forces between the balloons. Move your head near the balloons and you see that your hair is not repelled by the balloons but attracted to them. These observations are a consequence of electric forces and the property of electric charge acquired by the balloons and hair.

Electric charge is a property of matter in the same sense that mass is a property of matter. Because of the property of mass, two objects exert mutual gravitational forces. We see the result of gravitational forces when we drop a pencil and it is pulled downward toward the earth. Mutual electric forces are felt by two objects possessing the property of charge. Unlike the gravitational force, which is always attractive, electric forces can be attractive or repulsive. Remember, the balloons attracted the hair, but one balloon repelled the other balloon. If the electric force is attractive we say the charges acquired by the two objects are *unlike*. The charges are *like* when the two objects repel. We distinguish unlike charges from each other by calling one positive and

FIGURE 4.1
(a) This student's hair is attracted to a balloon that was previously rubbed against her hair. **(b)** The balloon filled with helium gas would normally rise rapidly in the air, but after it has been rubbed on a person's hair, it is held fast by electric forces to the wall.



the other negative. The charge on a balloon rubbed on your hair is negative. Any charge repelled by the balloon is negative; any charge attracted is positive.

Mass and charge are properties of matter. Because mass is a measure of the quantity of matter, it is easy to relate to it. Charge is a much more subtle property because we cannot see charge; we see only the effects produced by charge, namely electric forces. Some analogies may help in trying to obtain a feeling for charge.

The mass of an object is normally measured with something like a pan balance (Fig. 2.2). In principle mass could be determined using the law of gravitation (Eq. 2.5) and measuring the gravitational force between two objects separated a known distance. There is no "pan balance" to measure charge, but charge can be measured by determining the electric force between two charged objects separated a known distance. Augustin de Coulomb in 1784 discovered that the force between two charges labeled q and Q and separated a distance r obeys a law identical in form to the law of gravitation.

$$F = k\frac{qQ}{r^2} \tag{4.1}$$

In the metric system of units charges q and Q are measured in coulombs, symbol C, r is measured in meters, and the constant k has the value

$$k = 8.99 \times 10^9\ \frac{\text{newton meter}^2}{\text{coulomb}^2}.$$

In the same manner that mass could be measured using the law of gravitation, charge could be measured using Coulomb's law. It is not essential to our discussions to dwell on how charge is measured. It is important to remember that charge is a property of matter and that the unit of charge is the coulomb. Electric charge, electric force, and energy associated with the electric force play roles ranging from the structure of atoms to the liberation of energy in either a nuclear electric power plant or a coal-fired electric power plant.

4.3 Atomic Structure

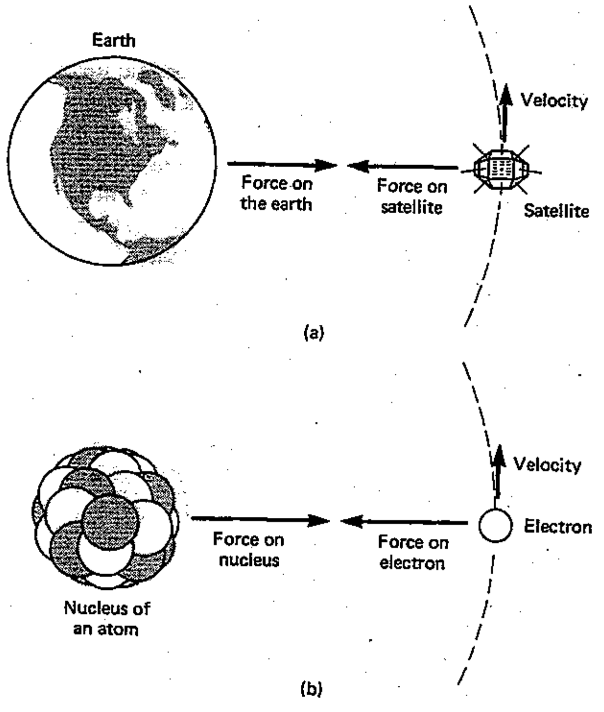
An atom is the basic structural component of matter. Accordingly, the property of charge exhibited by a balloon, for example, has its roots in atoms. To see this we need an atomic model. Our model, like any model, has limits but it is appropriate for our discussions. For now we want only to understand electricity. As we delve into chemical and nuclear reactions we will refine the model.

Visualize an ice skater moving smoothly in a nice, neat circle. Attached to the skater's waist is a rope, the other end of which is held by a person at the center of the circle. If the skater attempts to skate in a larger circle, she is pulled inward and confined to move in a circle that has a radius equal to the length of the rope. The language of physics describes this condition as *bound*. The skater is bound to the circular path by a binding force provided by the rope pulling on her waist. Bound systems, similar in principle, are common and very important.

An orbiting satellite and the earth constitute a bound system held together by the gravitational force between the two (Fig. 4.2). At any instant, the satellite tends to shoot off in a straight line, but gravity continually pulls the satellite toward the earth and the satellite executes circular motion about the earth. An elementary model of an atom incorporates features of the earth-satellite system. Electrons are satellites and a nucleus acts like the earth (Fig. 4.2b). An electron has a mass of 9.11×10^{-31} kilograms and a negative charge of -1.60×10^{-19} coulombs. A nucleus is positively charged and is much more massive than an electron. The mass of the nucleus is confined to a volume approximating a sphere of radius of about 1×10^{-15} meters. The closest electron is about 1×10^{-10} meters. In perspective, if the radius of the nucleus were about the thickness of a dime, the nearest electron would be about the length of a football field away. Having both mass and electric charge, electrons and a nucleus experience both attractive gravitational and electric forces that tend to bind the electrons to the nucleus. However, the overwhelming binding is due to the electric force.

FIGURE 4.2

(**a**) An orbiting satellite and the earth. The earth and the satellite are bound together by a gravitational force. The force of gravity continually pulls inward on the satellite and keeps the satellite progressing in a circular orbit. (**b**) A nucleus and an electron. The nucleus and electron are bound together by an electric force. The electric force continually pulls inward on the electron and keeps the electron progressing in a circular orbit.



In a normal atom the total negative charge of the electrons balances the positive charge of the nucleus and the atom is said to be electrically neutral. The number of electrons in a neutral atom is called the *atomic number*. The atomic number distinguishes different atomic species. For example, a carbon atom has 6 electrons and an oxygen atom has 8 electrons. Most electrical wires in homes are made of copper. Each atom of copper has 29 electrons. As the atomic number increases, the mass of the atom also increases. This results from the additional electrons and by an increase in the mass of the nucleus. It is possible to have atoms with the same number of electrons, but with nuclei of different masses. These are called *isotopes*. Later we will see the origin of the mass differences. Because isotopes have the same number of electrons, they share the same chemical characteristics. Table 4.2 lists the first 18 atoms in the order of increasing atomic number. The approximate relative mass corresponds to the most abundant isotope of a given atom.

Let's now use this atomic model to interpret the experiment with the balloons. The rubbing process initiated a transfer of electrons from the hair to the balloons. The balloons acquire electrons and become negatively charged; the hair loses electrons and is left

TABLE 4.2
The First 18 Atoms in Order of Increasing Atomic Number and Mass

ATOM	CHEMICAL SYMBOL	ATOMIC NUMBER	APPROXIMATE RELATIVE MASS
Hydrogen	H	1	1
Helium	He	2	4
Lithium	Li	3	7
Beryllium	Be	4	9
Boron	B	5	11
Carbon	C	6	12
Nitrogen	N	7	14
Oxygen	O	8	16
Fluorine	F	9	19
Neon	Ne	10	20
Sodium	Na	11	23
Magnesium	Mg	12	24
Aluminum	Al	13	27
Silicon	Si	14	28
Phosphorus	P	15	31
Sulfur	S	16	32
Chlorine	Cl	17	35
Argon	Ar	18	40

The mass is that of the most abundant isotope and is based on a scale of exactly 12 for the most abundant form of carbon.

with a deficiency of negative charge and, therefore, an excess of positive charge. The balloons repel each other because they both have a net negative charge.

4.4 Electricity

A current is defined as "a steady and smooth onward movement, as of water." A steady movement of cars on a highway would be a car current. The rate at which cars pass a point on the highway is a measure of the car current. To determine the car current you would count the cars, measure the time for the cars to pass, and divide the number by the time to obtain the rate in units like cars per minute. If each car had two passengers, then multiplying the car rate by two yields a passenger current measured in passengers per minute.

An electric current is a flow of electric charges. In wires and appliances the flow is due to electrons because they are much freer than the positive charges in the nucleus. Electrons moving through a wire are analogous to cars moving on a highway. You can't see the electrons but in principle you can stand at the edge of the wire and count the electrons passing by in a measured time interval, and express the rate in units of electrons per second. Multiplying the electron rate by the charge per electron yields the rate at which charge flows in units of coulombs per second. As an equation,

$$\text{electric current} = \frac{\text{coulombs of charge flowing through a wire}}{\text{time required for the flow}}.$$

$$I = \frac{Q}{t}. \qquad (4.2)$$

Recording charge (Q) in coulombs and the time interval (t) in seconds yields coulombs per second as the units of electric current (I). A coulomb per second is called an *ampere*, symbol A. If 100 coulombs of charge flow by a position in a wire in 10 seconds, we say the current is 10 amperes. The electric current in a lit flashlight bulb is about one ampere. If the bulb were on for 10 minutes the total charge passing through the bulb in 10 minutes is

$$1\,\frac{\text{coulomb}}{\text{second}} \times 10 \text{ minutes} \times 60\,\frac{\text{seconds}}{\text{minute}} = 600 \text{ coulombs}.$$

A force must be exerted on the electrons to cause them to flow through a wire, just as a force must be applied on water to keep it moving through a pipe. The electric force has its origin in the force between electric charges. Electrons pulled toward a positive charge create an electric current. Electric forces do work on the electrons, just as work is done on an automobile pushed some distance by a person. It is the role of a battery or an electric generator in an electric power plant to supply electrical "pressure" for moving electrons. This electrical "pressure" is called a *potential difference*.* A potential difference is analogous to a water pressure difference for moving water through a pipe. Potential difference is defined in terms of the amount of work done by electric forces on a charge as it moves between two positions. As an equation,

$$\text{potential difference} = \frac{\text{electrical work on the amount of charge moved}}{\text{amount of charge}},$$

$$V = \frac{W}{Q}. \qquad (4.3)$$

Work (W) is measured in joules and charge (Q) is measured in coulombs, making potential difference (V) joules per coulomb. A joule per coulomb is called a *volt*, symbol V. If 100 joules of work are done by electric forces on 1 coulomb of charge when it moves between two positions, the potential difference between the two positions is 100 volts. Batteries for most automobiles provide a 12-volt potential difference between 2 terminals. If 2 coulombs of charge flow between the terminals, electric forces do 24 joules of work on the two coulombs of charge.

The idea of potential difference is very abstract. You never see the charges, let alone what is exerting the electric forces. However, you can employ the same idea for the gravitational force. When you lift a box from the floor to a table top, gravity does work on the box. Divide the work by the mass of the box and you have a gravitational potential difference between the floor and table top.

Be sure you understand the notion of a difference in potential. An everyday analogy may help. If you were to tell a friend a building is 500 feet high, he would probably assume you mean the difference in "height" between the top and bottom is 500 feet. Clearly, though, if the building were on top of a mountain, its height would be more than 500 feet relative to the base of the mountain. Potential differences, like heights, are also relative. The potential difference between the terminals in a household electrical outlet is 115 volts. This means that one of the contacts is 115 volts relative to the other contact. This other contact in a household outlet is at the same potential as any other part of the room, including yourself. You can touch this contact and not get an electrical shock because there is no potential difference between you and that contact. This contact is called a *ground* because it is fastened to a metal stake driven into the ground (earth). Generally you can see this ground wire running down an electric utility pole holding wires bringing electricity to a house. The other contact in an outlet is referred to as "hot." Electrical shocks occur when you touch both the ground and the "hot" contact.

Any electrical appliance has two electrical connections. To operate the appliance, an appropriate potential difference must be connected to these two connections. If you were to connect two wires to a flashlight bulb and then touch the other ends of the wires to a flashlight battery, the bulb would light. The lit condition signals a complete electrical circuit. It is complete in the sense that a complete (or closed) path is provided for the flow of electrons. If you were to take a pair of scissors and cut one wire, the circuit is broken and the light no longer glows. A switch is a device that allows you to open and close electrical circuits. A switch is analogous to a faucet that can be opened or closed to control the flow of water. An example of a water circuit is shown in Fig. 4.3. A pump pulls water from the bottom of a container, forces it through a valve, past a water wheel, and back into the container. In a household electrical circuit,

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* We use the term *potential difference* initially to stress the involvement of two positions. Voltage, a less formal word describing the same idea, replaces potential difference as we proceed.

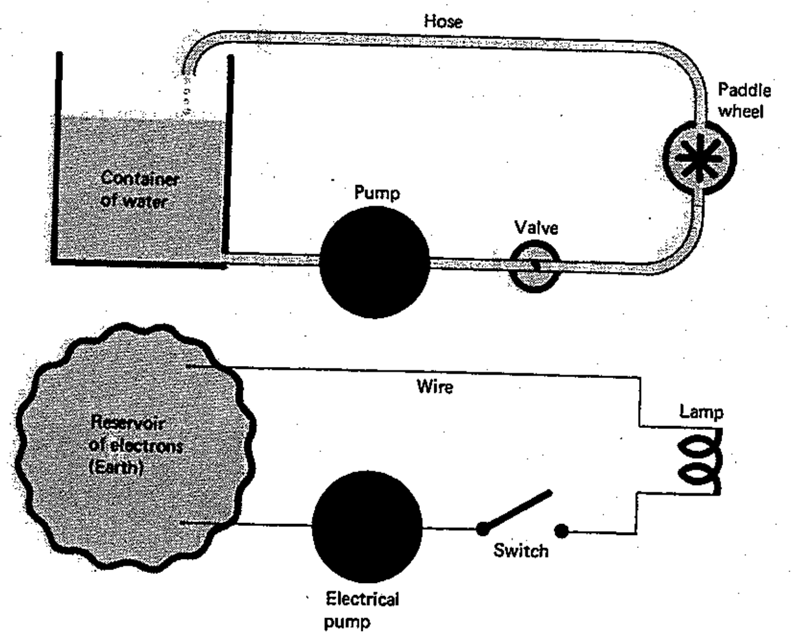


FIGURE 4.3

Schematic comparison of a fluid circuit and an electrical circuit. The water pump forces water to circulate through the water circuit. The electrical pump, a battery or generator, forces electrons to circulate through the electrical circuit. The sum total of electric charges never changes in the process, just as in the absence of leaks the sum total of water never changes in the water circuit.

an electric generator provided by an electric utility pulls electrons from the ground, forces them through a switch, through a light bulb, and back into the ground. The wire plays the role of a water pipe. The demonstration depicted in Fig. 4.4 illustrates the role of the ground connection in a household electrical circuit.

4.5 Electrical Resistance

Electrons migrate through a network of atoms as they move through a wire. This network impedes the flow, and we say the wire has *electrical resistance.* This resistance depends on the composition of the wire. For example, an aluminum wire having the same length and diameter as a copper wire offers more resistance than the copper wire. The resistance also depends on the dimensions of the wire. The longer the wire, the more the resistance; the larger the diameter, the smaller the resistance,

A current is produced in a wire when the ends of the wire are connected to a potential difference. We should expect the current to increase if the potential difference (the electrical "pressure") increases. If the resistance increases, the current should decrease. We model this reasoning in an equation by writing

$$\text{current} = \frac{\text{potential difference}}{\text{resistance}}$$

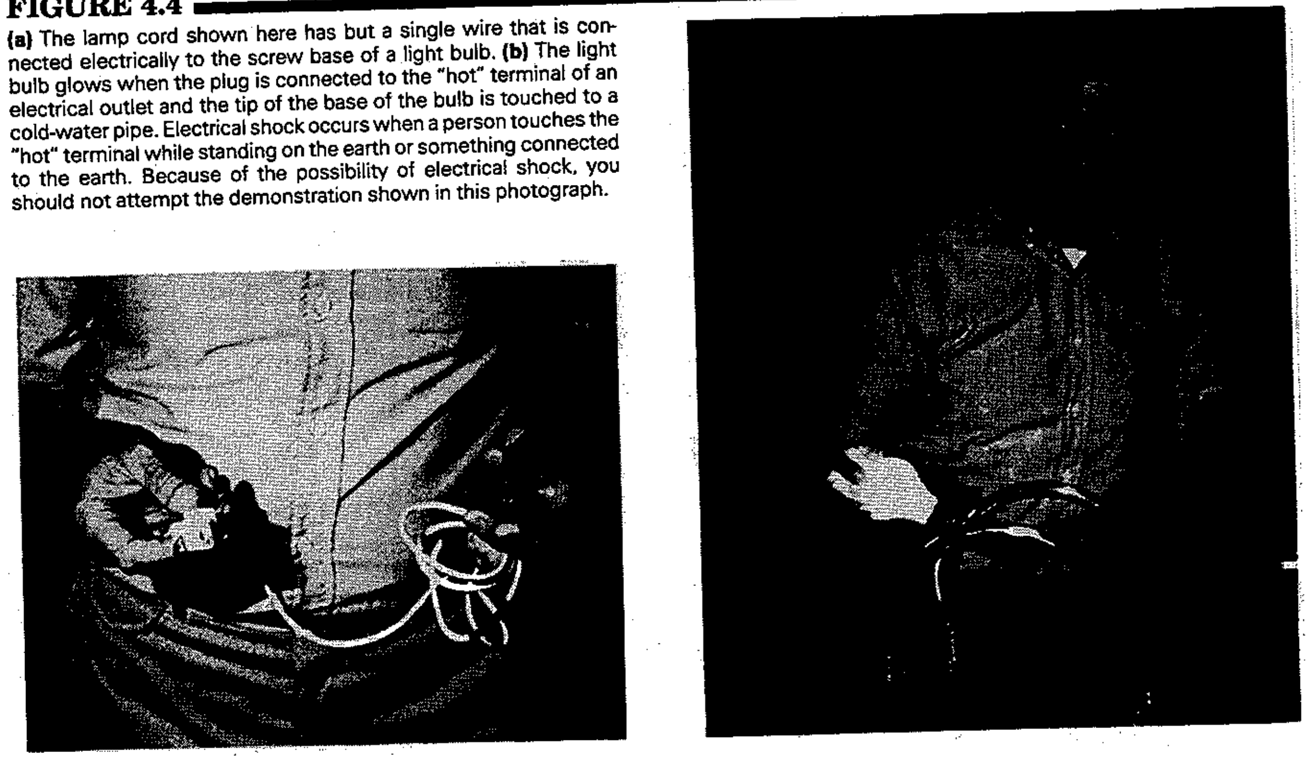
$$I = \frac{V}{R}. \tag{4.4}$$

Resistance has units of volts divided by amperes. This unit is called an *ohm.* If 1.5 amperes are produced in a bulb connected to a 12-volt battery, the resistance of the bulb is

$$R = \frac{V}{I} = \frac{12 \text{ volts}}{1.5 \text{ amperes}} = 8 \text{ ohms}.$$

FIGURE 4.4

(a) The lamp cord shown here has but a single wire that is connected electrically to the screw base of a light bulb. **(b)** The light bulb glows when the plug is connected to the "hot" terminal of an electrical outlet and the tip of the base of the bulb is touched to a cold-water pipe. Electrical shock occurs when a person touches the "hot" terminal while standing on the earth or something connected to the earth. Because of the possibility of electrical shock, you should not attempt the demonstration shown in this photograph.



(a)

(b)

The resistance need not be constant. Doubling the potential difference across the bulb may produce a current of 4 amperes, which produces a resistance of 6 ohms. If the resistance does not depend on the potential difference, we say the device obeys Ohm's law. Wires used for electrical conductors and heating elements in toasters and irons obey Ohm's law. Transistors doing impressive things in computers do not obey Ohm's law.

In a household where the potential difference is fixed at 115 volts, the current in an appliance depends on its resistance. As the resistance decreases, the current increases. The energy used to overcome this electrical resistance appears as heat. For example, the heat liberated in a toaster is produced by electrons overcoming the electrical resistance provided by the wire elements of the toaster.

4.6 Electric Power and Electric Energy

Like water accelerated over a dam by a gravitational force, electrons accelerated by an electric force acquire kinetic energy as a result of work done on them. This is an electrical example of the work-energy principle (Section 2.8). Electrons convert this energy in a variety of ways. In a lamp the energy is converted to heat and light. In an electric motor, the energy is converted to mechanical rotational energy. The rate at which moving charges convert energy is called *electric power.*

$$\text{power} = \frac{\text{energy converted in joules}}{\text{time required in seconds}}$$

$$P = \frac{W}{t}. \tag{4.5}$$

Electric power is expressed in joules per second, or watts (see Section 2.11). Electric clothes dryers use electric power in the range of a few thousands of watts; electric power plants produce power in the range of hundreds of millions of watts. Thousands of watts and millions of watts are usually expressed as kilowatts and megawatts, symbolized kW and MW.

A useful relation for electric power follows from combining the equation for definition of power, $P = W/t$, and the definition of potential difference, $V = W/Q$. Substituting for W in $P = W/t$, we have $P = VQ/t$. Recognizing that Q/t is current I, we find $P = VI$. Power equals voltage times current is a general relationship for any electrical device. For a resistance we can use $V = IR$ to arrive at $P = I^2R$ and $P = V^2/R$.

At this point you should understand that if a wire is connected to a potential difference provided by a battery or a household electrical outlet, a current is established in the wire. There are four quantities of interest—voltage, current, and resistance related through $V = IR$, and power related to voltage and current by $P = VI$. Two of these four quantities need to be known to determine the other two. Table 4.3 summarizes the use of these equations.

To illustrate the use of Table 4.3, suppose a kitchen toaster requiring 1000 watts is connected to a 115-volt outlet for 2 minutes. Line 4 in the table guides us for this situation. The current produced is

$$I = \frac{P}{V} = \frac{1000 \text{ watts}}{115 \text{ volts}} = 8.7 \text{ amperes}.$$

TABLE 4.3
Utility of the Equations $V = IR$ and $P = VI$

WHEN THE QUANTITIES IN THIS COLUMN ARE KNOWN,	THEN USE THESE EQUATIONS
current, I resistance, R	$V = IR$ and $P = I^2R$
voltage, V resistance, R	$I = \frac{V}{R}$ and $P = \frac{V^2}{R}$
voltage, V current, I	$R = \frac{V}{I}$ and $P = VI$
voltage, V power, P	$I = \frac{P}{V}$ and $V = IR$

The resistance of the toaster is

$$R = \frac{V}{I} = \frac{115 \text{ volts}}{8.7 \text{ amperes}} = 13.2 \text{ ohms}.$$

The energy converted in kilowatt-hours is

$$E = 1 \text{ kilowatt} \times 2 \text{ minutes} \times 1 \frac{\text{hour}}{60 \text{ minutes}}$$

$$= 0.033 \text{ kilowatt-hour}$$

$$= 0.033 \text{ kWh}.$$

Companies that provide the voltage for forcing electrons through our appliances are often referred to as power companies. It is tempting to expect that they are paid for power. They are not. They are paid for energy. Perhaps this is not obvious but a little thought should convince you.

Power is the rate of converting energy. A 100-watt light bulb requires energy at a rate of 100 joules per second regardless of how long it is turned on. However, the cost of operation depends on how long the bulb is lit. Using Eq. 4.5 it follows that energy, power, and time are related by

$$\text{energy} = \text{power} \times \text{time},$$

$$W = Pt.$$

So any unit of power multiplied by a unit of time yields a unit of energy. Watts (or kilowatts) and hours are units of power and time. The watt-hour (or kilowatt-hour) is a unit of energy. It is a little peculiar because the units of time (hours) do not cancel the time units of seconds in power.

$$W = P \text{ (watts)} \times t \text{ (hours)}$$

$$= P \frac{\text{joules}}{\text{second}} \times t \text{ (hours)}.$$

Note carefully that the units of hours do not cancel the units of seconds.

Table 4.4 lists the power requirements for several household appliances. Note that those involving the generation or removal of heat require the most power. These devices tend to have low resistance.

The energy consumed by a 1100-watt (1.1 kilowatt) toaster for 1 hour would be

$$E = 1.1 \text{ kilowatts} \times 1 \text{ hour} = 1.1 \text{ kWh}.$$

In 1987 residential consumers paid an average of 7.8 cents per kWh for electric energy. At the average price the cost of operating the toaster for one hour would be

$$\text{Cost} = 1.1 \text{ kWh} \times 7.8 \frac{\text{cents}}{\text{kWh}} = 8.6 \text{ cents}.$$

TABLE 4.4
Power Requirements (in watts) of Some Common Household Appliances

APPLIANCE	POWER (watts)
Cooking range (full operation)	12,000
Heat pump	12,000
Clothes dryer	5,000
Oven	3,200
Water heater	2,500
Air conditioner (window)	1,600
Microwave oven	1,500
Broiler	1,400
Hot plate	1,250
Frying pan	1,200
Toaster	1,100
Hand iron	1,000
Electric space heater	1,000
Hair dryer	1,000
Clothes washer	500
Televison (color)	330
Food mixer	130
Hi-fi stereo	100
Radio	70
Razor	14
Toothbrush	7
Clock	2

4.7 Electrical Shock

A train approaching a crossing of the track with a highway actuates a switch that causes a gate to block cars from crossing the track. An electrical signal has triggered a mechanical operation. Analogous operations occur in the human body. A visual signal stimulates electric currents that travel to the brain, where electrical signals are transmitted to an arm, which causes the arm to flex. Respiration, muscular activity, and beating of the heart are all controlled electrically. Both an electrically operated train warning system and the human electrical system can be damaged by excessive electric currents. For the human system the most susceptible parts are the brain, the heart, and the chest muscles and nerves that control respiration.

A current is produced in the body whenever a voltage appears between two parts of the body. The size of the current depends on the voltage and resistance between the two points. When the skin is dry the resistance is appreciable, around 100,000 ohms. But if the skin is moist the resistance may drop to around 1000 ohms. One thousand ohms connected to the common household voltage of 115 volts produces a current of about 0.1 ampere. One-tenth of an ampere is small compared to the current in a desk lamp. But one-tenth of an ampere in a human heart would likely produce uncontrolled stimulation of the heart muscles, resulting in no blood being pumped. This effect, called *ventricular fibrillation*, persists even after the electric current is removed. Ventricular fibrillation seldom stops of its own accord. It takes only a couple of minutes for ventricular fibrillation to weaken the heart muscles to the point where the normal operation of the heart cannot be restored and death results. Interestingly, one method of defibrillating the heart is to pass a large current of about 10 amperes through the heart for a few thousandths of a second.

Irregular breathing and respiratory paralysis may result from electric currents in the body in the range of 0.02 to 0.1 amperes. Respiratory paralysis is usually treated by artificial respiration. Electric currents of a few thousandths of an ampere in the hand will cause the finger and hand muscles to contract. If the source of the voltage is in the palm or fingertips, the hand clamps onto the source and the victim cannot let go. If for some reason a person must touch a wire to see if it is "hot," this should be done with the back of the hand. Then, when the muscles contract, the fingers pull away from the source rather than toward it. Lest you take offense at this morbid discussion, realize that about 2000 people are electrocuted each year in the United States.

4.8 Magnetic Force and Magnetism

We have discussed electric current and the idea that an electrical "pressure" is required to establish current. Nothing has been said about how the power company generates the pressure, or how it is transmitted to homes and factories. To understand this important aspect of producing electricity we must grasp some fundamentals of magnetic force and magnetism.

Magnets are as useful as they are fascinating. They hold notes on the kitchen refrigerator. Homeowners use magnets to hold quilted window insulation in place. For centuries navigators have relied on magnetic compasses to find their way. Materials containing iron are attracted to magnets. A magnet is attracted to a refrigerator door because the door has some iron content. Most metal paper clips contain iron and are attracted to a magnet. Either end of a magnet such as in a compass will attract a paper clip. But there is a relatively broad region between the ends that will not attract a paper clip. The magnetic properties of a magnet are concentrated near the ends. Years ago these regions were labelled as *poles*. The earth possesses magnetic poles located near the north and south geographic poles. If a pole of a magnet is placed near the poles of another magnet it will be attracted to one pole and repelled by the other pole (Fig. 4.5). We describe the fundamental difference between the two poles by calling one N and the other S. An N pole is the pole of a freely suspended magnet, such as a compass, that points toward the geographic north pole. The tip labeled N on a compass needle is an N magnetic pole. Any other