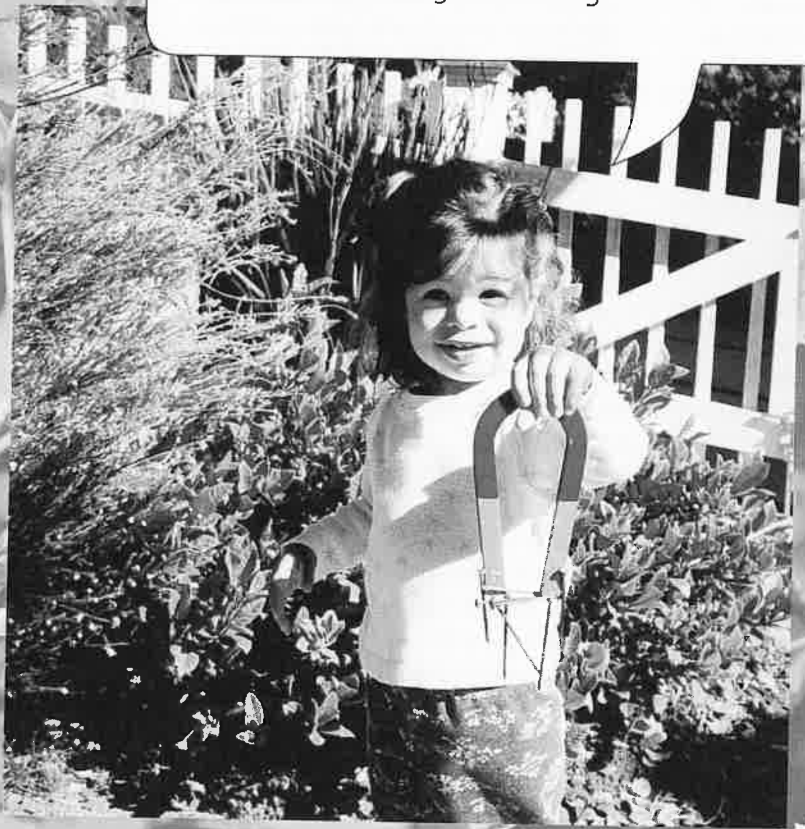
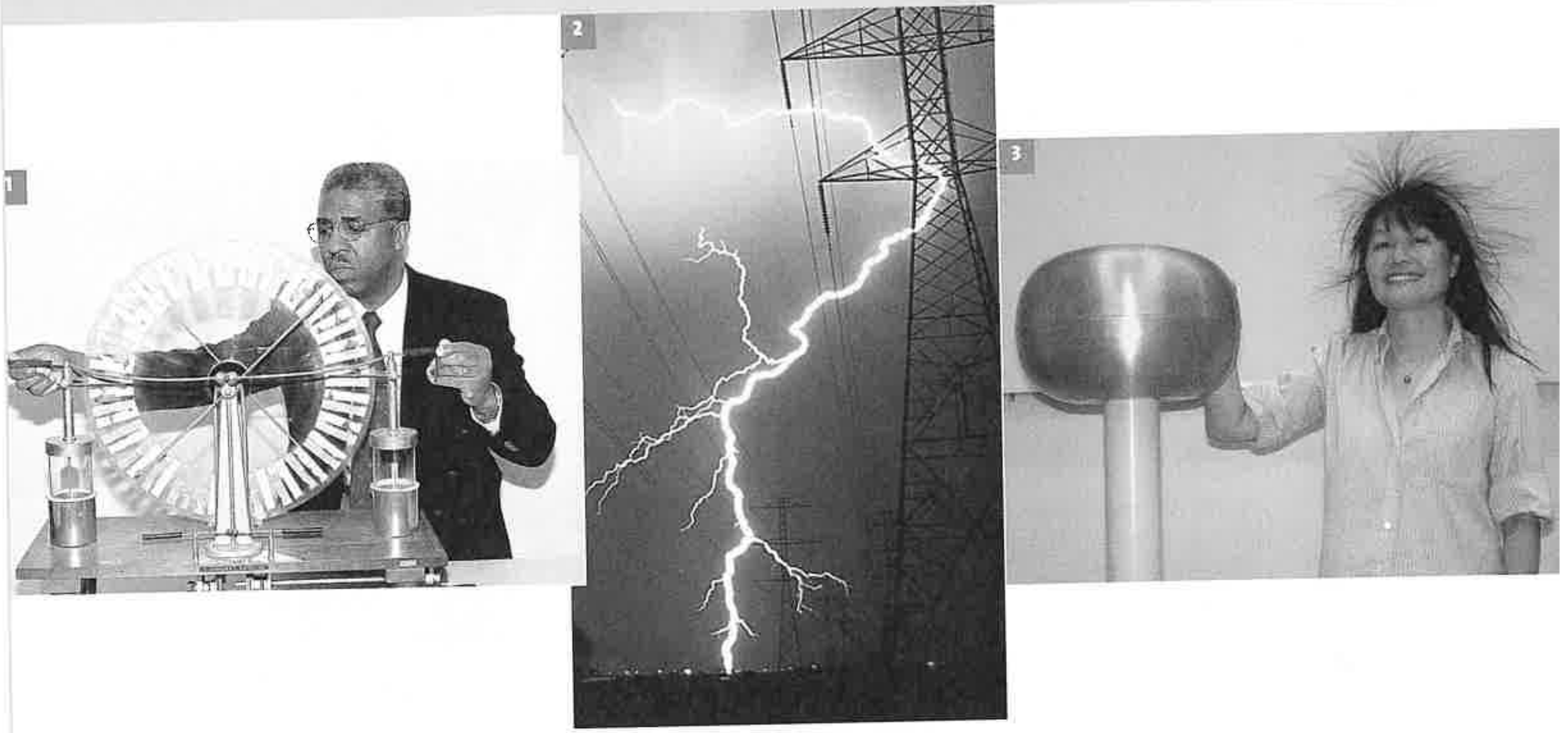
Part Five

Electricity and Magnetism

How intriguing that this magnet outpulls the whole world when it lifts these nails. The pull between the nails and the Earth I call a **gravitational force,** and the pull between the nails and the magnet I call a **magnetic force.** I can name these forces, but I don't yet understand them. My learning begins by realizing there's a big difference in knowing the names of things and really understanding those things.



22 Electrostatics



1 Jim Stith, former president of the American Association of Physics Teachers, demonstrates a Whimshurst generator that produces miniature lighting strokes. 2 Nature produces larger and more energetic ones. 3 Lillian, with her hand on a charged Van de Graaff generator, is charged to a high voltage as evidenced by the electrostatic repulsion of strands of her hair.

It's reasonable to say that if Benjamin Franklin had not been born, the birth of the American Revolution would have turned out differently. This is because Franklin, in addition to his contributions to the Declaration of Independence, influenced the French to position a fleet of warships near the American coast to prevent the British from reinforcing General Cornwallis, whom George Washington defeated in a defining battle of the war. Franklin's clout in Europe stemmed from the high level of respect he earned as America's leading diplomat and scientist. Wherever he went in France, admiring crowds formed.

Franklin was a man for all seasons. His accomplishments as printer, publisher, balladeer, inventor, philosopher, politician, soldier, firefighter, ambassador, cartoonist, and antislavery agitator were all parts of his commitment to public service. A very important part of his legacy has to do with his scientific accomplishments.

Although he is popularly remembered for his invention of the lightning rod, he also invented the glass harmonica, the Franklin stove, bifocal glasses, and the flexible urinary catheter. He never patented his inventions, stating in his autobiography, ". . . as we enjoy great advantages from the inventions of others, we should be glad of an opportunity to serve others by any invention of ours; and this we should do freely and generously." He is especially remembered for his investigations of electricity.

At a time when electricity was thought of as two types of fluid, called vitreous and resinous, Franklin proposed that electric current was of one electrical fluid under different pressures. He was the first to label these pressures as positive and negative, respectively, and he was the first to discover the principle of conservation of charge. The story of his lightning rod began with a publication in 1750. He proposed an experiment to prove that lightning is electricity by flying a kite in a storm, at a stage before it became a lightning storm. Legend has it that with a kite he successfully extracted sparks from a cloud. What he did not do was fly his kite in the midst of a lightning storm, which others unfortunately did and were electrocuted. Instead, the collection of electrical charge on Franklin's kite string proved to him that lightning was electrical.

His lightning rod came about by his experiments showing that metals with a sharp point could collect or discharge electricity silently, preventing charge buildup on buildings when charged clouds were overhead. On the roof of his home he installed rods of iron, with sharp tips, with a wire running from the foot of the rods to the ground below. His hypothesis was that the rods would draw 'electrical fire' silently from the clouds before it struck as lightning. Satisfied that lightning was prevented, he encouraged the installation of lightning rods on the Academy of Philadelphia (later the University of Pennsylvania) and the Pennsylvania State House (later Independence Hall) in 1752.

In recognition of his achievements with electricity, Franklin received the British Royal Society's Copley Medal in 1753, and in 1756 he became one of the few Americans to be elected as a Fellow of the Royal Society. With this reputation he was in a position to affect the outcome of the forthcoming War of Independence in America.

Benjamin Franklin truly reshaped the world.

Electricity

Electricity is the name given to a wide range of electrical phenomena that, in one form or another, underlie just about everything around us. It's in the lightning from the sky, it's in the spark when we strike a match, and it's what holds atoms together to form molecules. The control of electricity is evident in technological devices of many kinds, from lamps to computers. In this chapter, we will investigate electricity at rest, static electricity, or simply **electrostatics.**

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Electrostatics

Electrostatics involves electric charges, the forces between them, the aura that surrounds them, and their behavior in materials. In Chapter 23, we'll investigate the motion of electric charges, or *electric currents*. We'll also study the voltages that produce currents and how they can be controlled. In Chapter 24, we'll study the relationship of electric currents to magnetism, and, in Chapter 25, we'll learn how magnetism and electricity can be controlled to operate electrical devices and how electricity and magnetism connect to become light.

An understanding of electricity requires a step-by-step approach, for one concept is the foundation on which the next concept is based. So please put in extra attention in studying this material. It can be difficult, confusing, and frustrating if you're hasty; but, with careful effort, it can be comprehensible and rewarding. Onward!

Electrical Forces

What if there were a universal force that, like gravity, varies inversely as the square of the distance but is billions upon billions of times stronger? If there were such a force and if it were attractive like gravity, the universe would be pulled together into a tight ball, with all matter pulled as close together as it could get. But suppose this force were a repelling force, with every bit of matter repelling every other bit. What then? Then the universe would blow itself apart in short order. Suppose, however, that the universe consisted of two kinds of particles—positives and negatives, say. Suppose that positives repelled positives but attracted negatives and that negatives repelled negatives but attracted positives. In other words, like kinds repel and unlike kinds attract (Figure 22.1). Suppose that there were equal numbers of each so that this strong force were perfectly balanced! What would the universe

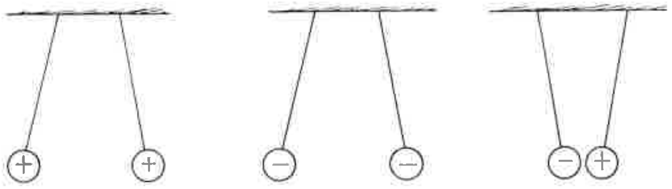

FIGURE 22.1

INTERACTIVE FIGURE

Like charges repel. Unlike charges attract.

be like? The answer is simple: It would be like the one we are living in. For there are such particles, and there is such a force. We call it the *electric force.*

Inside every piece of matter are atoms. And what is inside every atom? Positive and negative charges held together by the enormous attraction of electric force. By forming compact and evenly mixed clusters of positives and negatives, the huge electric forces have balanced themselves out almost perfectly. When two or more atoms join to form a molecule, the molecule also contains balanced positives and negatives. And when trillions of molecules combine to form a speck of matter, the electrical forces balance again. Between two pieces of ordinary matter, there is scarcely any electrical attraction or repulsion at all, because each piece contains equal numbers of positives and negatives. Between Earth and the Moon, for example, there is no electrical force. The much weaker gravitational force, which only attracts, remains as the predominant force between these bodies.

Electric Charges

The terms *positive* and *negative* refer to electric *charge,* the fundamental quantity that underlies all electrical phenomena. The positively charged particles in ordinary matter are protons, and the negatively charged particles are electrons. Protons and electrons, with neutral particles called neutrons, make up the atom. When two atoms get close together, the balance of attractive and repelling forces is not perfect, because electrons whiz around within the volume of each atom. The atoms may then attract each other and form a molecule. In fact, all the chemical bonding forces that hold atoms together to form molecules are electrical in nature. Anyone planning to study chemistry should first know something about electrical attraction and repulsion and, before studying electrical phenomena, should know something about atoms. Recall from Chapter 11 some important facts about atoms:

Which charges are called positive and which are called negative is the result of a choice made by Benjamin Franklin. It could have been the other way around.

1. Every atom is composed of a positively charged *nucleus* surrounded by negatively charged electrons.
2. The electrons of all atoms are identical. Each has the same quantity of negative charge and the same mass.
3. Protons and neutrons compose the nucleus. (The common form of the hydrogen atom, which has no neutron, is the only exception.) Protons are about 1800 times more massive than electrons, but they carry an amount of positive charge equal to the negative charge of electrons. Neutrons have slightly more mass than protons and have no net charge.
4. Atoms usually have as many electrons as protons, so the atom has zero *net* charge.

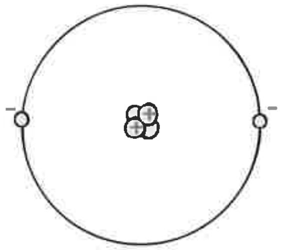

FIGURE 22.2

INTERACTIVE FIGURE

Model of a helium atom. The atomic nucleus is composed of two protons and two neutrons. The positively charged protons attract two negative electrons.

Why don't protons pull the oppositely charged electrons into the nucleus? You might think that electrons behave the same way as planets that orbit the Sun. But not so, for this planetary explanation is invalid for electrons. When the nucleus was discovered in 1911, scientists knew that electrons couldn't orbit placidly around the nucleus in the way Earth orbits the Sun. In only about a hundred-millionth of a second, according to classical physics, the electron would spiral into the nucleus, emitting electromagnetic radiation as it did so. So a new theory was needed, the theory called quantum mechanics. In describing electron motion, we still use old terminology, *orbit* and *orbital*, although the preferred word is *shell*, which suggests that the electrons are spread out over a spherical region. Today, the explanation for the atom's stability has to do with the wave nature of electrons. An electron behaves like a wave and requires a certain amount of space related to its wavelength. When we treat quantum mechanics in Chapter 32, we'll see that atomic size is determined by the minimum amount of 'elbow room' that an electron requires.

Why don't the protons in the nucleus mutually repel and fly apart? What holds the nucleus together? The answer is that, in addition to electrical forces in the nucleus, even stronger nonelectrical nuclear forces hold the protons together and overcome the electrical repulsion. In Chapter 33 we will learn about nuclear forces, and how neutrons put a needed distance between the protons.

CHECK POINT

1. Beneath the complexities of electrical phenomena, there lies a fundamental rule from which nearly all other effects stem. What is this fundamental rule?
2. How does the charge of an electron differ from the charge of a proton?

Check Your Answers

1. Like charges repel; opposite charges attract.
2. The charge of an electron is equal in magnitude, but opposite in sign, to the charge of a proton.

Conservation of Charge

A basic rule of physics is that, whenever something is charged, no electrons are created or destroyed. Electrons are simply transferred from one material to another. Charge is *conserved*. In every event, whether large scale or at the atomic and nuclear level, the principle of **conservation of charge** has always been found to apply. No case of the creation or destruction of net electric charge has ever been found. The conservation of charge ranks with the conservation of energy and momentum as a significant fundamental principle in physics.

In a neutral atom, there are as many electrons as protons, so there is no net charge. The positive balances the negative exactly. If an electron is removed from an atom, then it is no longer neutral. The atom then has one more positive charge (proton) than negative charge (electron) and is said to be positively charged.[1] A charged atom is called an *ion*. A *positive ion* has a net positive charge. A *negative ion*, an atom with one or more extra electrons, is negatively charged.

So we see that an object having unequal numbers of electrons and protons is electrically charged. If it has more electrons than protons, it is negatively charged. If it has fewer electrons than protons, it is positively charged.

Interestingly, any electrically charged object has an excess or deficiency of some whole number of electrons—meaning the charge of the object is a whole-number multiple of the charge of an electron. Electrons cannot be divided into fractions of electrons. Charge is 'grainy,' or made of elementary units called *quanta*. We say that charge is *quantized*, with the smallest quantum of charge being that of the electron

FIGURE 22.3

Electrons are transferred from the fur to the rod. The rod is then negatively charged. Is the fur charged? How much compared to the rod? Positively or negatively?

Charge is like a baton in a relay race. It can be passed from one object to another but isn't lost.

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[1] Each proton has a charge $+e$, equal to $+1.6 \times 10^{-19}$ coulomb. Each electron has a charge $-e$, equal to -1.6×10^{-19} coulomb. Why such different particles have the same magnitude of charge is an unanswered question in physics. The equality of the magnitudes has been tested to high accuracy.

Electronics Technology and Sparks

Electric charge can be dangerous. Two hundred years ago, young boys called powder monkeys ran barefooted below the decks of warships to bring sacks of black gunpowder to the cannons above. It was ship law that this task be done barefoot. Why? Because it was important that no static charge build up on the powder on their bodies as they ran to and fro. Bare feet scuffed the decks much less than shoes and assured no charge accumulation that might produce an igniting spark and an explosion.

Static charge is a danger in many industries today—not because of explosions, but because delicate electronic circuits may be destroyed by static charges. Some circuit components are sensitive enough to be 'fried' by sparks of static electricity. Electronics technicians frequently wear clothing of special fabrics with ground wires between their sleeves and their socks. Some wear special wristbands that are connected to a grounded surface so that static charges will not build up—when moving a chair, for example. The smaller the electronic circuit, the more hazardous are sparks that may short-circuit the circuit elements.

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- Static electricity is a problem at gasoline pumps. Even the tiniest of sparks ignite gasoline vapors and cause fires—frequently lethal. A good rule is to touch metal and discharge static charge from your body before you fuel. Also, don't use a cell phone when fueling.

(or proton). In all matter, no smaller units of charge have ever been observed.[2] All charged objects to date have a charge that is a whole-number multiple of the charge of a single electron or proton.

CHECK POINT

If you scuff electrons onto your feet while walking across a rug, are you negatively or positively charged?

Check Your Answer

You have more electrons after you scuff your feet, so you are negatively charged (and the rug is positively charged).

Coulomb's Law

The electrical force, like gravitational force, decreases inversely as the square of the distance between charged bodies. This relationship, discovered by Charles Coulomb in the 18th century, is called **Coulomb's law.** It states that, for two charged objects that are much smaller than the distance between them, the force between the two objects varies directly as the product of their charges and inversely as the square of the separation distance. (Review the inverse-square law back in Figure 9.5.) The force acts along a straight line from one charged object to the other. Coulomb's law can be expressed as

$$F = k\frac{q_1 q_2}{d^2}$$

where d is the distance between the charged particles, q_1 represents the quantity of charge of one particle, q_2 represents the quantity of charge of the other particle, and k is the proportionality constant.

Coulomb's law is like Newton's law of gravity. But, unlike gravity, electric forces can be attractive or repulsive.

The unit of charge is the **coulomb,** abbreviated C. It turns out that a charge of 1 C is the charge associated with 6.25 billion billion electrons. This might seem like a great number of electrons, but it only represents the amount of charge that flows in a common 100-watt lightbulb in a little over a second.

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[2] Within the atomic nucleus, however, elementary particles called *quarks* carry charges 1/3 and 2/3 the magnitude of the electron's charge. Each proton and each neutron is made up of three quarks. Since quarks always exist in such combinations and have never been found separated, the whole-number-multiple rule of electron charge holds for nuclear processes as well.

The proportionality constant k in Coulomb's law is similar to G in Newton's law of gravitation. Instead of being a very small number like G (6.67×10^{-11}), the electrical proportionality constant k is a very large number. It is approximately

$$9{,}000{,}000{,}000\ \mathrm{N \cdot m^2/C^2}$$

or, in scientific notation, $k = 9 \times 10^9\ \mathrm{N \cdot m^2/C^2}$. The unit $\mathrm{N \cdot m^2/C^2}$ is not central to our interest here; it simply converts the right-hand side of the equation for Coulomb's law to the unit of force, the newton (N). What is important is the large magnitude of k. If, for example, a pair of like charged particles of 1 C each were 1 m apart, the force of repulsion between them would be 9 billion N.[3] That would be more than 10 times the weight of a battleship! Obviously, such amounts of net charge do not exist in our everyday environment.

So Newton's law of gravitation for masses is similar to Coulomb's law for electrically charged bodies.[4] The most important difference between gravitational and electrical forces is that electrical forces may be either attractive or repulsive, whereas gravitational forces are only attractive. Coulomb's law underlies the bonding forces between molecules that are essential in the field of chemistry.

The greatest threat to civilization is an excess of certitude.

CHECK POINT

1. The proton that is the nucleus of the hydrogen atom attracts the electron that orbits it. Relative to this force, does the electron attract the proton with less force, with more force, or with the same amount of force?
2. If a proton at a particular distance from a charged particle is repelled with a given force, by how much will the force decrease when the proton is 3 times farther away from the particle? When it is 5 times farther away?
3. What is the sign of charge of the particle in this case?

Check Your Answers

1. The same amount of force, in accord with Newton's third law—basic mechanics! Recall that a force is an interaction between two things—in this case, between the proton and the electron. They pull on each other equally.
2. It decreases to 1/9 its original value; to 1/25 its original value.
3. Positive.

Conductors and Insulators

It is easy to establish an electric current in metals because one or more of the electrons in the outer shell of its atoms are not anchored to the nuclei of particular atoms but are free to wander in the material. Such a material is called a good

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[3] Contrast this to the gravitational force of attraction between two 1-kg masses 1 m apart: 6.67×10^{-11} N. This is an extremely small force. For the force to be 1 N, the masses at 1 m apart would have to be nearly 123,000 kg each! Gravitational forces between ordinary objects are exceedingly small, while electrical forces between ordinary objects can be exceedingly huge. We don't sense them because the positives and negatives normally balance out. Even for highly charged objects, the imbalance of electrons to protons is normally less than one part in a trillion trillion.

[4] According to quantum theory, a force that varies inversely as the square of the distance involves the exchange of particles with no mass. Exchange of massless photons is responsible for the electrical force, and exchange of massless gravitons accounts for the gravitational force. Some scientists pursue an even deeper relationship between gravity and electricity. Albert Einstein spent the latter part of his life searching with little success for a "unified field theory." More recently, the electrical force has been unified with one of the two nuclear forces, the *weak force*, which plays a role in radioactive decay.

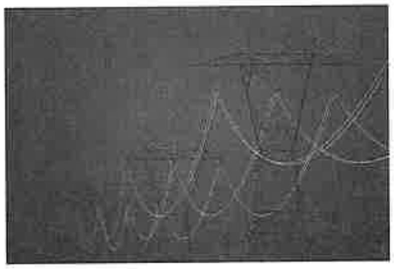

FIGURE 22.4

It is easier to establish an electric current through hundreds of kilometers of metal wire than through a few centimeters of insulating material.

conductor. Any metal is a good conductor of electric current for the same reason it is a good heat conductor—the electrons in the outer atomic shell of its atoms are "loose." The expensive metals such as silver, gold, and platinum are among the very best conductors, don't corrode, and are commonly used in small quantities for high-value products. Copper and aluminum are commonly used in wiring electrical systems because of their good performance and lower cost.

The electrons in other materials—rubber and glass, for example—are tightly bound and belong to particular atoms. They are not free to wander about among other atoms in the material. Consequently, it isn't easy to make them flow. These materials are poor conductors of electric current for the same reason they are generally poor heat conductors. Such a material is called a good **insulator.** Glass is an extremely good insulator and is used to keep electrical wires away from the metal towers that carry them. Many plastics are also good insulators, which is why wiring in your home is covered with a layer of plastic.

All substances can be arranged in order of their ability to conduct electric charge. Those at the top of such a list would be conductors and those at the bottom would be insulators. The ends of the list are very far apart. The conductivity of a metal, for example, can be more than a million trillion times greater than the conductivity of an insulator such as glass.

SEMICONDUCTORS

Some materials, such as germanium (Ge) and silicon (Si), are neither good conductors nor good insulators. These materials fall in the middle of the range of electrical resistivity, being fair insulators in their pure crystalline form and becoming excellent conductors when even 1 atom in 10 million is replaced with an impurity that adds or removes an electron from the crystal structure. A material that can be made to behave sometimes as an insulator and sometimes as a conductor is called a **semiconductor.** Thin layers of semiconducting materials sandwiched together make up *transistors,* which are used to control the flow of electrons in circuits, to detect and amplify radio signals, and to produce oscillations in transmitters; they also act as digital switches. These tiny solids were the first electrical components in which materials with different electrical characteristics were not interconnected by wires but were physically joined in one structure. They require very little power, and they last indefinitely in normal use.

A semiconductor will also conduct when light of the proper color shines on it. A pure selenium plate is normally a good insulator, and any electric charge built up on its surface will remain for extended periods in the dark. If the plate is exposed to light, however, the charge leaks away almost immediately. If a charged selenium plate is exposed to a pattern of light, such as the pattern of light and dark that makes up this page, the charge will leak away only from the areas exposed to light. If a black plastic powder were brushed across its surface, the powder would stick only to the charged areas where the plate had not been exposed to light. Now if a piece of paper with an electric charge on the back of it were put over the plate, the black plastic powder would be drawn to the paper to form the same pattern as, say, the one on this page. This is the nuts and bolts of photocopiers.

fyi

- The new memristor (short for memory resistor) utilizes a thin film of titanium oxide sandwiched between two platinum layers. It packs into chips 100 times more densely than transistors and remembers information without electric power. Will memristors soon appear in computers and wireless devices?

Superconductors

An ordinary conductor has only a small resistance to the flow of electric charge. An insulator has much greater resistance (we'll treat the topic of electric resistance in the following chapter). Remarkably, in certain materials at sufficiently low temperatures, electrical resistance disappears. The materials acquire zero resistance (infinite conductivity) to the flow of charge. Such a material is called a

superconductor. Once electric current is established in a superconductor, the electrons flow indefinitely. With no electrical resistance, current passes through a superconductor without losing energy; no heat loss occurs when charges flow. Superconductivity in metals near absolute zero was discovered in 1911. In 1987, superconductivity at a "high" temperature (above 100 K) was discovered in a nonmetallic compound. Superconductivity has since progressed with applications that include low-loss power-line transmission and high-speed, magnetically levitated vehicles intended to replace traditional rail trains.

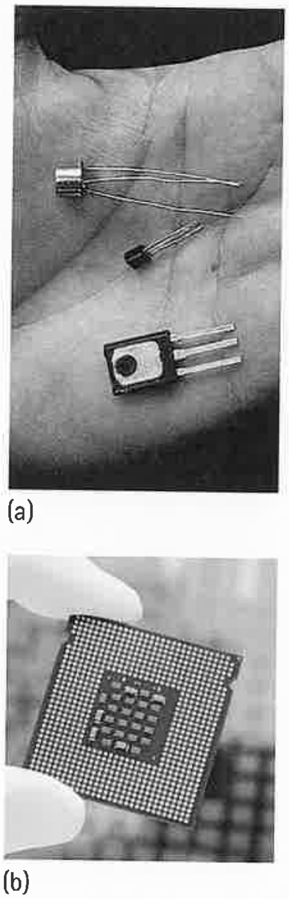

FIGURE 22.5

(a) Three transistors.
(b) Many transistors in an integrated circuit.

Charging

We charge things by transferring electrons from one place to another. We can do this by physical *contact*, as occurs when substances are rubbed together or simply touched. Or we can redistribute the charge on an object simply by putting a charged object near it—this is called *induction*.

CHARGING BY FRICTION AND CONTACT

We are all familiar with the electrical effects produced by friction. We can stroke a cat's fur and hear the crackle of sparks that are produced, or comb our clean, dry hair in front of a mirror in a dark room and see as well as hear the sparks. We can scuff our shoes across a rug and feel a tingle as charge flows when we touch a doorknob. Talk to old-timers and they'll tell you about the surprising shock that was typical of sliding across a plastic seat cover while parked in an automobile (Figure 22.6). Charge is transferred in clothes in a clothes dryer. In all these cases, electrons are transferred by friction when one material rubs against another.

Electrons can transfer from one material to another by simply touching. For example, when a negatively charged rod is placed in contact with a neutral object, some electrons will move to the neutral object. This method of charging is simply called **charging by contact.** If the object is a good conductor, electrons will spread to all parts of its surface because the transferred electrons repel one another. If it is a poor conductor, it may be necessary to touch the rod at several places on the object in order to get a more-or-less uniform distribution of charge.

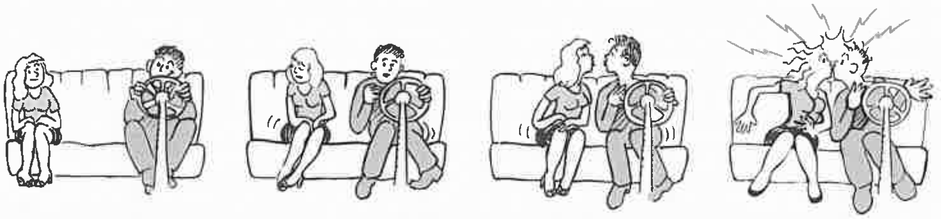

FIGURE 22.6

Charging by friction and then by contact.

CHARGING BY INDUCTION

If you bring a charged object *near* a conducting surface, electrons are made to move in the surface material, even without physical contact. Consider the two insulated metal spheres, A and B, in Figure 22.7. (a) They touch each other, so in effect they form a single uncharged conductor. (b) When a negatively charged rod is brought near A, electrons in the metal, being free to move, are repelled as far as possible until their mutual repulsion is big enough to balance the influence of the rod: The charge is redistributed. (c) If A and B are separated while the rod is still present, (d) each will be equal and oppositely charged. This is **charging by induction.** The charged rod has never touched them, and the rod retains the same charge it had initially.

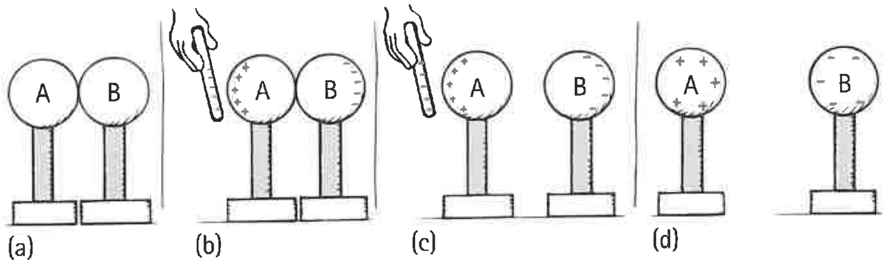

FIGURE 22.7

INTERACTIVE FIGURE

Charging by induction.

We can similarly charge a single sphere by induction if we touch it when different parts of it are differently charged. Consider the metal sphere that hangs from a nonconducting string, as shown in Figure 22.8. When we touch the metal surface with a finger, we are providing a path for charge to flow to or from a very large reservoir for electric charge—the ground. We say that we are *grounding* the sphere, a process that may leave it with a net charge. We will return to this idea of grounding in Chapter 23 when we discuss electric currents.

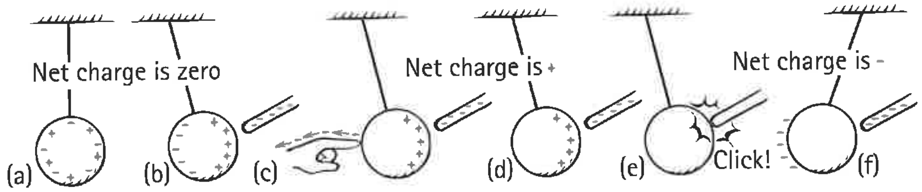

FIGURE 22.8

INTERACTIVE FIGURE

Stages of charge induction by grounding. (a) The net charge on the metal sphere is zero. (b) Charge redistribution is induced on the sphere by the presence of the charged rod. The net charge on the sphere is still zero. (c) Touching the negative side of the sphere removes electrons by contact. (d) This leaves the sphere positively charged. (e) The sphere is more strongly attracted to the negative rod, and, when it touches, charging by contact occurs. (f) The negative sphere is repelled by the still somewhat negatively charged rod.

Charging by induction occurs during thunderstorms. The negatively charged bottoms of clouds induce a positive charge on the surface of the ground below. As mentioned at the beginning of this chapter, Benjamin Franklin was the first to demonstrate this when his famous kite-flying experiment proved that lightning is an electrical phenomenon.[5] Lightning is an electrical discharge between a cloud and the oppositely charged ground or between oppositely charged parts of clouds.

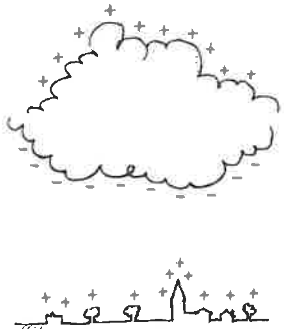

FIGURE 22.9

The negative charge at the bottom of the cloud induces a positive charge at the surface of the ground below.

Franklin also found that charge flows readily to or from sharp metal points, and he fashioned the first lightning rod. The primary purpose of the lightning rod is to

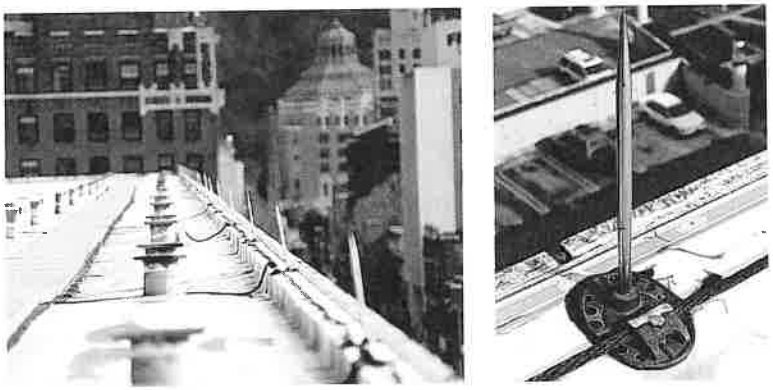

FIGURE 22.10

Lightning rods are connected by heavy-duty wires so that very large currents can be conducted to the ground if lightning strikes. Most often, charge leaks off the pointed tips to prevent the occurrence of lightning.

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[5] Benjamin Franklin invented many things that improved the quality of life. He was certainly a very busy man! Only a task as important as helping to form the United States' system of government prevented him from devoting even more of his time to his favorite activity—the scientific investigation of nature.

prevent a fire caused by lightning. If, for any reason, sufficient charge does not leak from the air to the rod and lightning strikes anyway, it may be attracted to the rod and take a direct path to the ground, thereby sparing the building.

fyi

- Lightning occurs mainly in warm climates. As warm water vapor rises in air it brushes against ice crystals high in the air above, producing a charge similar to what occurs when you scuff your feet on a carpet. The ice crystals gain a slight positive charge, and the updraft carries them to the top of the cloud. So the top of a cloud is usually positively charged, with the bottom negatively charged. Lightning is the bolt that arcs between these regions and between the cloud and the ground below.

CHECK POINT

1. Would the charges induced on the spheres A and B of Figure 22.7 necessarily be exactly equal and opposite?
2. Why does the negative rod in Figure 22.7 have the same charge before and after the spheres are charged, but not when charging takes place, as in Figure 22.8?

Check Your Answers

1. Yes, because each positive charge on sphere A results from an electron taken from A and moved to B. This is like removing bricks from the surface of a brick road and placing them all on the sidewalk. The number of bricks on the sidewalk exactly matches the number of holes in the road. Likewise, the number of extra electrons on B will exactly match the number of "holes" (positive charges) left in A. The positive charge is the result of an absent electron.
2. In the charging process of Figure 22.7, no contact was made between the negative rod and either of the spheres. In Figure 22.8, however, the rod touched the positively charged sphere. A transfer of charge by contact reduced the negative charge on the rod.

Charge Polarization

Charging by induction is not restricted to conductors. When a charged rod is brought near an insulator, there are no free electrons that can migrate throughout the insulating material. Instead, there is a rearrangement of charges within the atoms and molecules themselves (Figure 22.11). Although atoms don't move from their relatively fixed positions, their "centers of charge" are moved. One side of the atom or molecule is induced into becoming more negative (or positive) than the opposite side. The atom or molecule is said to be **electrically polarized.** If the charged rod is negative, say, then the positive part of the atom or molecule is tugged in a direction toward the rod, and the negative side of the atom or molecule is pushed in a direction away from the rod. The positive and negative parts of the atoms and molecules become aligned. They are electrically polarized.

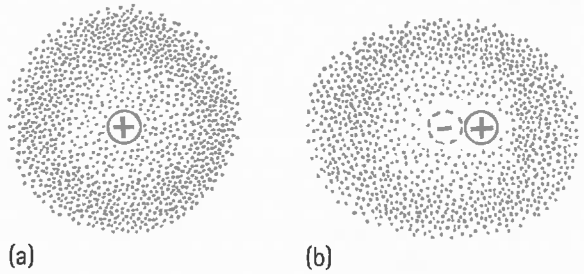

FIGURE 22.11

An electron buzzing around the atomic nucleus produces an electron cloud. (a) The center of the negative cloud normally coincides with the center of the positive nucleus in an atom. (b) When an external negative charge is brought nearby to the right, as on a charged balloon, the electron cloud is distorted so that the centers of negative and positive charge no longer coincide. The atom is now electrically polarized.

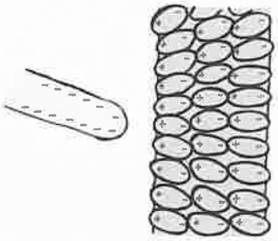

FIGURE 22.12

INTERACTIVE FIGURE

All the atoms or molecules near the surface become electrically polarized. Surface charges of equal magnitude and opposite sign are induced on opposite surfaces of the material.

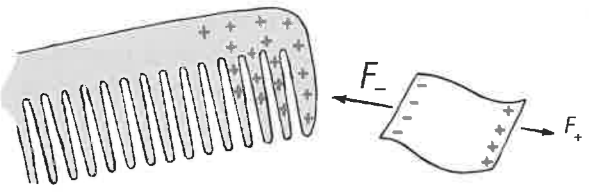

FIGURE 22.13

A charged comb attracts an uncharged piece of paper because the force of attraction for the closer charge is greater than the force of repulsion for the farther charge.

We can understand why electrically neutral bits of paper are attracted to a charged object—a comb passed through your hair, for example. When the charged comb is brought nearby, molecules in the paper are polarized. The sign of charge closest to the comb is opposite to the comb's charge. Charges of the same sign are slightly more distant. Closeness wins, and the bits of paper experience a net attraction. Sometimes they will cling to the comb and then suddenly fly off. This repulsion occurs because the paper bits acquire the same sign of charge as the charged comb when they come in contact. Rub an inflated balloon on your hair, and it becomes charged. Place the balloon against the wall, and it sticks. This is because the charge on the balloon induces an opposite surface charge on the wall. Again, closeness wins, for the charge on the balloon is slightly closer to the opposite induced charge than to the charge of same sign (Figure 22.14).

Many molecules—H_2O, for example—are electrically polarized in their normal states. The distribution of electric charge is not perfectly even. There is a little more negative charge on one side of the molecule than the other (Figure 22.15). Such molecules are said to be *electric dipoles.*

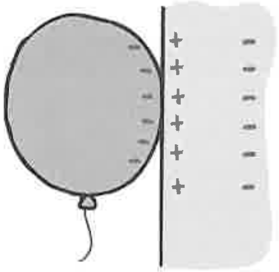

FIGURE 22.14

The negatively charged balloon polarizes atoms in the wooden wall and creates a positively charged surface, so the balloon sticks to the wall.

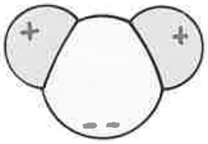

FIGURE 22.15

An H_2O molecule is an electric dipole.

CHECK POINT

1. A negatively charged rod is brought close to some small pieces of neutral paper. The positive sides of molecules in the paper are attracted to the rod and the negative sides of the molecules are repelled. Why don't these attractive and repulsive forces cancel out?
2. In a humorous vein, if you rub a balloon on your hair and put your head to the wall, will it stick to the wall like the balloon would?

Check Your Answers

1. The positive sides are simply closer to the rod. They therefore experience a greater electrical force than the father-away negative sides. Hence we say that closeness wins. Can you see that a positive rod would still produce attraction?
2. It would, if you were an airhead—that is, if the mass of your head were about that of the balloon, so that the force produced would be evident.

Electric Field

Electrical forces, like gravitational forces, act between things that are not in contact with each other. For both electricity and gravity, a *force field* exists that influences charged and massive bodies, respectively. Recall, from Chapter 9, that the properties of space surrounding any massive body are altered such that another massive body introduced to this region will experience a force. The force is gravitational, and the altered space surrounding a massive body is its *gravitational field.* We can think of any other massive body as interacting with the field and not directly with the massive body producing it. For example, when an apple falls from a tree, we say it is interacting with Earth, but we can also think of the apple as interacting with the gravitational field of Earth. The field plays an intermediate role in the force between bodies. It is common to think of distant rockets and the like as interacting with gravitational fields rather than with the masses of Earth and other bodies responsible for

Sharks and related species of fish are equipped with specialized receptors in their snouts that sense extremely weak electric fields generated by other creatures in seawater.

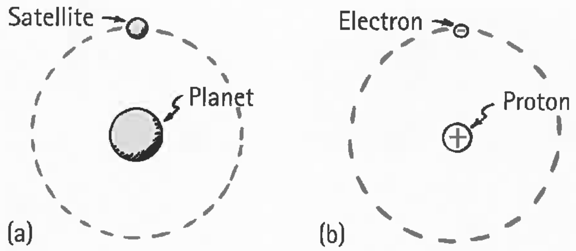

FIGURE 22.16

(a) A gravitational force holds the satellite in orbit about the planet, and (b) an electrical force holds the electron in orbit about the proton. In both cases, there is no contact between the bodies. We say that the orbiting bodies interact with the *force fields* of the planet and proton and are everywhere in contact with these fields. Thus, the force that one electrically charged body exerts on another can be described as the interaction between one body and the field set up by the other.

An electric field is nature's storehouse of electrical energy.

the fields. Just as the space around a planet (and around every other massive body) is filled with a gravitational field, the space around every electrically charged body is filled with an **electric field**—an energetic aura that extends through space.

An electric field has both magnitude (strength) and direction. The magnitude of the field at any point is simply the force per unit of charge. If a body with charge q experiences a force F at some point in space, then the electric field E at that point is

$$E = \frac{F}{q}$$

The electric field is depicted with vector arrows in Figure 22.17a. The direction of the field is shown by the vectors and is defined to be the direction in which a small positive test charge at rest would be pushed.[6] The direction of the force and that of the field at any point are the same. In the figure, we see that all the vectors therefore point to the center of the negatively charged ball. If the ball were positively charged, the vectors would point away from its center because a positive test charge in the vicinity would be repelled.

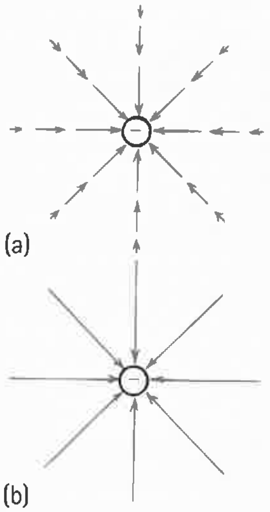

FIGURE 22.17

INTERACTIVE FIGURE

Electric-field representations about a negative charge. (a) A vector representation. (b) A lines-of-force representation.

A more useful way to describe an electric field is with lines of force, as shown in Figure 22.17b. The lines of force shown in the figure represent a small number of the infinitely numerous possible lines that indicate the direction of the field. The figure is a two-dimensional representation of three dimensions. Where the lines are farther apart, the field is weaker. For an isolated charge, the lines extend to infinity; for two or more opposite charges, we represent the lines as emanating from a positive charge and terminating on a negative charge. Some electric-field configurations are shown in Figure 22.18, and photographs of field patterns are shown in Figure 22.19. The photographs show bits of thread that are suspended in an oil bath surrounding charged conductors. The ends of the thread bits are charged by induction and tend to line up end-to-end with the field lines, like iron filings in a magnetic field.

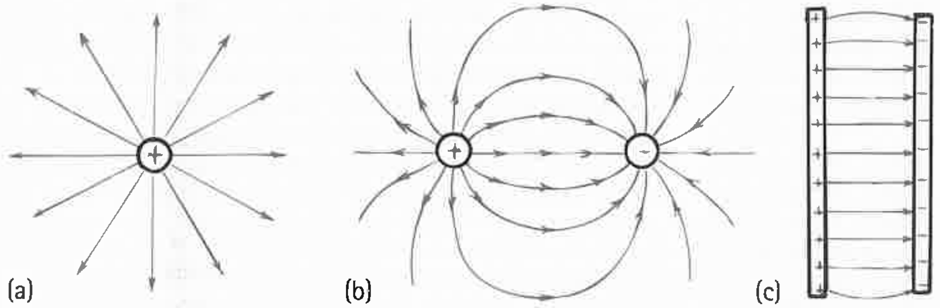

FIGURE 22.18

INTERACTIVE FIGURE

Some electric-field configurations.
(a) Lines of force emanating from a single positively charged particle.
(b) Lines of force for a pair of equal but oppositely charged particles. Note that the lines emanate from the positive particle and terminate on the negative particle.
(c) Uniform lines of force between two oppositely charged parallel plates.

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[6] The test charge is small so that it does not appreciably influence the sources of the field being measured. Recall, from our study of heat, the similar need for a thermometer of small mass when measuring the temperature of bodies of larger masses.

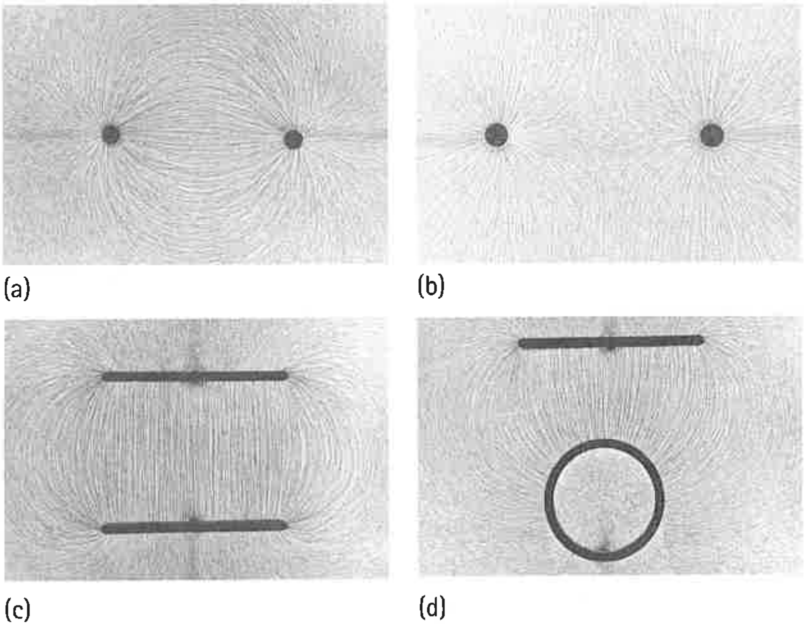

FIGURE 22.19
The electric field due to a pair of charged conductors is shown by bits of thread suspended in an oil bath surrounding the conductors. Note that the threads line up end-to-end along the direction of the electric field.
(a) Equal and oppositely charged conductors (like those in Figure 22.18b).
(b) Equal and identically charged conductors.
(c) Oppositely charged plates.
(d) Oppositely charged cylinder and plate.

A candy bar in Percy Spencer's pocket mysteriously melted while he was experimenting with electrical oscillations in a new vacuum tube in 1946. Intrigued, he placed some popcorn kernels near the tube and saw them pop. The birth of the microwave oven soon followed.

The electric-field concept helps us understand not only the forces between isolated stationary charged bodies but also what happens when charges move. When charges move, their motion is communicated to neighboring charged bodies in the form of a field disturbance. Such a disturbance emanates from an accelerating charged body at the speed of light. We will learn that the electric field is a storehouse of energy and that energy can be transported over long distances in an electric field. Energy that is traveling in an electric field may be directed through, and guided by, metal wires, or it may be teamed up with a magnetic field to move through empty space. We will return to this idea in the next chapter and later when we learn about electromagnetic radiation.

ELECTRIC SHIELDING

An important difference between electric fields and gravitational fields is that electric fields can be shielded by various materials, while gravitational fields cannot. The amount of shielding depends on the material used for shielding. For example, air

Microwave Oven

Imagine an enclosure with Ping-Pong balls among a few batons, all at rest. Now imagine the batons suddenly flipping to and fro like semirotating propellers, striking neighboring Ping-Pong balls. The balls are energized, moving in all directions. A microwave oven operates similarly. The batons are water molecules (or other polar molecules) made to flip to and fro in rhythm with the oscillating microwaves in the enclosure. The Ping-Pong balls are nonpolar molecules that make up the bulk of the food being cooked.

Each H_2O molecule is an electric dipole that aligns with an electric field, like a compass needle aligns with a magnetic field. When the electric field is made to oscillate, the H_2O molecules oscillate also. The H_2O molecules move quite energetically when the oscillation frequency matches their natural frequency—at resonance. Food is cooked by a sort of "kinetic friction" as flip-flopping H_2O molecules (or other polar molecules) impart thermal motion to surrounding molecules. The metal enclosure reflects microwaves to and fro throughout the oven for rapid cooking.

Dry paper, foam plates, or other materials recommended for use in microwave ovens contain no water or any other polar molecules, so microwaves pass through them with no effect. Likewise for ice, in which the H_2O molecules are locked in position and can't rotate to and fro. Metallic materials reflect microwaves, which is why metal pans do not work well in a microwave oven.

A note of caution is due when boiling water in a microwave oven. Water can sometimes heat faster than bubbles can form, and the water then heats beyond its boiling point—it becomes superheated. If the water is bumped or jarred just enough to cause the bubbles to form rapidly, they'll violently expel the hot water from its container. More than one person has had boiling water blast into his or her face.

makes the electric field between two charged objects slightly weaker than it would be in a vacuum, while oil placed between the objects can diminish the field to nearly a hundredth of its original strength. Metal can completely shield an electric field. Quite interestingly, when no current is flowing, the electric field inside metal is zero, regardless of the field strength outside.

Consider, for example, electrons on a spherical metal ball. Because of mutual repulsion, the electrons will spread out uniformly over the outer surface of the ball. It is not difficult to see that the electrical force exerted on a sample test charge placed at the exact center of the ball is zero, because opposing forces balance in every direction. Interestingly enough, complete cancellation occurs *anywhere* inside a conducting sphere. Understanding why this is true requires more thought and involves the inverse-square law and a bit of geometry. Consider the test charge at point P in Figure 22.20. The test charge is twice as far from the left side of the charged sphere as it is from the right side. If the electrical force between the test charge and the charges depended only on distance, then the test charge would be attracted only 1/4 as much to the left side as to the right side. (Remember the inverse-square law: Twice as far away means only 1/4 the effect, three times as far away means only 1/9 the effect, and so on.) But the force depends also on the amount of charge. In the figure, the cones extending from point P to areas A and B have the same apex angle, but one has twice the altitude of the other. This means that area A at the base of the longer cone is 4 times area B at the base of the shorter cone, which is true for any apex angle. Since 1/4 of 4 is equal to 1, a test charge at P is attracted equally to each side. Cancellation occurs. A similar argument applies if the cones emanating from point P are oriented in any direction. Complete cancellation occurs at all points within the sphere. (Recall this argument back in Chapter 9, Figure 9.25, for the cancellation of gravity inside a hollow planet. The metal ball behaves the same way, whether hollow or not, because all of its charge gathers on its outer surface.)

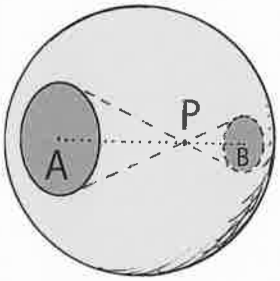

FIGURE 22.20

The test charge at P is attracted just as much to the greater amount of charge at farther region A as it is to the smaller amount of charge at closer region B. The net force on the test charge is zero—there, or anywhere inside the conductor. The electric field everywhere inside is also zero.

If the conductor is not spherical, then the charge distribution will not be uniform. The charge distribution over conductors of various shapes is shown in Figure 22.21. Most of the charge on a conducting cube, for example, is mutually repelled toward the corners. The remarkable thing is this: The exact charge distribution over the surface of a conductor is such that the electric field everywhere inside the conductor is zero. Look at it this way: If there were an electric field inside a conductor, then free electrons inside the conductor would be set in motion. How far would they move? Until equilibrium is established—which is to say, when the positions of all the electrons produce a zero field inside the conductor.

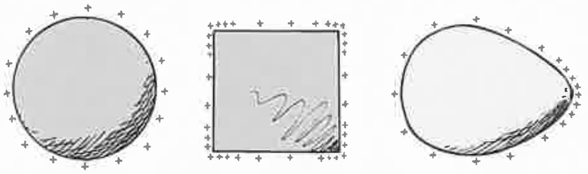

FIGURE 22.21

Electric charge distributes itself on the surface of all conductors in such a way that the electric field inside the conductors is zero.

FIGURE 22.22

Electrons from the lightning bolt mutually repel to the outer metal surface. Although the electric field the electrons set up may be great *outside* the car, the net electric field *inside* the car is zero.

We cannot shield ourselves from gravity, because gravity only attracts. There are no repelling parts of gravity to offset attracting parts. Shielding electric fields, however, is quite simple. Surround yourself, or whatever you wish to shield, with a conducting surface. Put this surface in an electric field of any field strength. The free charges in the conducting surface will arrange themselves on the surface of the conductor in such a way that all field contributions inside cancel one another.

That's why certain electronic components are encased in metal boxes and why certain cables have a metal covering—to shield them from outside electrical activity.

CHECK POINT

Small bits of aligned thread vividly show the electric fields in the four photos of Figure 22.19. But the threads are not aligned inside the cylinder in Figure 22.19d. Why?

Check Your Answer

The electric field is shielded inside the cylinder, shown as a circle in the two-dimensional photograph. Hence, the threads are without alignment. The electric field inside any conductor is zero—so long as no electric charge is flowing.

Electric Potential

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Video
Electric Potential

When we studied energy in Chapter 7, we learned that an object has gravitational potential energy because of its location in a gravitational field. Similarly, a charged object has potential energy by virtue of its location in an electric field. Just as work is required to lift a massive object against the gravitational field of Earth, work is required to push a charged particle against the electric field of a charged body. This work changes the electric potential energy of the charged particle.[7] Consider the particle with the small positive charge located at some distance from a positively charged sphere in Figure 22.23b. If you push the particle closer to the sphere, you will expend energy to overcome electrical repulsion; that is, you will do work in pushing the charged particle against the electric field of the sphere. This work done in moving the particle to its new location increases its energy. We call the energy the particle possesses by virtue of its location **electric potential energy.** If the particle is released, it accelerates in a direction away from the sphere, and its electric potential energy changes to kinetic energy.

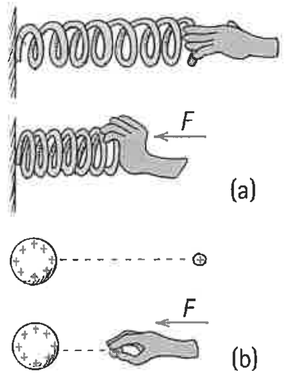

FIGURE 22.23

(a) The spring has more mechanical PE when compressed.
(b) The charged particle similarly has more electrical PE when pushed closer to the charged sphere. In both cases, the increased PE is the result of work input.

If we instead push a particle with twice the charge, we do twice as much work pushing it, so the doubly charged particle in the same location has twice as much electric potential energy as before. A particle with 3 times the charge has 3 times as much potential energy and so on. Rather than dealing with the potential energy of a charged particle, it is convenient, when working with charged particles in an electric field, to consider the electric potential energy *per unit of charge*. The unit of electric

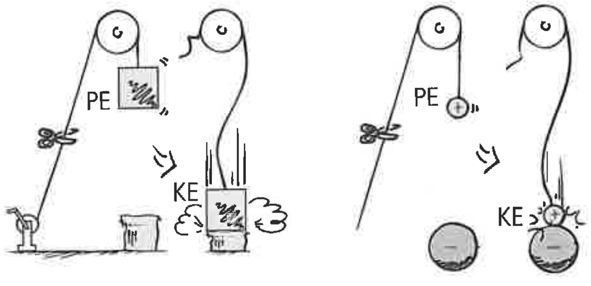

FIGURE 22.24

(a) The PE (gravitational potential energy) of a mass held in a gravitational field, when released, transforms to KE (kinetic energy).
(b) The PE of a charged particle held in an electric field, when released, becomes KE. Can you see that the KE acquired by each equals the decrease in PE?

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[7] This work is positive if it increases the electric potential energy of the charged particle and negative if it decreases it.

charge is the coulomb, so we consider the electric potential energy *per coulomb* of charge. Then at any location the electric potential energy per coulomb will be the same—for however much charge. For example, an object with 10 coulombs of charge at a specific location has 10 times as much electric potential energy as an object with 1 coulomb of charge. But 10 times as much electric potential energy for 10 times as much charge gives the same value as the electric potential energy per 1 coulomb of charge. The concept of electric potential energy per unit charge has a special name, **electric potential:**

$$\text{Electric potential} = \frac{\text{electric potential energy}}{\text{charge}}$$

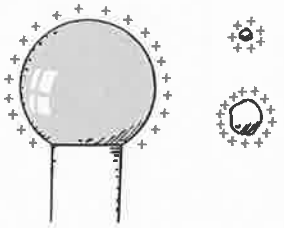

FIGURE 22.25

Of the two charged bodies near the charged dome, the one with the greater charge has the higher electrical PE in the field of the dome. But the *electric potential* of each is the same—likewise for any amount of charge in the same location. Can you see why?

The unit of measurement for electric potential is the volt, so electric potential is often called *voltage*. A potential of 1 volt (V) equals 1 joule (J) of energy per 1 coulomb (C) of charge.

$$1\text{ volt} = 1\frac{\text{joule}}{\text{coulomb}}$$

Thus, a 1.5-volt battery gives 1.5 joules of energy to every 1 coulomb of charge passing through the battery. Both the names *electric potential* and *voltage* are common, so either may be used. In this book, the names will be used interchangeably.

So *electric potential* and *voltage* mean the same thing—electrical potential energy per unit charge—in units of volts.

Electric potential (voltage) plays the same role for charge that pressure does for fluids. When a pressure difference exists between two ends of a pipe filled with fluid, the fluid flows from the high pressure end towards the lower pressure end. We will see in the next chapter that charges respond to differences in potential in a similar way.

If you rub a balloon on your hair, the balloon becomes negatively charged—perhaps to several thousand volts! That would be several thousand joules of energy, if the charge were 1 coulomb. However, 1 coulomb is a very large amount of charge. The charge on a balloon rubbed on hair is more typically much less than a millionth of a coulomb. Therefore, the amount of energy associated with the charged balloon is very, very small. A high voltage means a lot of energy only if a lot of charge is involved. There is an important difference between electric potential energy and electric potential.

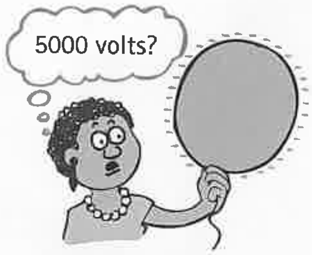

FIGURE 22.26

Although the electric potential (voltage) of the charged balloon is high, the electric potential energy is low because of the small amount of charge. Therefore, very little energy transfers when the balloon is discharged.

CHECK POINT

If twice as many coulombs were in the test charge near the charged sphere in Figure 22.23b, how would the electric potential energy of the test charge relative to the sphere be affected? How would its electric potential be affected?

Check Your Answers

Twice as many coulombs means that the test charge has twice as much electric potential energy (because twice as much work put the charge at that location). But the electric potential would not be affected. Electric potential (measured in volts) is different from electric potential energy (measured in joules). Be sure you understand this before you study further.

High voltage at low energy is similar to the harmless high-temperature sparks of a fireworks sparkler. Recall that temperature is average kinetic energy per molecule, which means total energy is large only for a large number of molecules. Similarly, high voltage means a large quantity of energy only for a large amount of charge.

Electric Energy Storage

Electric energy can be stored in a common device called a **capacitor.** The simplest capacitor is a pair of conducting plates separated by a small distance, but not touching each other. When the plates are connected to a charging device, such as the battery shown in Figure 22.27, electrons are transferred from one plate to the other. This occurs as the positive battery terminal pulls electrons from the plate connected to it. These electrons, in effect, are pumped through the battery and through the negative terminal to the opposite plate. The capacitor plates then have equal and opposite charges—the positive plate connected to the positive battery terminal, and the negative plate connected to the negative terminal. The charging process is complete when the potential difference between the plates equals the potential difference between the battery terminals—the battery voltage. The greater the battery voltage, and the larger and closer the plates, the greater the charge that can be stored. In practice, the plates may be thin metallic foils separated by a thin sheet of paper. This "paper sandwich" is then rolled up to save space and inserted into a cylinder. Such a practical capacitor is shown with others in Figure 22.29.

Capacitors are found in nearly all electronic circuits. A capacitor stores energy in common photoflash units. The rapid release of this energy is evident in the short duration of the flash. Likewise for a defibrillator, where short bursts of energy are applied to a heart attack victim. Similarly, but on a grander scale, enormous amounts of energy are stored in banks of capacitors that power giant lasers in national laboratories.

The energy stored in a capacitor comes from the work required to charge it. Discharging a charged capacitor can be a shocking experience if you happen to be the conducting path. The energy transfer that occurs can be fatal where high voltages are present, such as the power supply in a TV set—even after the set has been turned off. This is the main reason for the warning signs on such devices. The energy is stored in the electric field between its plates. Between parallel plates, the electric field is uniform, as indicated in Figure 22.18c and Figure 22.19c. So the energy stored in a capacitor is the energy of its electric field. In Chapter 23, we'll consider the role of capacitors in electric circuits. Then in Chapters 25 and 26, we will see how energy from the Sun is radiated in the form of electric and magnetic fields. The fact that energy is contained in electric fields is truly far-reaching.

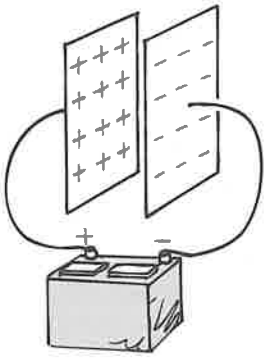

FIGURE 22.27
A capacitor consisting of two closely spaced parallel metal plates. When connected to a battery, the plates acquire equal and opposite charges. The voltage between the plates then matches the electric potential difference between the battery terminals.

FIGURE 22.28
Mona El Tawil-Nassar adjusts demonstration capacitor plates.

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Van de Graaff Generator

FIGURE 22.29
Practical capacitors.

CHECK POINT

What is the net charge of a charged capacitor?

Check Your Answer

Zero, because the charges on its two plates are equal in number and opposite in sign. Even when the capacitor is discharged—say, by providing a path for charge flow between the oppositely charged plates—the net charge of the capacitor remains zero, for then each plate has zero charge.

VAN DE GRAAFF GENERATOR

A common laboratory device for producing high voltages and creating static electricity is the *Van de Graaff generator* (invented by American physicist Robert J. Van de Graaff in 1931 to supply the high voltage needed for early particle accelerators). These accelerators were known as atom smashers because they accelerated subatomic particles to very high speeds and then "smashed" them into the target atoms. The resulting collisions could knock protons and neutrons out of atomic nuclei and create high-energy radiation such as X-rays and gamma rays. The ability to create these high-energy collisions is essential for particle and nuclear physics.

Van de Graaff generators are also the lightning machines that mad scientists used in old science-fiction movies. A classroom model of a Van de Graaff generator provides the static charge to make Lillian's hair stand out in the opening photo to this chapter, and likewise for her friend in Figure 22.30.

Figure 22.31 shows the interior of a simple model of the generator. A hollow metal sphere is supported by a cylindrical insulating stand. A motor-driven rubber belt inside the support stand passes by a comblike set of metal tips that are maintained at a large negative potential relative to ground. Discharge by the tips deposits a continuous supply of electrons on the belt, which are carried up into the hollow conducting sphere. Since the electric field inside the sphere is zero, the charge is not prevented from leaking onto metal points (tiny lightning rods) inside the sphere. The electrons repel one another to the outer surface of the sphere, just as static charge always lies on the outside surface of any conductor. This leaves the inside uncharged and able to receive more electrons as they are brought up by the belt. The process is continuous and the charge builds up until the negative potential on the sphere is much greater than at the voltage source at the bottom—on the order of millions of volts.

A sphere with a radius of 1 m can be raised to a potential of 3 million V before electrical discharge occurs through the air. The voltage can be further increased by increasing the radius of the sphere or by placing the entire system in a container filled with high-pressure gas. Van de Graaff generators can produce voltages as high as 20 million V. Touching one can be a hair-raising experience.

FIGURE 22.30

Both Lori and the dome of the Van de Graaff generator are charged to a high voltage. Why does her hair stand out?

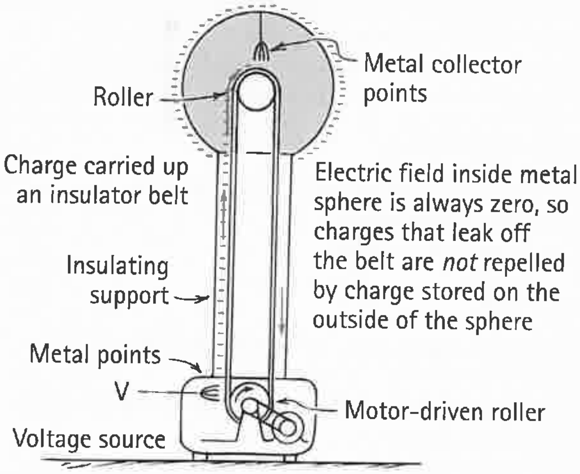


FIGURE 22.31

A simple model of a Van de Graaff generator.

SUMMARY OF TERMS

Electricity General term for electrical phenomena, much like gravity has to do with gravitational phenomena, or sociology with social phenomena.

Electrostatics The study of electric charge at rest (not *in motion*, as in electric currents).

Conservation of charge Electric charge is neither created nor destroyed. The total charge before an interaction equals the total charge after.

Coulomb's law The relationship between electrical force, charge, and distance:

$$F = k\frac{q_1 q_2}{d^2}$$

If the charges are alike in sign, the force is repulsive; if the charges are unlike, the force is attractive.

Coulomb The SI unit of electrical charge. One coulomb (symbol C) is equal to the total charge of 6.25×10^{18} electrons.

Conductor Any material having free charged particles that easily flow through it when an electric force acts on them.

Insulator A material without free charged particles and through which charge does not easily flow.

Semiconductor A material with properties that fall between a conductor and an insulator and whose resistance can be affected by adding impurities.

Superconductor A material that is a perfect conductor with zero resistance to the flow of electric charge.

Charging by contact Transfer of electric charge between objects by rubbing or simple touching.

Charging by induction Redistribution of electric charges in and on objects caused by the electrical influence of a charged object close by but not in contact.

Electrically polarized Term applied to an atom or molecule in which the charges are aligned so that one side has a slight excess of positive charge and the other side a slight excess of negative charge.

Electric field Defined as electric force per unit charge, it can be considered to be an "aura" surrounding charged objects and is a storehouse of electric energy. About a charged point, the field decreases with distance according to the inverse-square law, like a gravitational field. Between oppositely charged parallel plates, the electric field is uniform.

$$\text{Electric field} = \frac{F}{q}$$

Electric potential energy The energy a charged object possesses by virtue of its location in an electric field.

Electric potential The electric potential energy per unit of charge, measured in volts, and often called *voltage:*

$$\text{Voltage} = \frac{\text{electric potential energy}}{\text{charge}}$$

Capacitor An electrical device—in its simplest form, a pair of parallel conducting plates separated by a small distance—that stores electric charge and energy.

REVIEW QUESTIONS

Electricity

1. What term is used for "electricity at rest"?

Electrical Forces

2. Why does the gravitational force between Earth and Moon predominate over electrical forces?

Electric Charges

3. What part of an atom is *positively* charged and what part is *negatively* charged?
4. How does the charge of one electron compare to that of another electron? How does it compare with the charge of a proton?
5. What is normally the net charge of an atom?

Conservation of Charge

6. What is a positive ion? A negative ion?
7. What is meant by saying charge is *conserved?*
8. What is meant by saying charge is *quantized?*
9. What particle has exactly one quantum unit of charge?

Coulomb's Law

10. How does one *coulomb* of charge compare with the charge of a *single* electron?
11. How is Coulomb's law similar to Newton's law of gravitation? How is it different?

Conductors and Insulators

12. Why are metals good conductors both of heat and of electricity?
13. Why are materials such as glass and rubber good insulators?
14. How does a *semiconductor* differ from a *conductor* or an *insulator?*
15. What is a transistor composed of, and what are some of its functions?

Superconductors

16. How does the flow of current differ in a superconductor compared with the flow in ordinary conductors?

Charging

17. What happens to electrons in any charging process?
18. Cite an example of something charged by friction.
19. Cite an example of something charged by contact.
20. Give an example of something charged by induction.
21. What is the primary purpose of a lightning rod?

Charge Polarization

22. How does an electrically *polarized* object differ from an electrically *charged* object?
23. What is an electric dipole?

Electric Field

24. How is the magnitude of an electric field defined? Its direction?
25. Why is there no electric field at the center of a charged spherical conductor?
26. When charges mutually repel and distribute themselves on the surface of conductors, what becomes of the electric field inside the conductor?

Electric Potential

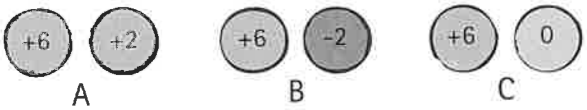
27. How much energy is given to each coulomb of charge that flows through a 1.5-V battery?
28. A balloon may easily be charged to several thousand volts. Does that mean it has several thousand joules of energy? Explain.

Electric Energy Storage

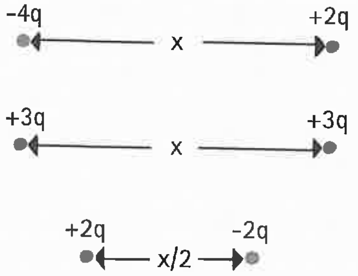
29. Where is the energy stored in a capacitor?
30. What is the magnitude of the electric field inside the dome of a charged van de Graaff generator?

RANKING

1. The three pairs of metal same-size spheres have different charges on their surfaces, as indicated. Each pair is brought together, allowed to touch, and then separated. Rank from greatest to least the total amount of charge on the pairs of spheres after separation.

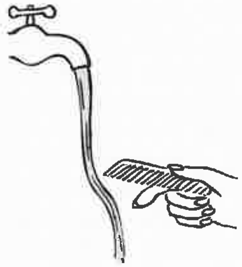


2. Shown are three separate pairs of point charges. Assume the pairs interact only with each other. Rank the magnitudes of the force between the pairs from largest to smallest.



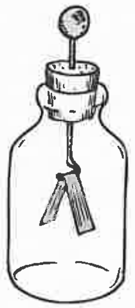
PROJECTS

1. Demonstrate charging by friction and discharging from points with a friend who stands at the far end of a carpeted room. Scuff your way across the rug until your noses are close together. This can be a delightfully tingling experience, depending on how dry the air is and how pointed your noses are.
2. Write a letter to Grandpa and tell him why he'd be safe in a lightning storm if he's inside an automobile.
3. Briskly rub a comb through your hair or on a woolen garment and bring it near a small but smooth stream of running water. Is the stream of water deflected?



EXERCISES

1. At the atomic level, what is meant by saying something is electrically charged?
2. Why is charge usually transferred by electrons rather than by protons?
3. Why are objects with vast numbers of electrons normally not electrically charged?
4. Why do clothes often cling together after tumbling in a clothes dryer?
5. Why will dust be attracted to a DVD wiped with a dry cloth?
6. When you remove your wool suit from the dry cleaner's garment bag, the bag becomes positively charged. Explain how this occurs.
7. Plastic wrap becomes electrically charged when pulled from its box. As a result, it is attracted to objects such as food containers. Does the wrap stick better to plastic containers or to metal containers?
8. When combing your hair, you scuff electrons from your hair onto the comb. Is your hair then positively or negatively charged? How about the comb?
9. At some automobile toll booths, a thin metal wire protrudes from the road, making contact with cars before they reach the toll collector. What is the purpose of this wire?
10. Why are the tires for trucks carrying gasoline and other flammable fluids manufactured to be electrically conducting?
11. An electroscope is a simple device consisting of a metal ball that is attached by a conductor to two thin leaves of metal foil protected from air disturbances in a jar, as shown. When the ball is touched by a charged body, the leaves that normally hang straight down spread apart. Why? (Electroscopes are useful not only as charge detectors but also for measuring the quantity of charge: the more charge transferred to the ball, the more the leaves diverge.)



12. The leaves of a charged electroscope collapse in time. At higher altitudes, they collapse more rapidly. Why is this true? (*Hint:* The existence of cosmic rays was first indicated by this observation.)
13. Is it necessary for a charged body actually to touch the ball of the electroscope for the leaves to diverge? Defend your answer.
14. Strictly speaking, when an object acquires a positive charge by the transfer of electrons, what happens to its mass? What happens to its mass when it acquires a negative charge? (Think small!)
15. Strictly speaking, will a penny be slightly more massive if it has a negative charge or a positive charge? Explain.
16. A crystal of salt consists of electrons and positive ions. How does the net charge of the electrons compare with the net charge of the ions? Explain.
17. How can you charge an object negatively with only the help of a positively charged object?
18. It is relatively easy to strip the outer electrons from a heavy atom like that of uranium (which then becomes a uranium ion), but it is very difficult to remove the inner electrons. Why do you suppose this is so?
19. When one material is rubbed against another, electrons jump readily from one to the other but protons do not. Why is this? (Think in atomic terms.)
20. If electrons were positive and protons were negative, would Coulomb's law be written the same or differently?
21. What does the inverse-square law tell you about the relationship between force and distance?
22. The 5000 billion billion (5×10^{21}) freely moving electrons in a penny repel one another. Why don't they fly out of the penny?

23. How does the magnitude of electrical force between a pair of charged particles change when the particles are moved half as far apart? One-third as far apart?

24. How does the magnitude of electric force compare between a pair of charged particles when they are brought to half their original distance of separation? To one-quarter their original distance? To 4 times their original distance? (What law guides your answers?)

25. When you double the distance between a pair of charged particles, what happens to the force between them? Does it depend on the sign of the charges? What law defends your answer?

26. When you double the charge on only one of a pair of particles, what effect does this have on the force between them? Does the effect depend on the sign of the charge?

27. When you double the charge on both particles in a pair, what effect does this have on the force between them? Does it depend on the sign of the charge?

28. The proportionality constant k in Coulomb's law is huge in ordinary units, whereas the proportionality constant G in Newton's law of gravitation is tiny. What does this indicate about the relative strengths of these two forces?

29. How do electrical field lines indicate the strength of an electric field?

30. How is the direction of an electric field indicated with electrical field lines?

31. Suppose that the strength of the electric field about an isolated point charge has a certain value at a distance of 1 m. How will the electric field strength compare at a distance of 2 m from the point charge? What law guides your answer?

32. In the phenomenon of superconductivity, what happens to electrical resistance at low temperatures?

33. Measurements show that there is an electric field surrounding Earth. Its magnitude is about 100 N/C at Earth's surface, and it points inward toward Earth's center. From this information, can you state whether Earth is negatively or positively charged?

34. Why are lightning rods normally at a higher elevation than the buildings they protect?

35. Why are metal-spiked shoes not a good idea for golfers on a stormy day?

36. If you are caught outdoors in a thunderstorm, why should you not stand under a tree? Can you think of a reason why you should not stand with your legs far apart? Or why lying down can be dangerous? (*Hint:* Consider electric potential difference.)

37. If a large enough electric field is applied, even an insulator will conduct an electric current, as is evident in lightning discharges through the air. Explain how this happens, taking into account the opposite charges in an atom and how ionization occurs.

38. If you rub an inflated balloon against your hair and place it against a door, by what mechanism does it stick? Explain.

39. When a car is moved into a painting chamber, a mist of paint is sprayed around its body. When the body is given a sudden electric charge and mist is attracted to it—presto—the car is quickly and uniformly painted. What does the phenomenon of polarization have to do with this?

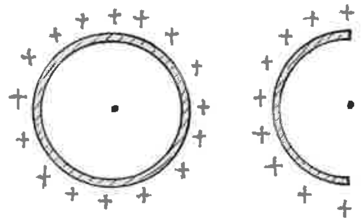
40. How can a charged atom (an ion) attract a neutral atom?

41. If you place a free electron and a free proton in the same electric field, how will the forces acting on them compare?

42. How will the accelerations of the proton and electron in the previous problem compare?

43. How will the directions of travel compare for the electron and proton in the previous problem?

44. Two pieces of plastic, a full ring and a half ring, have the same radius and charge density. Which electric field at the center has the greater magnitude? Defend your answer.



45. Why is the magnitude of the electric field zero midway between identical point charges?

46. Imagine a proton at rest a certain distance from a negatively charged plate. It is released and collides with the plate. Then imagine the similar case of an electron at rest the same distance away from a positively charged plate. In which case will the moving particle have the greater speed when the collision occurs? Why?

47. A gravitational field vector points toward Earth; an electric field vector points toward an electron. Why do electric field vectors point away from protons?

48. By what specific means do the bits of fine threads align in the electric fields shown in Figure 22.19?

49. Suppose that a metal file cabinet is charged. How will the charge concentration at the corners of the cabinet compare with the charge concentration on the flat parts of the cabinet?

50. If you were to expend 10 J of work to push a 1-C charge against an electric field, what would be its change of voltage?

51. When released, what will be the kinetic energy of the 1-C charge of the previous problem if it flies past its starting position?

52. You are not harmed by contact with a charged metal ball, even though its voltage may be very high. Is the reason similar to why you are not harmed by the greater-than-1000°C sparks from a Fourth-of-July sparkler? Defend your answer in terms of the energies that are involved.

53. What is the voltage at the location of a 0.0001-C charge that has an electric potential energy of 0.5 J (both measured relative to the same reference point)?

54. Why is it safe to remain inside a car during a lightning storm?

55. How do the charges on opposing plates of a capacitor compare?

56. In order to store more energy in a parallel-plate capacitor whose plates differ by a fixed voltage, what change would you make in the plates?

57. Why is it dangerous to touch the terminals of a high-voltage capacitor even after the charging circuit is turned off?

58. An electron volt, eV, is a unit of energy. Which is larger, a GeV or a MeV?

59. Would you feel any electrical effects if you were inside the charged sphere of a Van de Graaff generator? Why or why not?

60. A friend says that the reason one's hair stands out while touching a charged Van de Graaff generator is simply that the hair strands become charged and are light enough so that the repulsion between strands is visible. Do you agree or disagree?

PROBLEMS

1. Two point charges are separated by 6 cm. The attractive force between them is 20 N. Find the force between them when they are separated by 12 cm. (Why can you solve this problem without knowing the magnitudes of the charges?)

2. Suppose that the charges attracting each other in the preceding problem have equal magnitude. Rearrange Coulomb's law and show that the magnitude of each charge is 2.8×10^{-6} C (2.8 microcoulombs).

3. Two pellets, each with a charge of 1 microcoulomb (10^{-6} C), are located 3 cm (0.03 m) apart. Show that the electric force between them is 10 N. What would be the mass of an object that would experience this same force in Earth's gravitational field?

4. Electronic types neglect the force of gravity on electrons. To see why, compute the force of Earth's gravity on an electron and compare it with the force exerted on the electron by an electric field of magnitude 10,000 V/m (a relatively small field). The mass and charge of an electron are given on the inside back cover.

5. Atomic physicists ignore the effect of gravity within an atom. To see why, calculate and compare the gravitational and electrical forces between an electron and a proton separated by 10^{-10} m. The charges and masses are given on the inside back cover.

6. A droplet of ink in an industrial ink-jet printer carries a charge of 1.6×10^{-10} C and is deflected onto paper by a force of 3.2×10^{-4} N. Show that the strength of the electric field to produce this force is 2 million N/C.

7. The potential difference between a storm cloud and the ground is 100 million V. If a charge of 2 C flashes in a bolt from cloud to Earth, what is the change of potential energy of the charge?

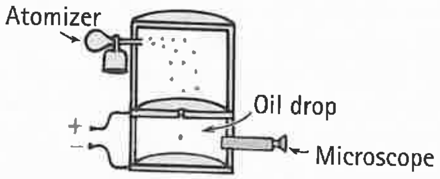
8. An energy of 0.1 J is stored in the metal sphere on top of a Van de Graaff generator. A spark carrying 1 microcoulomb (10^{-6} C) discharges the sphere. Show that the sphere's potential relative to ground is 100,000 V?

9. Find the voltage change when (a) an electric field does 12 J of work on a 0.0001-C charge; (b) the same electric field does 24 J of work on a 0.0002-C charge.

•10. In 1909, Robert Millikan was the first to find the charge of an electron in his now-famous oil-drop experiment. In that experiment tiny oil drops were sprayed into a uniform electric field between a horizontal pair of oppositely charged plates. The drops were observed with a magnifying eyepiece, and the electric field was adjusted so that the upward force on some negatively charged oil drops was just sufficient to balance the downward force of gravity. That is, when suspended, upward force qE just equaled mg. Millikan accurately measured the charges on many oil drops and found the values to be whole-number multiples of 1.6×10^{-19}C—the charge of the electron. For this he won the Nobel Prize.

   a. If a drop of mass 1.1×10^{-14} kg remains stationary in an electric field of 1.68×10^5 N/C, what is the charge of this drop?

   b. How many extra electrons are on this particular oil drop (given the presently known charge of the electron)?



CHAPTER 22 ONLINE RESOURCES

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23 Electric Current

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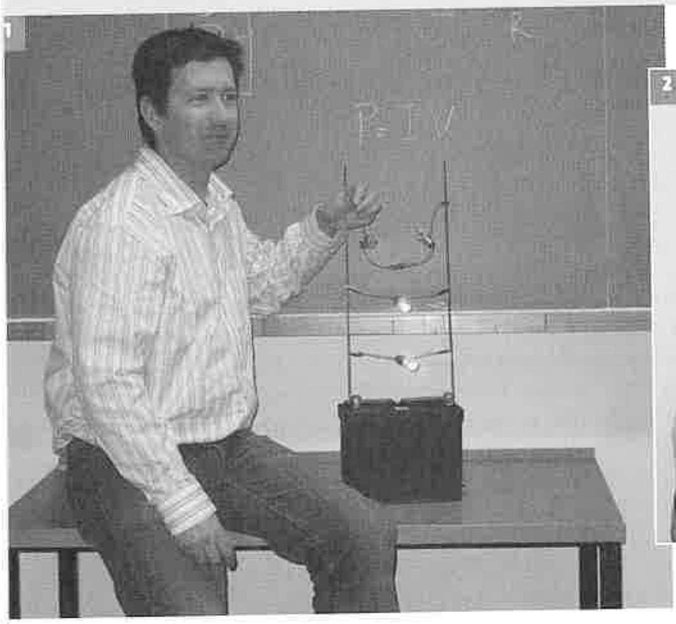

2


3


1 David Housden constructs a parallel circuit by fastening lamps to extended terminals of a common car battery. He asks his class to predict the relative brightness of the identical lamps in the top branch. 2 Juliet Layugan leads her class in a discussion of the relative efficiencies of a compact fluorescent lamp and an incandescent bulb. 3 Will Maynez shows his lab class how to connect batteries in series, and then in parallel, and predict their effects on lighting the lamps.

Electric current is the flow of charge, pressured into motion by voltage, and hampered by resistance. The mathematical relationship among the three quantities current, voltage, and resistance is credited to the German scientist Georg Simon Ohm, who was born in 1789. His father was a locksmith and his mother was the daughter of a tailor. Neither had formal education. Ohm's self-educated father gave his sons an excellent home education, with his brother Martin going on to become a well-known mathematician.

Georg Simon Ohm
(1789–1854)

In 1805, at age 15, Ohm entered the University of Erlangen. But instead of concentrating on his studies, he spent much time dancing, ice skating, and playing billiards. Ohm's father, angry that Georg was wasting his educational opportunity, sent him to Switzerland, where, in September 1806, at a mere 16 years of age, he became a mathematics teacher. He left his teaching post 2½ years later and became a tutor, continuing with his passion of studying mathematics. His studies paid off. Returning to the University of Erlangen, he earned his doctorate in 1811, joining the staff of that university as a mathematics lecturer. But the lectureship paid so little that he soon gave it up and spent the next 6 years teaching in undistinguished schools in Bavaria. During this time he wrote an elementary book on geometry. The book impressed King Wilhelm III of Prussia, who offered Ohm a teaching position in Cologne. Luckily, the physics lab at the school was well equipped, so Ohm devoted himself to experimentation on physics. His practical experience with his father's locksmith activities proved helpful.

Ohm wrote extensively, and his Ohm's law was not fully appreciated at the time. His work was eventually recognized in 1841 by the Royal Society with its award of the prestigious Copley Medal. Ohm became a professor of experimental physics at the University of Munich, where he remained until he died at age 65.

The SI unit of electrical resistance, the ohm (symbol Ω), is named after him.

Flow of Charge

From our study of heat and temperature, recall that when the ends of a conducting material are at different temperatures, heat energy flows from the higher temperature to the lower temperature. The flow ceases when both ends reach the same temperature. Similarly, when the ends of an electrical conductor are at different electric potentials—when there is a **potential difference**—charge flows from one end to the other.[1] The flow of charge persists for as long as there is a potential difference. Without a potential difference, no charge flows. Connect one end of a wire to the charged sphere of a Van de Graaff generator, for example, and the other end to the ground, and a surge of charge will flow through the wire. The flow will be brief, however, because the sphere will quickly reach a common potential with the ground.

To attain a sustained flow of charge in a conductor, some arrangement must be provided to maintain a difference in potential while charge flows from one end to the other. The situation is analogous to the flow of water from a higher reservoir to a lower one (Figure 23.1a). Water will flow in a pipe that connects the reservoirs only as long as a difference in water level exists. The flow of water in the pipe, like the flow of charge in the wire that connects the Van de Graaff generator to the ground, will cease when the pressures at each end are equal (we imply this when we say that water seeks its own level). A continuous flow is possible if the difference in water levels—hence the difference in water pressures—is maintained with the use of a suitable pump (Figure 23.1b).

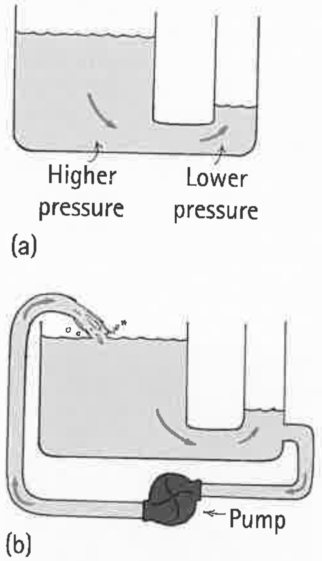

FIGURE 23.1

(a) Water flows from the reservoir of higher pressure to the reservoir of lower pressure. The flow ceases when the difference in pressure ceases.
(b) Water continues to flow because a difference in pressure is maintained with the pump.

CHECK POINT

Okay, so a potential difference across the ends of a wire produces current. Instead of saying *potential difference*, can we as well say *voltage?*

Check Your Answer

Yes. Recall from the previous chapter that potential difference and voltage are interchangeable terms—the difference in electrical potential between two points in a conducting path. Both are measured in units of volts.

Electric Current

Just as water current is the flow of H_2O molecules, **electric current** is simply the flow of electric charge. In circuits of metal wires, electrons make up the flow of charge. This is because one or more electrons from each metal atom are free to move throughout the atomic lattice. These charge carriers are called *conduction electrons.* Protons, on the other hand, do not move because they are bound inside the nuclei of atoms that are more or less locked in fixed positions. In conducting fluids, however—such as in a car battery—positive ions as well as electrons compose the flow of electric charge.

We often think of current flowing through a circuit, but don't say this around somebody who is picky about grammar because the expression "current flows" is redundant. More properly, charge flows—which *is* current.

---

[1] When we say that charge flows, we mean that charged *particles* flow. Charge is a property of particular particles, most significantly electrons, protons, and ions. When the flow is of negative charge, electrons or negative ions constitute the flow. When the flow of charge is positive, protons or positive ions are flowing.

The *rate* of electrical flow is measured in *amperes.* One ampere is a rate of flow equal to 1 coulomb of charge per second. (Recall that 1 coulomb, the standard unit of charge, is the electric charge of 6.25 billion billion electrons.) In a wire that carries 5 amperes, for example, 5 coulombs of charge pass any cross section in the wire each second. So that's a lot of electrons! In a wire that carries 10 amperes, twice as many electrons pass any cross section each second.

fyi

- Andre Marie Ampere is often referred to as "the Newton of electricity." In the 1820s, he showed that parallel wires carrying current in the same direction attract each other, and he postulated that circulating charge is responsible for magnetism. In his honor, the unit for current is amperes, often shortened to *amps*.

Voltage Sources

Charges flow only when they are "pushed" or "driven." A sustained current requires a suitable pumping device to provide a difference in electric potential—a voltage. If we charge one metal sphere positively and another negatively, we can develop a large voltage between the spheres. This voltage source is not a good electrical pump because, when the spheres are connected by a conductor, the potentials equalize in a single brief surge of moving charges—like discharging a Van de Graaff generator. It is not practical. Generators or chemical batteries, on the other hand, are suitable pumps in electric circuits and can maintain a steady flow.

FIGURE 23.2

Each coulomb of charge made to flow in a circuit that connects the ends of this 1.5-V flashlight cell is energized with 1.5 J.

Batteries and electric generators do work to pull negative charges away from positive ones. In chemical batteries, this work is usually, but not always, done by the chemical disintegration of zinc or lead in acid, and the energy stored in the chemical bonds is converted to electric potential energy.[2] Generators, such as alternators in automobiles, separate charge by electromagnetic induction, a process we will describe in Chapter 25. The work done by whatever means in separating the opposite charges is available at the terminals of the battery or generator. These different values of energy per charge create a difference in potential (voltage). This voltage provides the "electrical pressure" to move electrons through a circuit.

fyi

- A single flashlight cell supplies 1.5 V. Inside a 9-V battery are six little cells of 1.5 V each.

The unit of electric potential difference (voltage) is the *volt.*[3] A common automobile battery will provide an electrical pressure of 12 V to a circuit connected across its terminals. Then 12 J of energy are supplied to each coulomb of charge that is made to flow in the circuit joined to these terminals.

FIGURE 23.3

An unusual source of voltage. The electric potential between the head and tail of the electric eel *(Electrophorus electricus)* can be up to 600 V.

There is often some confusion about charge flowing *through* a circuit and voltage placed, or impressed, *across* a circuit. We can distinguish between these ideas by considering a long pipe filled with water. Water will flow *through* the pipe if

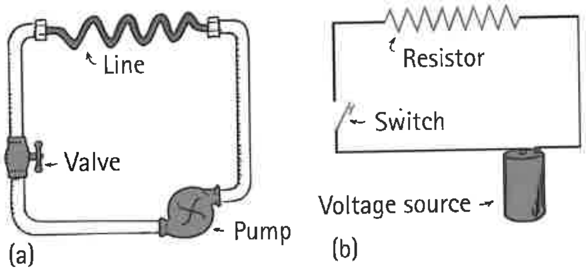

FIGURE 23.4

(a) In a hydraulic circuit, a narrow pipe (green) offers resistance to water flow. (b) In an electric circuit, a lamp or other device (shown by the zigzag symbol for resistance) offers resistance to electron flow.

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[2] The life of a battery depends on the length of time it shares its chemical energy with circuit devices. Like water pipes that become clogged with overuse and time, batteries build up resistance that further shortens their useful lives. An explanation of how batteries operate can be found in almost any chemistry textbook.

[3] The terminology of this area of physics can be confusing, so a repetition of terms may be useful: *Electric potential* and *potential* mean the same thing—electrical potential energy per unit charge. Its units are volts. The term *voltage* is usually used to indicate the *difference* in electrical potential between two points in a conducting path. Units of voltage are also volts.

there is a difference in pressure *across* (or between) its ends. Water flows from the high-pressure end to the low-pressure end. Only the water flows, not the pressure. Similarly, electric charge flows because of the differences in electrical pressure (voltage). You say that charges flow *through* a circuit because of an applied voltage *across* the circuit. You don't say that voltage flows through a circuit. Voltage doesn't go anywhere, for it is the charges that move. Voltage produces current (if there is a complete circuit).

Store your batteries in a cool, dry place. If you put them in a refrigerator they'll last a bit longer.

CHECK POINT

Is the voltage between two points in an electric circuit related to the flow of electrons between the points?

Check Your Answer

Yes, and we will soon see it relates to the amount of energy given to the electrons.

fyi

- While Alessandro Volta was experimenting with metals and acids in 1791 he touched a silver spoon and a piece of tin to his tongue (saliva is slightly acidic) and connected them with a piece of copper wire. The sour taste indicated electricity. He went on to assemble a pile of cells to form a battery. In Volta's honor, electric potential is measured in units of "volts." (Touch the two terminals of a 9-volt battery to your tongue to experience this for yourself.)

Electrical Resistance

We know that a battery or generator of some kind is the prime mover and source of voltage in an electric circuit. How much current exists depends not only on the voltage but also on the **electrical resistance** the conductor offers to the flow of charge. This is similar to the rate of water flow in a pipe, which depends not only on the pressure difference between the ends of the pipe but also on the resistance offered by the pipe itself. A short pipe offers less resistance to water flow than a long pipe; the wider the pipe, the less the resistance. Likewise for the resistance of wires that carry current. The resistance of a wire depends both on the thickness and length of the wire and on its particular conductivity. Thick wires have less resistance than thin wires. Longer wires have more resistance than short wires. Copper wire has less resistance than steel wire of the same size. Electrical resistance also depends on temperature. The greater the jostling about of atoms within the conductor, the greater resistance the conductor offers to the flow of charge. For most conductors, increased temperature means increased resistance.[4] The resistance of some materials reaches zero at very low temperatures. These are the superconductors discussed briefly in the previous chapter.

Electrical resistance is measured in units called *ohms.* The Greek letter *omega,* Ω, is commonly used as the symbol for the ohm. As mentioned at the beginning of this chapter, this unit is named after Georg Simon Ohm, who, in 1826, discovered a simple and very important relationship among voltage, current, and resistance.

FIGURE 23.5

More water flows through a thick hose than through a thin one connected to a city's water system (same water pressure). Likewise for electric current in thick and thin wires connected across the same potential difference.

CHECK POINT

When electrons flow in a thin lamp filament they experience "friction." What is the practical outcome of this?

Check Your Answer

Heat and light!

The unit of electrical resistance is the ohm, Ω, like the song of old: "Ω, Ω on the Range."

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[4] Carbon is an interesting exception. As temperature increases, more carbon atoms shake loose an electron. This increases the electric current. So the resistance of carbon lowers with increasing temperature. This and (primarily) its high melting point are why carbon is used in arc lamps.

Ohm's Law

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Video
Ohm's Law

The relationship among voltage, current, and resistance is summarized by a statement called **Ohm's law.** Ohm discovered that the current in a circuit is directly proportional to the voltage established across the circuit and is inversely proportional to the resistance of the circuit. In short,

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}$$

Or, in units form,

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}$$

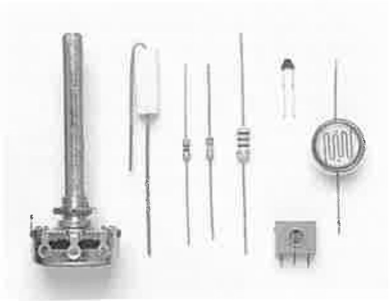


FIGURE 23.6
Resistors. The symbol of resistance in an electric circuit is -/\/\/\-.

So, for a given circuit of constant resistance, current and voltage are proportional to each other.[5] This means that we'll get twice the current for twice the voltage. The greater the voltage, the greater the current. But, if the resistance of a circuit is doubled, the current will be half what it would be otherwise. The greater the resistance, the smaller the current. Ohm's law makes good sense.

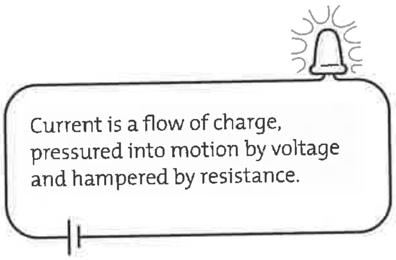
Ohm's law tells us that a potential difference of 1 V established across a circuit that has a resistance of 1 Ω will produce a current of 1 A. If a voltage of 12 V is impressed across the same circuit, the current will be 12 A. The resistance of a typical lamp cord is much less than 1 Ω, while a typical incandescent bulb has a resistance of more than 100 Ω. An iron or an electric toaster has a resistance of 15–20 Ω. Remember that for a given potential difference, less resistance means more current. In the interior of such electrical devices as computers and television receivers, current is regulated by circuit elements called *resistors,* whose resistance may be a few ohms or millions of ohms.

CHECK POINT

1. How much current is drawn by a 60-Ω resistor when a voltage of 12 V is impressed across it?
2. What is the resistance of an electric frying pan that draws 12 A when connected to a 120-V circuit?

Check Your Answers

1. 1/5 A. From Ohm's law: Current $= \frac{\text{voltage}}{\text{resistance}} = \frac{12\ \text{V}}{60\ \Omega} = 0.2\ \text{A}.$
2. 10 Ω. Rearrange Ohm's law: Resistance $= \frac{\text{voltage}}{\text{current}} = \frac{120\ \text{V}}{12\ \text{A}} = 10\ \Omega.$



Current is a flow of charge, pressured into motion by voltage and hampered by resistance.

OHM'S LAW AND ELECTRIC SHOCK

The damaging effects of electric shock are the result of current passing through the body. What causes electric shock in the body—current or voltage? From Ohm's law, we can see that this current depends both on the voltage that is applied and on the electrical resistance of the human body. The resistance of one's body, which depends on its condition, ranges from about 100 Ω if it is soaked with saltwater to about 500,000 Ω if the skin is very dry. If we touch the two electrodes of a battery with

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[5] Many texts use V for voltage, I for current, and R for resistance, and express Ohm's law as $V = IR$. It then follows that $I = \frac{V}{R}$, or $R = \frac{V}{I}$, so if any two variables are known, the third can be found. Units are abbreviated V for volts, A for amperes, and Ω for ohms.

dry fingers, completing the circuit from one hand to the other, we can expect to offer a resistance of about 100,000 Ω. We usually cannot feel the current produced by 12 V, and 24 V just barely tingles. If our skin is moist, 24 V can be quite uncomfortable. Table 23.1 describes the effects of different amounts of current on the human body.

Many people are killed each year by current from common 120-V electric circuits. If you touch a faulty 120-V light fixture with your hand while you are standing on the ground, there is a 120-V "electrical pressure" between your hand and the ground, so the current would probably not be enough to do serious harm. But if you are standing barefoot in a wet bathtub connected through its plumbing to the ground, the resistance between you and the ground is very small. Your overall resistance is so low that the 120-V potential difference may produce a harmful current in your body. Handling electrical devices while taking a bath is a definite no-no. Drops of water that collect around the on–off switches of such devices as a hair dryer can conduct current to the user. Although distilled water is a good insulator, the ions in ordinary tap water greatly reduce the electrical resistance. These ions are contributed by dissolved materials, especially salts. There is usually a layer of salt left from perspiration on your skin, which, when your skin is wet, lowers your skin resistance to a few hundred ohms or less, depending on the distance over which the voltage acts.

To receive a shock, there must be a *difference* in electric potential between one part of your body and another part. Most of the current will pass along the path of least electrical resistance connecting these two points. Suppose you fell from a bridge and managed to grab onto a high-voltage power line, halting your fall. So long as you touch nothing else of different potential, you will receive no shock at all. Even if the wire is a few thousand volts above ground potential and you hang by it with two hands, no appreciable charge will flow from one hand to the other. This is because there is no appreciable difference in electric potential between your hands. If, however, you reach over with one hand and grab onto a wire of different potential . . . *zap!* We have all seen birds perched on high-voltage wires. Every part of their bodies is at the same high potential as the wire, so they feel no ill effects.

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Video
Handling Electric Wires
Birds and High-Voltage Wires

FIGURE 23.7

The bird can stand harmlessly on one wire of high potential, but it had better not reach over and grab a neighboring wire!

TABLE 23.1

Effect of Electric Currents on the Body

Current (A)	Effect
0.001	Can be felt
0.005	Is painful
0.010	Causes involuntary muscle contractions (spasms)
0.015	Causes loss of muscle control
0.070	If through the heart, causes serious disruption; probably fatal if current lasts for more than 1 s

CHECK POINT

If the two feet of a bird on the high-potential wire of a power line are widely spaced, won't it get a shock?

Check Your Answer

No, because there is no appreciable *difference* in potential between its feet.

Most electric plugs and sockets today are wired with three, instead of two, connectors. The principal two flat prongs on an electrical plug are for the current-carrying

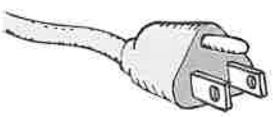

FIGURE 23.8

The round prong connects the body of the appliance directly to ground (Earth). Any charge that builds up on an appliance is therefore conducted to the ground, thereby preventing accidental shock.

double wire, one part of which is "live" (energized) and the other neutral, while the round prong connects to a wire in the electrical system that is grounded—connected directly to the ground (Figure 23.8). The electric appliance at the other end of the plug is, therefore, connected to all three wires. If the live wire of the appliance accidentally comes in contact with the metal surface of the appliance and you touch the appliance, you could receive a dangerous shock. This won't occur when the appliance casing is grounded via the ground wire, which assures that the appliance casing is always at zero ground potential.

Electric shock can overheat tissues in the body and disrupt normal nerve functions. It can upset the rhythmic electrical patterns that maintain proper heartbeat, and it can upset the nerve center that controls breathing. In rescuing shock victims, the first thing to do is to locate and turn off the power source. Then do CPR until help arrives. For heart-attack victims, on the other hand, a properly administered electric shock can sometimes be beneficial in getting the heartbeat started again.

CHECK POINT

1. If your body resistance is 100,000 Ω, how much current will you experience if you touch the terminals of a 12-V battery?
2. If your skin is very moist, so that your resistance is only 1000 Ω, and you again touch the battery terminals, how much current will you experience?

Check Your Answers

1. $\text{Current} = \dfrac{\text{voltage}}{\text{resistance}} = \dfrac{12\text{ V}}{100{,}000\ \Omega} = 0.00012\text{ A.}$
2. $\text{Current} = \dfrac{\text{voltage}}{\text{resistance}} = \dfrac{12\text{ V}}{1{,}000\ \Omega} = 0.012\text{ A. Ouch!}$

Direct Current and Alternating Current

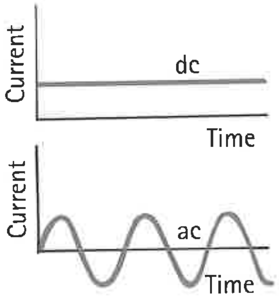

FIGURE 23.9

Time graphs of dc and ac.

Electric current may be dc or ac. By *dc,* we mean **direct current,** which refers to the flowing of charges in *one direction.* A battery produces direct current in a circuit because each terminal of a battery always has the same sign: the positive terminal is always positive, and the negative terminal is always negative. Electrons move from the repelling negative terminal toward the attracting positive terminal, always moving through the circuit in the same direction. Even if the current occurs in unsteady pulses, so long as electrons move in one direction only, it is dc.

Alternating current (ac) acts as the name implies. Electrons in the circuit are moved first in one direction and then in the opposite direction, alternating to and fro about relatively fixed positions. This is accomplished by alternating the polarity of voltage at the generator or other voltage source. Nearly all commercial ac circuits in North America involve voltages and currents that alternate back and forth at a frequency of 60 cycles per second. This is 60-hertz current. In some places, 25-hertz, 30-hertz, or 50-hertz current is used. Throughout the world, most residential and commercial circuits are ac because electric energy in the form of ac can easily be stepped up to high voltage for long-distance transmission with small heat losses, then stepped down to convenient voltages where the energy is consumed. Why this is so will be discussed in Chapter 25.

The voltage of ac in North America is normally 120 V. In the early days of electricity, higher voltages burned out the filaments of electric lightbulbs. Tradition has it that 110 V was first adopted as the standard because it made bulbs of the day glow as brightly as a gas lamp. So the hundreds of power plants built in the United States prior to 1900 produced electricity at 110 V (or 115 or 120 V). By the time electricity became popular in Europe, engineers had figured out how to manufacture lightbulbs

In ac circuits, 120 V is the "root-mean-square" average of the voltage. The actual voltage in a 120-V ac circuit varies between −170 volts and 170 volts, delivering the same power to an iron or a toaster as a 120-V dc circuit.

that would not burn out so fast at higher voltages. Power transmission is more efficient at higher voltages, so Europe adopted 220 volts as their standard. The United States continued with 110 V (today officially 120 V) because so much 110-V equipment was already installed. (Certain appliances, such as electric stoves and clothes dryers, presently use higher voltage.)

The primary use of electric current, whether dc or ac, is to transfer energy quietly, flexibly, and conveniently from one place to another.

CONVERTING AC TO DC

Household current is ac. The current in a battery-operated device, such as a laptop computer, is dc. You can operate these devices on ac instead of batteries with an ac–dc converter. In addition to a transformer to lower the voltage (Chapter 25), the converter uses a *diode,* a tiny electronic device that acts as a one-way valve to allow electron flow in one direction only (Figure 23.10). Since alternating current changes its direction each half-cycle, current passes through a diode only half of each period. The output is a rough dc, and it is off half the time. To maintain continuous current while smoothing the bumps, a capacitor is used (Figure 23.11).

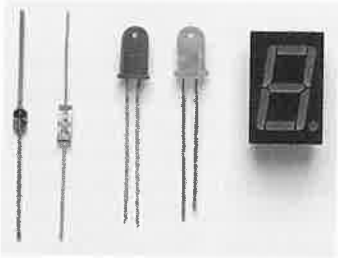

FIGURE 23.10

Diodes. As the symbol —▶|— suggests, current flows in the direction of the arrow but not in the reverse direction.

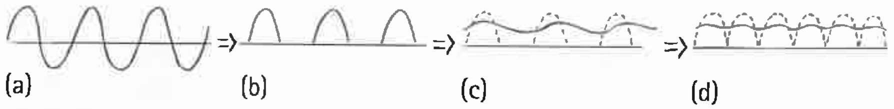

FIGURE 23.11

(a) When input to a diode is ac, (b) output is pulsating dc. (c) Slow charging and discharging of a capacitor provides continuous and smoother current. (d) In practice, a pair of diodes is used, so there are no gaps in current output. The pair of diodes reverses the polarity of alternate half-cycles instead of eliminating them.

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Alternating Current

Recall, from the previous chapter, that a capacitor acts as a storage reservoir for charge. Just as it takes time to raise the water level in a reservoir when water is added, it takes time to add or remove electrons from the plates of a capacitor. A capacitor, therefore, produces a retarding effect on changes in the flow of charge. It opposes changes in voltage and smoothes the pulsed output.

FIGURE 23.12

Water input to the reservoir may be in repeated spurts or pulses, but the output is a fairly smooth stream. Likewise with a capacitor.

Speed and Source of Electrons in a Circuit

When we flip the light switch on a wall and the circuit is completed, either ac or dc, the lamp appears to glow immediately. Current is established through the wires at nearly the speed of light. It is *not* the electrons that move at this speed.[6] Although electrons inside metal at room temperature have an average speed of a few million kilometers per hour, they make no current because they are moving in all possible directions. There is no net flow in any preferred direction. But, when a battery or generator is connected, an electric field is established inside the conductor. The electrons continue their random motions while simultaneously being nudged by this field. It is the electric field that can travel through a circuit at nearly the speed of light. The conducting wire acts as a guide or "pipe" for electric field lines (Figure 23.13). In the space outside the wire, the electric field has a pattern determined by the location of electric charges, including some charges that accumulate on the surface of the wire. Inside the wire, the electric field is directed along the wire.

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[6] Much effort and expense are expended in building particle accelerators that accelerate electrons and protons to speeds near that of light. If electrons in a common circuit traveled that fast, one would only have to bend a wire at a sharp angle and electrons traveling through the wire would possess so much momentum that they would fail to make the turn and would fly off, providing a beam comparable to that produced by the accelerators!

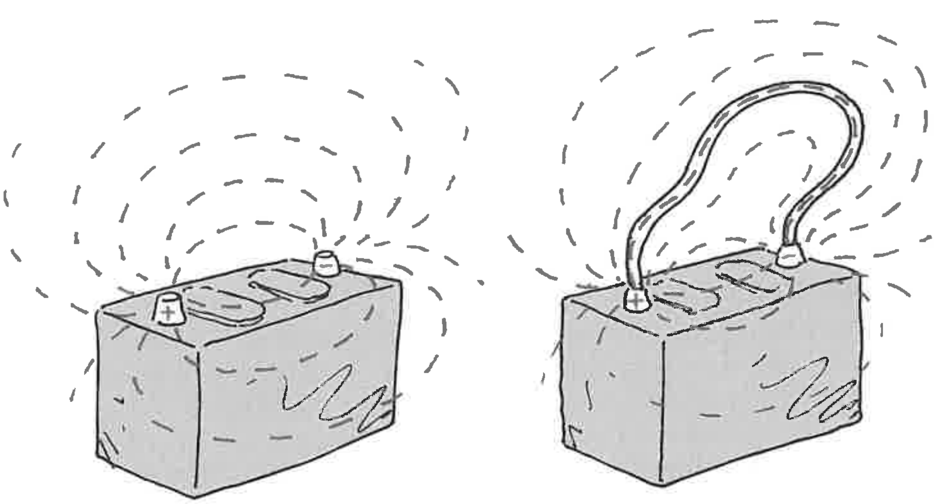

FIGURE 23.13

The electric field lines between the terminals of a battery are directed mainly through a conductor that joins the terminals. A thick metal wire is shown here, but the path from one terminal to the other is usually an electric circuit. (You won't be shocked if you touch this connecting wire, but you might be burned because the wire would likely be very hot!)

If the voltage source is dc, like the battery shown in Figure 23.13, the electric field lines are maintained in one direction in the conductor. Conduction electrons are accelerated by the field in a direction parallel to the field lines. Before they gain appreciable speed, they "bump into" the anchored metallic ions in their paths and transfer some of their kinetic energy to them. This is why current-carrying wires become hot. These collisions interrupt the motion of the electrons, so the speed at which they migrate along a wire is extremely low. This net flow of electrons is the *drift velocity*. In a typical dc circuit—the electrical system of an automobile, for example—electrons have a drift velocity that averages about a hundredth of a centimeter per second. At this rate, it would take about 3 hours for an electron to travel through 1 meter of wire! Large currents are possible because of large numbers of flowing electrons. So although an electric signal travels at nearly the speed of light in a wire, the electrons that move in response to this signal actually travel slower than a snail's pace.

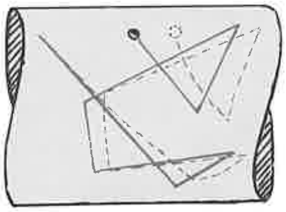

FIGURE 23.14

The solid lines suggest the random path of an electron jostling about in an atomic lattice at an average speed of about 1/200 the speed of light. The dashed lines suggest an exaggerated and idealized view of how this path is altered when an electric field is applied. The electron drifts toward the right with a *drift velocity* that is very slow.

In an ac circuit, the conduction electrons don't progress along the wire at all. They oscillate rhythmically to and fro about relatively fixed positions. When you talk to your friend on a conventional land telephone, it is the *pattern* of oscillating motion that is transmitted across town at nearly the speed of light. The electrons already in the wires vibrate to the rhythm of the traveling pattern.

A common misconception regarding electrical currents is that the current is propagated through the conducting wires by electrons bumping into one another—that an electrical pulse is transmitted in a manner similar to the way the pulse of a tipped domino is transferred along a row of closely spaced standing dominoes. This simply isn't true. The domino idea is a good model for the transmission of sound, but not for the transmission of electric energy. Electrons that are free to move in a conductor are accelerated by the electric field impressed upon them, but not because they bump into one another. True, they do bump into one another and other atoms, but this slows them down and offers resistance to their motion. Electrons throughout the entire closed path of a circuit all react simultaneously to the electric field.

After failing more than 6000 times before perfecting the first electric lightbulb, Edison stated that his trials were not failures, because he successfully discovered 6000 ways that don't work.

Another common misconception about electricity is the source of electrons. In a hardware store, you can buy a water hose that is empty of water. But you can't buy a piece of wire, an "electron pipe," that is empty of electrons. The source of electrons in a circuit is the conducting circuit material itself. Some people think that the electrical outlets in the walls of their homes are a source of electrons. They incorrectly assume that electrons flow from the power utility through the power lines and into the wall outlets of their homes. This assumption is false. The outlets in homes are ac. Electrons make no net migration through a wire in an ac circuit.

When you plug a lamp into an outlet, *energy* flows from the outlet into the lamp, not electrons. Energy is carried by the pulsating electric field and causes vibratory motion of the electrons that already exist in the lamp filament. If a voltage of 120 V is impressed on a lamp, then an average of 120 J of energy is dissipated by each coulomb of charge that is made to vibrate. Most of this electrical energy appears as heat, while some transforms to light. Power utilities do not sell electrons. They sell *energy*. You supply the electrons.

So, when you are jolted by an electric shock, the electrons making up the current in your body originate in your body. Electrons do not emerge from the wire and pass through your body and into the ground; energy does. The energy simply causes free electrons already existing in your body to vibrate in unison. Small vibrations tingle; large vibrations can be fatal.

fyi

- Thomas Edison did much more than invent a functioning incandescent bulb in 1879. He solved the problems of building the dynamos, cable systems, and connections to light New York City. He made the phone work properly, and he gave us recorded music and movies. He also invented a method of inventing: His New Jersey lab was the forerunner of the modern industrial research lab.

CHECK POINT

Consider members of a marching band standing at rest. You can set them into motion in two ways: (1) Give the last person in line a shove that cascades to the first person in line. (2) Issue the command "forward, march." Which of these two is analogous to the way electrons move in a circuit when the switch is closed, and which is analogous to the way sound travels?

Check Your Answer

Issuing the command "forward, march" is analogous to the way electrons move when they sense the electric field that energizes the circuit when the switch is closed. One marcher lurching against the other is analogous to the way sound travels.

Why is it correct to say that the energy from a car battery ultimately comes from the fuel the car consumes?

Electric Power

Unless it is in a superconductor, a charge moving in a circuit expends energy. This may result in heating the circuit or in turning a motor. The rate at which electric energy is converted into another form, such as mechanical energy, heat, or light, is called **electric power.** Electric power is equal to the product of current and voltage.[7]

$$\text{Power} = \text{current} \times \text{voltage}$$

If the voltage is expressed in volts and the current in amperes, then the power is expressed in watts. So, in units form,

$$\text{Watts} = \text{amperes} \times \text{volts}$$

An incandescent bulb rated at 60 W draws a current of 0.5 A (60 W = 0.5 A × 120 V). A 100-W bulb draws about 0.8 A. Interestingly, a 26-W compact fluorescent lamp (CFL) provides about the same amount of light as a 100-W incandescent bulb—only one-quarter of the power for the same light![8]

The relationship between energy and power is a practical matter. From the definition, power = energy per unit time, it follows that energy = power × time.

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[7] Recall, from Chapter 7, that Power = work/time; 1 Watt = 1 J/s. Note that the units for mechanical power and electrical power check (work and energy are both measured in joules):

$$\text{Power} = \frac{\text{charge}}{\text{time}} \times \frac{\text{energy}}{\text{charge}} = \frac{\text{energy}}{\text{time}}$$

[8] It turns out that the power formula, $P = IV$, doesn't hold for CFLs. This is because in a CFL, the alternating voltage and current are out of step with each other (out of phase), and the product of current and voltage is larger than the actual power consumption. How much larger? Check the printed data at the base of a CFL and you can find out.

So an energy unit can be a power unit multiplied by a time unit, such as kilowatt-hours (kWh). One kilowatt-hour is the amount of energy transferred in 1 hour at the rate of 1 kW. Therefore in a locality in which electric energy costs 15 cents per kWh, a 1000-W iron can operate for 1 hour at a cost of 15 cents. A refrigerator, typically rated at around 500 W, costs less for an hour, but much more over the course of a month.

CHECK POINT

At 15¢/kWh, what does it cost to operate a 1200-W hair dryer for 1 h?

Check Your Answer

18¢: 1200 W = 1.2 kW; so 1.2 kW × 1 h × 15¢/kWh = 18¢.

FIGURE 23.15

The power and voltage on a compact fluorescent lamp (CFL) reads "13 W 120 V."

Compact Fluorescent Lamps (CFLs)

The brightness of incandescent lightbulbs can be judged by wattage. A 100-W bulb, for example, glows brighter than a 60-W bulb. But most of the power dissipated by these bulbs is not light—it is heat. At least 90% of the energy transferred by an incandescent bulb is heat. Fluorescent lamps, on the other hand, emit much less heat, which is why you can touch them without burning yourself. Incandescent bulbs are today being replaced by compact fluorescent lamps (CFLs), which are a type of fluorescent lamp that fits into a standard lightbulb socket. For the same wattage, CFLs emit much more light and much less heat than incandescents. That's why you can replace a 100-W incandescent with a CFL of about 25 W and get about the same amount of light. So unless you're using incandescent bulbs to heat a room (which farmers do in chicken coops in the winter), you'll probably benefit by using lower-wattage CFLs. And the lifetimes of CFLs are typically more than 10 times that of incandescent bulbs.

A light source even more long-lasting is the light-emitting diode (LED), the most primitive being the little red lights that tell you whether your stereo is on or off. Between CFLs and LEDs, watch for common-use incandescent bulbs to be history. We'll return to the physics of CFLs and LEDs in Chapter 30.

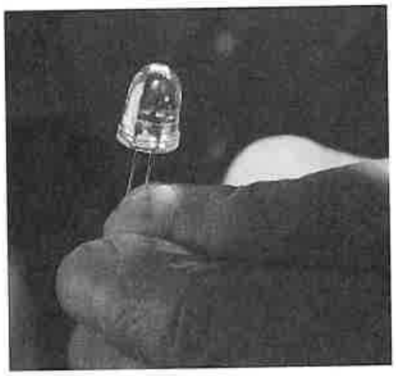

FIGURE 23.16

Another common light source for tomorrow is the light-emitting diode (LED).

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Electric Circuits

Electric Circuits

Any path along which electrons can flow is a *circuit.* For a continuous flow of electrons, there must be a complete circuit with no gaps. A gap is usually provided by an electric switch that can be opened or closed to either cut off or allow energy flow. Most circuits have more than one device that receives electric energy. These devices are commonly connected in a circuit in one of two ways, *series* or *parallel.* When connected in series, they form a single pathway for electron flow between the terminals of the battery, generator, or wall socket (which is simply an extension of these terminals). When connected in parallel, they form branches, each of which is a separate path for the flow of electrons. Both series and parallel connections have their own distinctive characteristics. We shall briefly treat circuits using these two types of connections.

A downside to CFLs is the trace amounts of mercury in them. But the single largest source of mercury emissions in the environment is coal-fired power plants. According to the EPA, when coal power is used to illuminate a single incandescent lamp, more mercury is released in the air than exists in a comparably luminous CFL.

SERIES CIRCUITS

A simple **series circuit** is shown in Figure 23.17. All devices, lamps in this case, are connected end-to-end, forming a single path for electrons to flow. The same current

Fuel Cells

A battery is an energy-storage device. Once its stored chemical energy is converted to electrical energy, its energy is depleted. Then it must be discarded (if it is a disposable battery) or recharged with an opposite flow of electricity.

A *fuel cell,* on the other hand, converts the chemical energy of a fuel to electrical energy continuously and indefinitely, as long as fuel is supplied to it. In one version, hydrogen fuel reacts chemically with oxygen from the air to produce electrons and ions—and water. The ions flow internally within the cell in one direction; the electrons flow externally through an attached circuit in the other direction. Because this reaction directly converts chemical energy to electricity, it is more efficient than if the fuel were burned to produce heat, which, in turn, produces steam to turn turbines to generate electricity. The only "waste product" of such a fuel cell is pure water, suitable for drinking!

The space shuttle uses hydrogen fuel cells to meet its electrical needs. (Its hydrogen and oxygen are both brought on board in pressurized containers.) The cells also produce more than 100 gallons of drinking water for the astronauts during a typical week-long mission. Back on Earth, researchers are perfecting fuel cells for a variety of vehicles. Some fuel-cell buses operate in several cities, such as Vancouver, British Columbia, and Chicago, Illinois. In the future, commercial buildings as well as individual homes may be outfitted with fuel cells as an alternative to receiving electricity from regional power stations.

So why aren't fuel cells more widespread today? Currently, they are more costly than other sources of electricity. But mainly, there is the question of the availability of the choice fuel—hydrogen. Although hydrogen is the most plentiful element in the universe, and is plentiful in our immediate surroundings, it is locked away in water and hydrocarbon molecules. It is not available in a free state (a fact overlooked by people cheering for hydrogen-fueled vehicles NOW). Energy is required to separate hydrogen from molecules in which it is tightly bonded. The energy needed to make hydrogen is presently supplied by conventional energy sources.

Hydrogen is, in effect, an energy-storage medium. Like electricity, it is created in one place and used in another. Hydrogen is a highly volatile gas that is difficult to store, transport, and use safely. Fuel cells will be attractive in the future when these difficulties are minimized, when the cost of fuel cells comes down, and mainly, when the hydrogen needed to fuel them is generated by alternative energy sources such as wind or solar.

exists almost immediately in all three lamps, and also in the battery, when the switch is closed. The greater the current in a lamp, the brighter it glows. Electrons do not "pile up" in any lamp but flow *through* each lamp—simultaneously. Some electrons move away from the negative terminal of the battery, some move toward the positive terminal, and some move through the filament of each lamp. Eventually, the electrons may move all the way around the circuit (the same amount of current passes through the battery). This is the only path of the electrons through the circuit. A break anywhere in the path results in an open circuit, and the flow of electrons ceases. Burning out one of the lamp filaments or simply opening the switch could cause such a break.

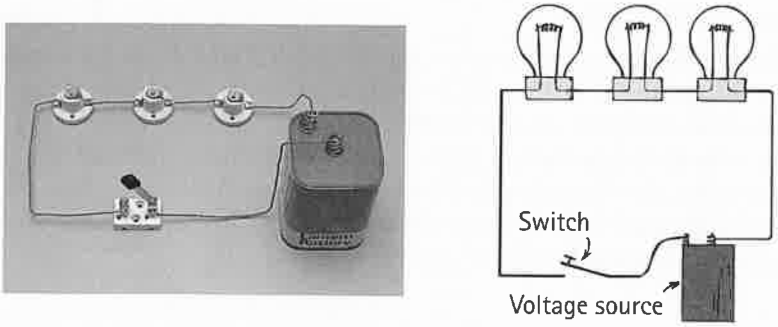

FIGURE 23.17

INTERACTIVE FIGURE

A simple series circuit. The 6-V battery provides 2 V across each lamp.

The circuit shown in Figure 23.17 illustrates the following important characteristics of series connections:

1. Electric current has only a single pathway through the circuit. This means that the current passing through the resistance of each electrical device along the pathway is the same.
2. This current is resisted by the resistance of the first device, the resistance of the second, and that of the third also, so the total resistance to current in the circuit is the sum of the individual resistances along the circuit path.

What is it that gets "used up" in an electric circuit—current or energy?

3. The current in the circuit is numerically equal to the voltage supplied by the source divided by the total resistance of the circuit. This is in accord with Ohm's law.
4. The supply voltage is equal to the sum of the individual "voltage drops" across each device. This is consistent with the total energy supplied to the circuit being equal to the sum of the energies supplied to each device.
5. The voltage drop across each device is proportional to its resistance—Ohm's law applies separately to each device. This follows from the fact that more energy is dissipated when a current passes through a large resistance than when the same current passes through a small resistance.

fyi

- The words *open* and *closed* applied to a door are different when applied to electric circuits. For a door, "open" means free passage and "closed" means blockage. With electrical switches, the terms are opposite: "open" means no flow while "closed" means free passage of electrons.

It is easy to see the main disadvantage of a series circuit: If one device fails, current in the whole circuit ceases. In days of yore, Christmas tree lights were connected in series. When one bulb burned out, it was fun and games (or frustration) trying to locate which bulb to replace.

Most circuits are wired so that it is possible to operate several electrical devices, each independently of the other. In your home, for example, a lamp can be turned on or off without affecting the operation of other lamps or electrical devices. This is because these devices are connected not in series but in parallel with one another.

CHECK POINT

1. What happens to current in other lamps if one lamp in a series circuit burns out?
2. What happens to the brightness of light from each lamp in a series circuit when more lamps are added to the circuit?

Check Your Answers

1. The circuit is broken and all lamps will go out.
2. Adding more lamps in series produces a greater circuit resistance. This decreases the current in the circuit and therefore in each lamp, so the lamps dim. Since all voltages have to add up to the same total voltage, the voltage drop across each lamp will be less.

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PARALLEL CIRCUITS

A simple **parallel circuit** is shown in Figure 23.18. Three lamps are connected to the same two points, A and B. Electrical devices connected to the same two points of an electrical circuit are said to be *connected in parallel.* The pathway for current from one terminal of the battery to the other is completed if only *one* lamp is lit. In this illustration, the circuit branches into three separate pathways from A to B. A break in any one path does not interrupt the flow of charge in the other paths. Each device operates independently of the other devices.

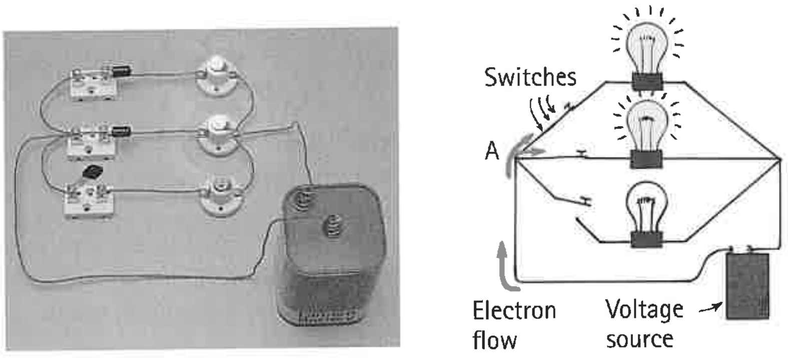


FIGURE 23.18
INTERACTIVE FIGURE

A simple parallel circuit. A 6-V battery provides 6 V across each lamp.

The circuit shown in Figure 23.18 illustrates the following major characteristics of parallel connections:

1. Each device connects the same two points A and B of the circuit. The voltage is therefore the same across each device.
2. The current divides among the parallel branches. Ohm's law applies separately to each branch.
3. The total current in the circuit equals the sum of the currents in its parallel branches. This sum equals the current in the battery or other voltage source.
4. As the number of parallel branches is increased, the overall resistance of the circuit is *decreased.* Overall resistance is lowered with each added path between any two points of the circuit. This means the overall resistance of the circuit is less than the resistance of any one of the branches.

CHECK POINT

1. What happens to the current in other lamps if one of the lamps in a parallel circuit burns out?
2. What happens to the brightness of light from each lamp in a parallel circuit when more lamps are added in parallel?
3. What happens to the current in the battery when more lamps are added in parallel?

Check Your Answers

1. If one lamp burns out, the other lamps are unaffected. This is because current in each branch, according to Ohm's law, is equal to voltage/resistance, and since neither voltage nor resistance is affected in the other branches, the current in those branches is unaffected.
2. The brightness of each lamp is unchanged as other lamps are introduced (or removed).
3. Current in the battery increases by an amount that feeds the added branch(es). In the overall circuit, added paths means decreased resistance. (There is resistance in a battery also, which we assume is negligible here.)

PARALLEL CIRCUITS AND OVERLOADING

Electricity is usually fed into a home by way of two wires called *lines.* These lines, which are very low in resistance, branch into parallel circuits connecting ceiling lights and wall outlets in each room. Lights and wall outlets are connected in parallel, so all are impressed with the same voltage, usually about 110–120 V. As more devices are plugged in and turned on, more pathways for current result in lowering of the combined resistance of each circuit. Therefore, a greater amount of current occurs in the circuits. The sum of these currents equals the line current, which may be more than is safe. The circuit is then said to be *overloaded.*

We can see how overloading occurs by considering the circuit in Figure 23.19. The supply line is connected in parallel to an electric toaster that draws 8 A, to an electric heater that draws 10 A, and to an electric lamp that draws 2 A. When only the toaster is operating and drawing 8 A, the total line current is 8 A. When the heater is also operating, the total line current increases to 18 A (8 A to the toaster and 10 A to the heater). If you turn on the lamp, the line current increases to 20 A. Connecting any more devices increases the current still more. Connecting too many devices into the same circuit results in overheating that may cause a fire.

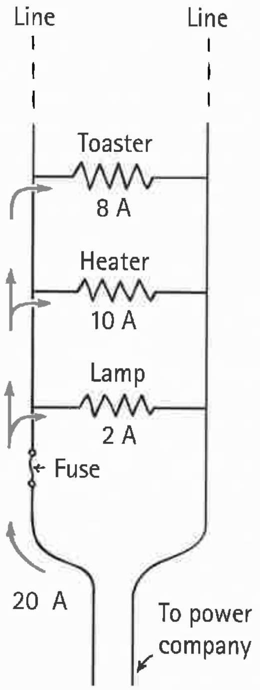


FIGURE 23.19
Circuit diagram for appliances connected to a household circuit.

SAFETY FUSES

To prevent overloading in circuits, fuses may be connected in series along the supply line. In this way, the entire line current must pass through the fuse. The fuse shown in Figure 23.20 is constructed with a wire ribbon that will heat and melt at a given

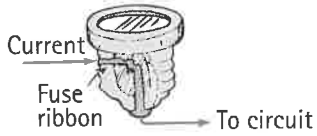


FIGURE 23.20
A safety fuse.

current. If the fuse is rated at 20 A, it will pass 20 A, but no more. A current above 20 A will melt the fuse, which "blows out" and breaks the circuit. Before a blown fuse is replaced, the cause of overloading should be determined and remedied. Often, insulation that separates the wires in a circuit erodes and allows the wires to touch. This greatly reduces the resistance in the circuit, effectively shortening the circuit path, and is called a *short circuit.*

In modern buildings, fuses have been largely replaced by circuit breakers, which use magnets or bimetallic strips to open a switch when the current is too great. Utility companies use circuit breakers to protect their lines all the way back to the generators.

FIGURE 23.21
Electrician Dave Hewitt with a safety fuse and a circuit breaker. He favors the old fuses, which he has found more reliable.

SUMMARY OF TERMS

Potential difference The difference in electric potential between two points, measured in volts. When two points of different electric potential are connected by a conductor, charge flows so long as a potential difference exists. (Synonymous with *voltage difference.*)

Electric current The flow of electric charge that transports energy from one place to another. Measured in amperes, where 1 A is the flow of 6.25×10^{18} electrons per second, or 1 coulomb per second.

Electrical resistance The property of a material that resists electric current. Measured in ohms (Ω).

Ohm's law The statement that the current in a circuit varies in direct proportion to the potential difference or voltage across the circuit and inversely with the circuit's resistance.

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}$$

A potential difference of 1 V across a resistance of 1 Ω produces a current of 1 A.

Direct current (dc) Electrically charged particles flowing in one direction only.

Alternating current (ac) Electrically charged particles that repeatedly reverse direction, vibrating about relatively fixed positions. In the United States, the vibrational rate is commonly 60 Hz.

Electric power The rate of energy transfer, or the rate of doing work; the amount of energy per unit time, which electrically can be measured by the product of current and voltage.

$$\text{Power} = \text{current} \times \text{voltage}$$

Electric power is measured in watts (or kilowatts), where $1\text{ W} = 1\text{ A} \times 1\text{ V} = 1\text{ J/s}$.

Series circuit An electric circuit in which electrical devices are connected along a single wire such that the same electric current exists in all of them.

Parallel circuit An electric circuit in which electrical devices are connected in such a way that the same voltage acts across each one, and any single one completes the circuit independently of all the others.

REVIEW QUESTIONS

Flow of Charge

1. What condition is necessary for the flow of heat? What analogous condition is necessary for the flow of charge?
2. What condition is necessary for the sustained flow of water in a pipe? What analogous condition is necessary for the sustained flow of charge in a wire?

Electric Current

3. Why are *electrons,* rather than *protons,* the principal charge carriers in metal wires?
4. What exactly is an *ampere?*

Voltage Sources

5. Name two kinds of practical "electric pumps."
6. How much energy is supplied to each coulomb of charge that flows through a 12-V battery?
7. Does charge flow *through* a circuit or *into* a circuit? Does voltage flow *through* a circuit, or is voltage established *across* a circuit?

Electrical Resistance

8. Will water flow more easily through a wide pipe or a narrow pipe? Will current flow more easily through a thick wire or a thin wire?
9. Does heating a metal wire increase or decrease its electrical resistance?

Ohm's Law

10. If the voltage impressed across a circuit is held constant while the resistance doubles, what change occurs in the current?
11. If the resistance of a circuit remains constant while the voltage across the circuit decreases to half its former value, what change occurs in the current?
12. How does wetness affect the resistance of your body?
13. What is the function of the round third prong in a modern household electric plug?

Direct Current and Alternating Current

14. Does a battery produce dc or ac? Does the generator at a power station produce dc or ac?
15. What does it mean to say that a certain current is 60 Hz?
16. What property of a diode enables it to convert ac to pulsed dc?
17. A diode converts ac to pulsed dc. What electrical device smoothes the pulsed dc to a smoother dc?

Speed and Source of Electrons in a Circuit

18. What is the error in saying that electrons in a common battery-driven circuit travel at about the speed of light?
19. Why does a wire that carries electric current become hot?
20. What is meant by *drift velocity?*
21. A tipped domino sends a pulse along a row of standing dominoes. Is this a good analogy for the way electric current, sound, or both travel?
22. What is the error in saying the source of electrons in a circuit is the battery or generator?
23. When you make your household electric payment at the end of the month, which of the following are you billed for: voltage, current, power, energy?
24. From where do the electrons originate that produce an electric shock when you touch a charged conductor?

Electric Power

25. What is the relationship among electric power, current, and voltage?
26. Which of these is a unit of power and which is a unit of energy—a watt, a kilowatt, a kilowatt-hour?

Compact Fluorescent Lamps (CFLs)

27. How does the heat emitted by lamps affect their efficiency?

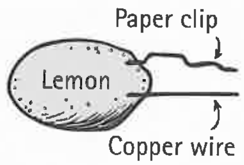
Electric Circuits

28. In a circuit of two lamps in series, if the current through one lamp is 1 A, what is the current through the other lamp? Defend your answer.
29. If a voltage of 6 V is impressed across the circuit in the preceding question and the voltage across the first lamp is 2 V, what is the voltage across the second lamp? Defend your answer.
30. In a circuit of two lamps in parallel, if there is a voltage of 6 V across one lamp, what is the voltage across the other lamp?
31. How does the sum of the currents through the branches of a simple parallel circuit compare with the current that flows through the voltage source?
32. What is the function of fuses or circuit breakers in a circuit?

PROJECTS

1. An electric cell is made by placing two plates made of different materials that have different affinities for electrons in a conducting solution. The voltage of a cell depends on the materials used and the solutions they are placed in, not on the size of the plates. (A cell is often called a battery, but strictly speaking, a battery is a series of cells—for instance, six cells in a 12-V car battery.) You can make a simple 1.5-V cell by placing a strip of copper and a strip of zinc in a tumbler of saltwater.

   An easy cell to construct is the citrus cell. Stick a straightened paper clip and a piece of copper wire into a lemon. Hold the ends of the wire close together, but not touching, and place the ends on your tongue. The slight tingle you feel and the metallic taste you experience result from a slight electric current from the citrus cell through the wires when your moist tongue closes the circuit.



2. Examine the electric meter in your house. It is probably in the basement or on the outside of the house. You will see that, in addition to the clocklike dials in the meter, there is a circular aluminum disk that spins between the poles of magnets when electric current goes into the house. The more electric current, the faster the disk turns. The speed of the disk is directly proportional to the number of watts used; for example, it spins 5 times as fast for 500 W as for 100 W.

   You can use the meter to determine how many watts an electrical device uses. First, see that all electrical devices in your home are disconnected (okay to neglect electric clocks and other 2-W devices, which will hardly be noticeable). The disk will be practically stationary. Then connect a 100-W bulb and note how many seconds it takes for the disk to make five complete revolutions. The black spot painted on the edge of the disk makes this easy. Disconnect the 100-W bulb and plug in a device of unknown wattage. Again, count the seconds for five revolutions. If it takes the same time, it's a

100-W device; if it takes twice the time, it's a 50-W device; half the time, a 200-W device; and so forth. In this way you can estimate the power consumption of devices fairly accurately.

3. Write a letter to Grandma and convince her that whatever electric shocks she may have received over the years have been due to the movement of electrons already in her body—not electrons from somewhere else.

PLUG AND CHUG

Ohm's Law: $I = \dfrac{V}{R}$

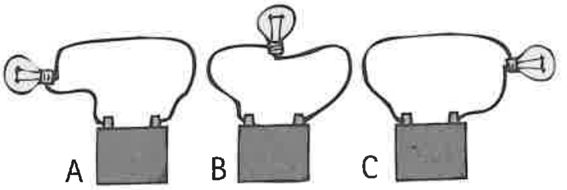
1. Calculate the current in a toaster that has a heating element of 15 Ω when connected to a 120-V outlet.
2. Calculate the current that moves through your fingers (resistance 1000 Ω) when you touch them to the terminals of a 6-V battery.
3. Calculate the current in the 240-Ω filament of a bulb connected to a 120-V line.

Power $= I \times V$

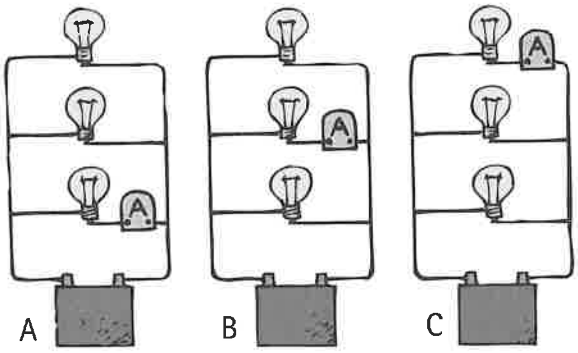
4. Calculate the power of a device that carries 0.5 A when impressed with 120 V.
5. Calculate the power of a hair dryer that operates on 120 V and draws a current of 10 A.
6. Given that the power consumed by a device is 1200 W operating on a 120-V line, calculate the amount of current it draws.

RANKING

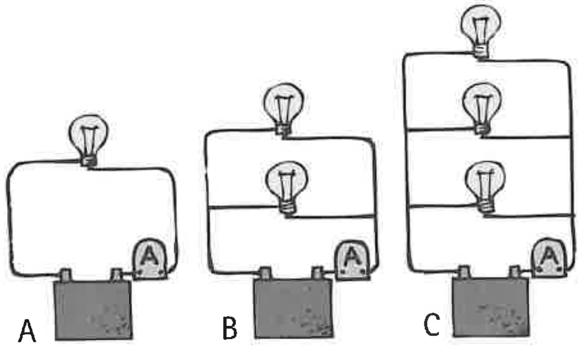
1. Rank the circuits illustrated according to the brightness of the identical bulbs, from brightest to dimmest.



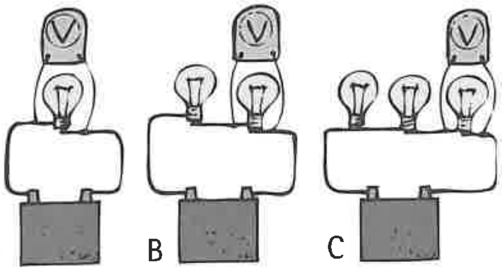
2. The bulbs shown are identical. An ammeter is placed in different locations, as shown. Rank the current readings in the ammeter from greatest to least.



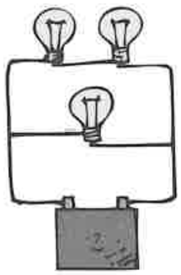
3. All bulbs are identical in the circuits shown. An ammeter is connected next to the battery, as shown. Rank the current readings in the ammeter, from greatest to least.



4. All bulbs are identical in the following circuits. A voltmeter is connected across a single bulb to measure the voltage drop across it. Rank the voltage readings from greatest to least.



5. Consider the three parts of the circuit: A, the top branch with two bulbs; B, the middle branch with one bulb; C, the battery.
   a. Rank the current through each, from greatest to least.
   b. Rank the voltage across each from greatest to least.



EXERCISES

1. What two things can be done to increase the amount of flow in a water pipe? Similarly, what two things can be done to increase the current in an electrical circuit?
2. Consider a water pipe that branches into two smaller pipes. If the flow of water is 10 gallons per minute in the main pipe and 4 gallons per minute in one of the branches, how much water per minute flows in the other branch?
3. Consider a circuit with a main wire that branches into two other wires. If the current is 10 A in the main wire and 4 A in one of the branches, how much current is in the other branch?
4. One example of a water system is a garden hose that waters a garden. Another is the cooling system of an automobile. Which of these exhibits behavior more analogous to an electric circuit? Explain.
5. What happens to the brightness of light emitted by a lightbulb when the current flowing through it increases?
6. Your friend says that a battery supplies the electrons in an electric circuit. Do you agree or disagree? Defend your answer.
7. Is a current-carrying wire electrically charged because of the electrons moving in it?
8. Your tutor tells you that an *ampere* and a *volt* really measure the same thing and that the different terms only serve to make a simple concept seem confusing. Why should you consider getting a different tutor?
9. In which of the circuits shown does a current exist to light the bulb?

10. Does more current flow out of a battery than into it? Does more current flow into a lightbulb than out of it? Explain.
11. Something gets "used up" in a battery that eventually dies and goes flat. One friend says that current is used up. Another friend says that energy is used up. Who, if either, do you agree with, and why?
12. Suppose you leave your car lights on while at a movie. When you return, your battery is too "weak" to start your car. A friend gives you a jump-start with his battery and battery cables. What physics is occurring here?
13. Your friend says that, when jump-starting a dead battery, you should connect your live battery in parallel with the dead battery, which, in effect, replaces the dead one. Do you agree?
14. An electron moving in a wire collides repeatedly with atoms and travels an average distance between collisions called the *mean free path*. If the mean free path is less in some metals, what can you say about the resistance of these metals? For a given conductor, what can be done to lengthen the mean free path?
15. Why is the current in an incandescent bulb greater immediately after it is turned on than it is a few moments later? (That's why bulbs usually burn out just as they are being turned on.)
16. Only a small percentage of the electric energy fed into a common lightbulb is transformed into light. What happens to the remaining energy?
17. Why are all compact fluorescent lamps more efficient than incandescent lamps?
18. A simple lie detector consists of an electric circuit, often from one finger to another. A sensitive meter shows the current that flows when a small voltage is applied. How does this technique indicate that a person is lying? (And when does this technique *not* indicate when someone is lying?)
19. Why are thick wires rather than thin wires usually used to carry large currents?
20. Why does the filament of a lightbulb glow while the connecting wires do not?
21. It is commonly said that a certain resistor draws a certain current. Does this mean that the resistor "attracts" the current? Defend your answer.
22. Will a lamp with a thick filament draw more current or less current than a lamp with a thin filament?
23. What causes electric shock—current or voltage?
24. If a current of one- or two-tenths of an ampere were to flow into one of your hands and out the other, you would probably be electrocuted. But if the same current were to flow into your hand and out the elbow above the same hand, you would survive even though the current might be large enough to burn your flesh. Explain.
25. Would you expect to find dc or ac in the filament of a lightbulb in your home? In the headlight of an automobile?
26. Are automobile headlights wired in parallel or in series? What is your evidence?
27. As more lanes are added to toll booths, the resistance to vehicles passing through is reduced. How is this similar to what happens when more branches are added to a parallel circuit?
28. A car's headlights dissipate 40 W on low beam and 50 W on high beam. Is there more or less resistance in the high-beam filament?
29. What unit is represented by (a) joule per coulomb, (b) coulomb per second, (c) watt·second?
30. To connect a pair of resistors so that their combined (equivalent) resistance will be greater than the resistance of either one, should you connect them in series or in parallel?
31. To connect a pair of resistors so that their combined (equivalent) resistance will be less than the resistance of either one, should you connect them in series or in parallel?
32. Between current and voltage, which remains the same for a 10-Ω and a 20-Ω resistor in series in a series circuit?
33. Between current and voltage, which remains the same for a 10-Ω and a 20-Ω resistor in parallel in a parallel circuit?
34. The damaging effects of electric shock result from the amount of current that flows in the body. Why, then, do

we see signs that read "Danger—High Voltage" rather than "Danger—High Current"?

35. Comment on the warning sign shown in the sketch.

36. Is the following label on a household product cause for concern? "Caution: This product contains tiny, electrically charged particles moving at speeds in excess of 100,000,000 kilometers per hour."

37. Which will do less damage—plugging a 110-V hairdryer into a 220-V circuit or a 220-V hairdryer into a 110-V circuit? Defend your answer.

38. Why are the wingspans of birds a consideration in determining the spacing between parallel wires in a power line?

39. Estimate the number of electrons that a power company delivers annually to the homes of a typical town of 40,000 people.

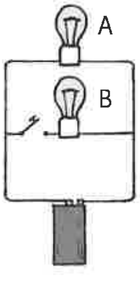
40. If electrons flow very slowly through a circuit, why does it not take a noticeably long time for a lamp to glow when you turn on a distant switch?

41. Why is the speed of an electric signal so much greater than the speed of sound?

42. If a glowing incandescent lightbulb is jarred and oxygen leaks inside, the bulb will momentarily brighten considerably before burning out. Putting excess current through a lightbulb will also burn it out. What physical change occurs when a lightbulb burns out?

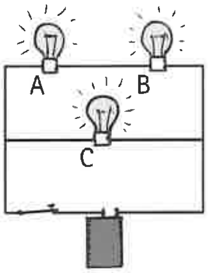
43. Consider a pair of flashlight bulbs connected to a battery. Will they glow brighter if they are connected in series or in parallel? Will the battery run down faster if they are connected in series or in parallel?

44. What happens to the brightness of Bulb A when the switch is closed and Bulb B lights up?



45. If several bulbs are connected in series to a battery, they may feel warm to the touch but not visibly glow. What is your explanation?

46. In the circuit shown, how do the brightnesses of the identical lightbulbs compare? Which bulb draws the most current? What will happen if Bulb A is unscrewed? If Bulb C is unscrewed?



47. As more and more bulbs are connected in series to a flashlight battery, what happens to the brightness of each bulb? Assuming that heating inside the battery is negligible, what happens to the brightness of each bulb when more and more bulbs are connected in parallel?

48. What changes occur in the line current when more devices are introduced in a series circuit? In a parallel circuit? Why are your answers different?

49. Why is there no effect on other branches in a parallel circuit when one branch of the circuit is opened or closed?

50. Your friend says that the equivalent (combined) resistance of resistors connected in series is always more than the resistance of the largest resistor. Do you agree?

51. Your friend says that the equivalent (combined) resistance of resistors connected in parallel is always less than the resistance of the smallest resistor. Do you agree?

52. Your electronics friend needs a 20-Ω resistor but has only 40-Ω resistors. He tells you that he can combine them to produce a 20-Ω resistor. How?

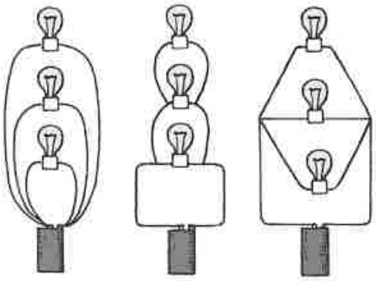
53. Your electronics friend needs a 10-Ω resistor, but only has 40-Ω ones. How can he combine them to produce an equivalent resistance of 10 Ω?

54. When a pair of identical resistors are connected in series, which of the following is the same for both resistors—(a) voltage across each, (b) power dissipated in each, (c) current through each? Do any of your answers change if the resistors are different from each other?

55. When two identical resistors are connected in parallel, which of the following is the same for both resistors—(a) voltage across each, (b) power dissipated in each, (c) current through each? Do any of your answers change if the resistors are different from each other?

56. Batteries do have internal resistance, which is not always negligible. It shows when the current a battery supplies increases, whereupon the voltage it supplies decreases. Taking internal resistance of the battery into consideration, will the brightness of many bulbs diminish when connected in parallel? Defend your answer.

57. Are these three circuits equivalent to one another? Why or why not?



58. Figure 23.19 shows a fuse placed in a household circuit. In what other locations might a fuse be placed in this circuit to be useful, melting only if a problem arises?

59. Is the resistance of a 100-W bulb greater or less than the resistance of a 60-W bulb? Assuming the filaments in each bulb are of the same length and made of the same material, which bulb has the thicker filament?

60. If a 60-W bulb and a 100-W bulb are connected in series in a circuit, across which bulb will there be a greater voltage drop? How about if they are connected in parallel?

PROBLEMS

1. What is the effect on the current in a wire if both the voltage across it and its resistance are doubled? If both are halved?

2. The wattage marked on a lightbulb is not an inherent property of the bulb, but depends on the voltage to which it is connected, usually 110 or 120 V. How many amperes flow through a 60-W bulb connected in a 120-V circuit?

3. Rearrange the equation current = voltage/resistance to express *resistance* in terms of current and voltage. Then solve the following: A certain device in a 120-V circuit has a current rating of 20 A. What is the resistance of the device (how many ohms)?

4. Using the formula power = current × voltage, find the current drawn by a 1200-W toaster connected to 120 V. Then, using the method from the previous problem, show that the resistance of the toaster is $12\ \Omega$.

5. The total charge that an automobile battery can supply without being recharged is given in terms of ampere-hours. A typical 12-V battery has a rating of 60 ampere-hours (60 A for 1 h, 30 A for 2 h, and so on). Suppose that you forget to turn the headlights off in your parked automobile. If each of the two headlights draws 3 A, how long will it be before your battery is "dead"?

6. Show that operating a 100-W lamp continuously for 1 week when the power utility rate is 15¢/kWh costs $2.52.

7. A 4-W night-light is plugged into a 120-V circuit and operates continuously for 1 year. Find the following: (a) the current it draws, (b) the resistance of its filament, (c) the energy consumed in a year. (d) Then show that for a utility rate of 15¢/kWh the cost for a year's operation is $5.25.

8. An electric iron connected to a 110-V source draws 9 A of current. Show that the amount of heat it generates in a minute is nearly 60,000 J.

9. Show in the previous problem that 540 C of charge flow through the iron in 1 minute.

•10. In periods of peak demand, power companies lower their voltage. This saves them power (and saves you money!). To see the effect, consider a 1200-W coffeemaker that draws 10 A when connected to 120 V. Suppose the voltage is lowered by 10% to 108 V. By how much does the current decrease? By how much does the power decrease? (*Caution:* The 1200-W label is valid only when 120 V is applied. When the voltage is lowered, it is the resistance of the toaster, not its power, that remains constant.)

CHAPTER 23 ONLINE RESOURCES

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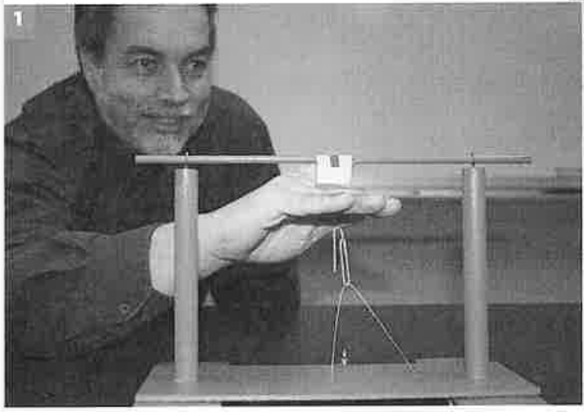
24 Magnetism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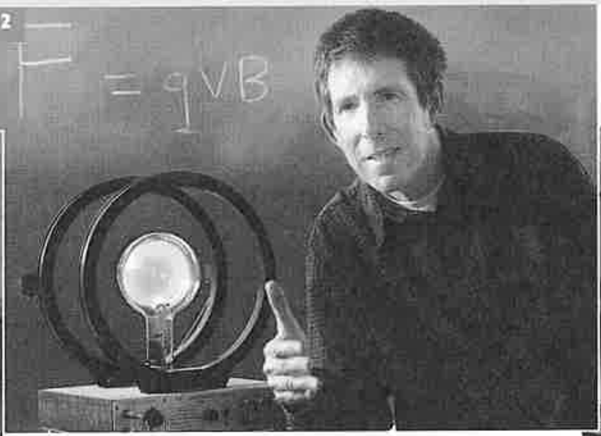
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1 Fred Myers shows that the magnetic field of a ceramic magnet penetrates flesh and the plastic coating on a paper clip. 2 Ken Ganezer shows the bluish-green glow of electrons circling the magnetic field lines inside a Thompson tube. 3 Paul Callaghan is about to load a nuclear magnetic resonance sample into the room temperature bore of a 7 Tesla superconducting magnet at Victoria University of Wellington in New Zealand.

During the time that whale oil was being used to light lamps and electric lighting was making its debut, a pressing question was what form of energy would power electric lighting. The person who best answered that question was Nikola Tesla, an ethnic Serb who emigrated to America from the Austrian Empire in 1884.

Tesla, an electrical engineer, was a prolific inventor and a genius who spoke seven languages. When he came to America he had little besides a letter of recommendation from his former employer to Thomas Edison. The letter was brief: "I know two great men, one is you and the other is this young man." Edison hired Tesla to work for his Edison Machine Works. Tesla was soon solving the company's most difficult problems. He worked day and night redesigning Edison's inefficient motors and generators, thinking that he was promised a handsome bonus if he were successful. When the bonus didn't materialize, Tesla quit. He then found himself digging ditches for a short period of time, ironically, for the Edison company.


Nikola Tesla
(1857–1943)

The major dispute between Tesla and Edison was about whether electric power should be carried by direct current or alternating current. Edison championed direct current, which didn't carry well over long distances. Tesla's alternating current did. Edison was furious with Tesla and aggressively campaigned against Tesla's alternating current. The two remained bitter antagonists over their lifetimes. But Tesla prevailed and formed his own company, which led to many patents that helped power modern cities and industry. Tesla was repeatedly honored and hailed as the patron saint of modern electricity.

In 1888 he teamed up with George Westinghouse and together they harnessed the energy of Niagara Falls to light up the nearby city of Buffalo. For sending electricity over longer distances, Westinghouse perfected a device called a transformer (next chapter). Power from Niagara Falls soon reached New York City and beyond. The efforts of Tesla and Westinghouse truly lit up the world.

Magnetism

Youngsters are fascinated with magnets, largely because they act at a distance. They act at a distance even when your hand is between them, as Fred Myers shows in the chapter-opening photo. Likewise, a neurosurgeon can guide a pellet through brain tissue to inoperable tumors, pull a catheter into position, or implant electrodes while doing little harm to brain tissue. The use of magnets grows daily.

The term *magnetism* comes from the name Magnesia, a coastal district of ancient Thessaly, Greece, where unusual stones were found by the Greeks more than 2000 years ago. These stones, called *lodestones,* had the intriguing property of attracting pieces of iron. Magnets were first fashioned into compasses and used for navigation by the Chinese in the 12th century.

In the 16th century, William Gilbert, Queen Elizabeth's physician, made artificial magnets by rubbing pieces of iron against lodestone, and he suggested that a compass always points north and south because Earth has magnetic properties. Later, in 1750, John Michell, an English physicist and astronomer, found that magnetic poles obey the inverse-square law, and his results were confirmed by Charles Coulomb. The subjects of magnetism and electricity developed almost independently of each other until 1820, when a Danish physicist named Hans Christian Oersted discovered, in a classroom demonstration, that an electric current affects a magnetic compass.[1] He saw confirming evidence that magnetism was related to electricity. Shortly thereafter, the French physicist André Marie Ampere proposed that electric currents are the source of all magnetic phenomena.

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Video
Oersted's Discovery

There's much bunk about magnetism. Hence the need of a *knowledge filter* to tell the difference between what's true and what's not. The best knowledge filter ever invented is science.

Magnetic Forces

In Chapter 22, we discussed the forces that electrically charged particles exert on one another: The force between any two charged particles depends on the magnitude of the charge on each and their distance of separation, as specified in Coulomb's law. But Coulomb's law is not the whole story when the charged particles are moving with respect to each other. The force between electrically charged particles depends also, in a complicated way, on their motion. We find that, in addition to *electric force,* there is a force due to the motion of the charged particles that we call the **magnetic force.** The source of magnetic force is the motion of charged particles, usually electrons. Both electrical and magnetic forces are actually different aspects of the same phenomenon of electromagnetism.

CHECK POINT

Do both electric forces and magnetic forces depend on motion?

Check Your Answer

Only the magnetic force requires motion. Read on.

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[1] We can only speculate about how often such relationships become evident when they "aren't supposed to" and are dismissed as "something wrong with the apparatus." Oersted, however, had the insight—characteristic of a good scientist—to see that nature was revealing another of its secrets.

Magnetic Poles

The forces that magnets exert on one another are similar to electrical forces, for they can both attract and repel without touching, depending on which ends of the magnets are held near one another. Also like electrical forces, the strength of their interaction depends on the separation distance between the two magnets. Whereas electric charge is responsible for electrical forces, regions called *magnetic poles* give rise to magnetic forces.

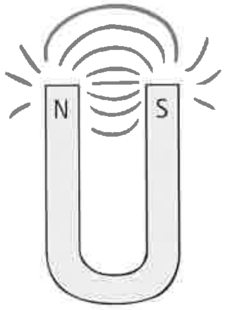

FIGURE 24.1
A horseshoe magnet.

If you suspend a bar magnet at its center by a piece of string, you'll have a compass. One end, called the *north-seeking pole,* points northward, and the opposite end, called the *south-seeking pole,* points southward. More simply, these are called the *north* and *south poles.* All magnets have both a north and a south pole (some have more than one of each). Refrigerator magnets, popular in recent years, have narrow strips of alternating north and south poles. These magnets are strong enough to hold sheets of paper against a refrigerator door, but they have a very short range because the north and south poles are close together and cancel at short distances. In a simple bar magnet, a single north pole and a single south pole are located at opposite ends. A common horseshoe magnet is simply a bar magnet that has been bent into a U shape. Its poles are also at its two ends (Figure 24.1).

When the north pole of one magnet is brought near the north pole of another magnet, they repel.[2] The same is true of a south pole near a south pole. If opposite poles are brought together, however, attraction occurs. We find that

Like poles repel each other; opposite poles attract.

This rule is similar to the rule for the forces between electric charges, where like charges repel one another and unlike charges attract. But there is a very important difference between magnetic poles and electric charges. Whereas electric charges can be isolated, magnetic poles cannot. Negatively charged electrons and positively charged protons are entities by themselves. A cluster of electrons need not be accompanied by a cluster of protons, and vice versa. But a north magnetic pole never exists without the presence of a south pole, and vice versa.

If magnets won't stick to your stainless steel refrigerator door, the door is probably a mixture of steel and nickel. But magnets will stick to stainless steel when made with chromium instead of nickel.

If you break a bar magnet in half, each half still behaves as a complete magnet. Break the pieces in half again, and you have four complete magnets. You can continue breaking the pieces in half and never isolate a single pole.[3] Even when your piece is one atom thick, there are two poles, which suggests that atoms themselves are magnets.

CHECK POINT

Does every magnet necessarily have a north and south pole?

Check Your Answer

Yes, just as every coin has two sides, a "head" and a "tail." Some "trick" magnets have more than one pair of poles, but, nevertheless, poles always occur in pairs.

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[2] The force of interaction between magnetic poles is given by $F \sim \frac{p_1 p_2}{d^2}$, where p_1 and p_2 represent magnetic pole strengths and d represents the separation distance between the poles. Note the similarity of this relationship to Coulomb's law.

[3] Theoretical physicists have speculated for more than 75 years about the possible existence of discrete magnetic "charges," called *magnetic monopoles.* These tiny particles would carry either a single north or a single south magnetic pole and would be the counterparts to the positive and negative charges in electricity. Various attempts have been made to find monopoles, but none have proved successful. All known magnets always have at least one north pole and one south pole.

Magnetic Fields

If you sprinkle some iron filings on a sheet of paper placed on a magnet, you'll see that the filings trace out an orderly pattern of lines that surround the magnet. The space around the magnet contains a **magnetic field.** The shape of the field is revealed by the filings, which align with the magnetic field lines that spread out from one pole and return to the other. It is interesting to compare the field patterns in Figures 24.2 and 24.4 with the electric field patterns in 22.19 back in Chapter 22.

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Tutorial
Magnetic Fields

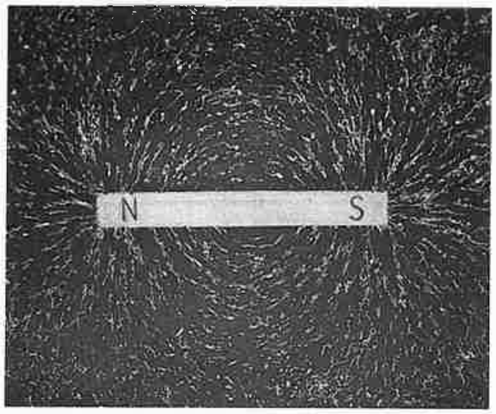

FIGURE 24.2

INTERACTIVE FIGURE

Top view of iron filings sprinkled around a magnet tracing a pattern of magnetic field lines. Interestingly, the magnetic field lines continue inside the magnet (not revealed by the filings) and form closed loops.

The direction of the field outside a magnet is from the north pole to the south pole. Where the lines are closer together, the field is stronger. The concentration of iron filings at the poles of the magnet in Figure 24.2 shows the magnetic field strength is greater there. If we place another magnet or a small compass anywhere in the field, its poles line up with the magnetic field.

Magnetism is very much related to electricity. Just as an electric charge is surrounded by an electric field, the same charge is also surrounded by a magnetic field if it is moving. This magnetic field is due to the "distortions" in the electric field caused by motion and was explained by Albert Einstein in 1905 in his special theory of relativity. We won't go into the details except to acknowledge that a magnetic field is a relativistic by-product of the electric field. Charged particles in motion have associated with them both an electric field and a magnetic field. A magnetic field is produced by the motion of electric charge.[4]

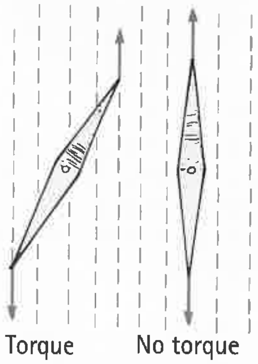

FIGURE 24.3

When the compass needle is not aligned with the magnetic field (left), the oppositely directed forces on the needle produce a pair of torques (called a *couple*) that twist the needle into alignment (right).

If the motion of electric charges produces magnetism, where is this motion in a common bar magnet? The answer is, in the electrons of the atoms that make up the magnet. These electrons are in constant motion. Two kinds of electron motion contribute to magnetism: electron spin and electron revolution. Electrons spin about their own axes like tops, and they also revolve about the atomic nucleus. In most common magnets, electron spin is the chief contributor to magnetism.

Every spinning electron is a tiny magnet. A pair of electrons spinning in the same direction makes up a stronger magnet. A pair of electrons spinning in opposite directions, however, work against each other. The magnetic fields cancel. This is why most substances are not magnets. In most atoms, the various fields cancel one another because the electrons spin in opposite directions. But in such materials as iron, nickel, and cobalt the fields do not cancel each other entirely. Each iron atom

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[4] Interestingly, since motion is relative, the magnetic field is relative. For example, when a charge moves by you, there is a definite magnetic field associated with the moving charge. But if you move along with the charge so that there is no motion relative to you, you'll find no magnetic field associated with the charge. Magnetism is relativistic. In fact, it was Albert Einstein who first explained this when he published his first paper on special relativity, "On the Electrodynamics of Moving Bodies." (More on relativity in Chapters 35 and 36.)

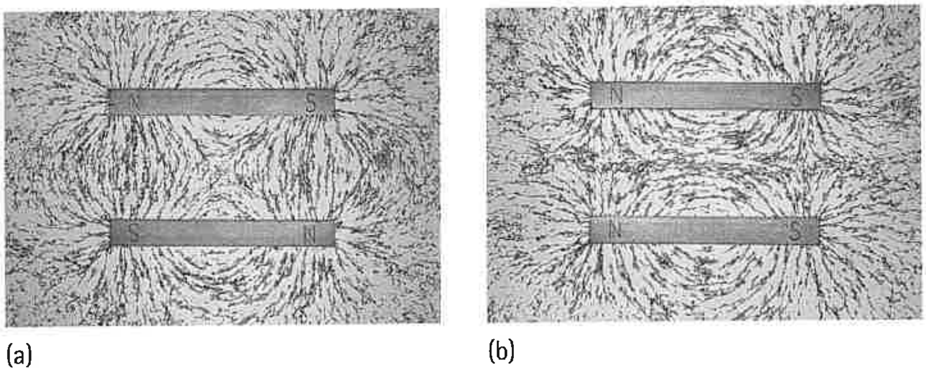

FIGURE 24.4
The magnetic field patterns for a pair of magnets. (a) Opposite poles are nearest each other, and (b) like poles are nearest each other.

has four electrons whose spin magnetism is not canceled. Thus, each iron atom is a tiny magnet. The same is true, to a lesser extent, for the atoms of nickel and cobalt. Most common magnets are made from alloys containing iron, nickel, and cobalt in various proportions.[5]

Magnetic Domains

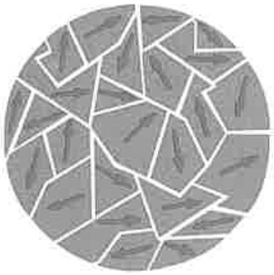

FIGURE 24.5
A microscopic view of magnetic domains in a crystal of iron. The blue arrows pointing in different directions tell us that these domains are not aligned.

The magnetic field of an individual iron atom is so strong that interactions among adjacent atoms cause large clusters of them to line up with one another. These clusters of aligned atoms are called **magnetic domains.** Each domain is made up of billions of aligned atoms. The domains are microscopic (Figure 24.5), and there are many of them in a crystal of iron. Like the alignment of iron atoms within domains, domains themselves can align with one another.

Not every piece of iron, however, is a magnet. This is because the domains in ordinary iron are not aligned. Consider a common iron nail: The domains in the nail are randomly oriented. Many of them are induced into alignment, however, when a magnet is brought nearby. (It is interesting to listen with an amplified stethoscope to the clickity-clack of domains undergoing alignment in a piece of iron when a strong magnet approaches.) The domains align themselves much as electrical charges in a piece of paper align themselves in the presence of an electrically charged rod. When you remove the nail from the magnet, ordinary thermal motion causes most or all of the domains in the nail to return to a random arrangement. If the field of the permanent magnet is very strong, however, the nail may retain some permanent magnetism of its own after the two are separated.

FIGURE 24.6
Wai Tsan Lee shows iron nails that have become induced magnets.

Permanent magnets are made by simply placing pieces of iron or certain iron alloys in strong magnetic fields. Alloys of iron differ; soft iron is easier to magnetize than steel. It helps to tap the iron to nudge any stubborn domains into alignment. Another way of making a permanent magnet is to stroke a piece of iron with a magnet. The stroking motion aligns the domains in the iron. If a permanent magnet is dropped or heated, some of the domains are jostled out of alignment and the magnet becomes weaker.

Cows often swallow metal objects that puncture their stomachs. That's why farmers feed *cow magnets* (long narrow alnico magnets) to cows, which attract metal pieces and lower the chance of stomach puncture.

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[5] Electron spin contributes virtually all of the magnetic properties in magnets made from alloys containing iron, nickel, cobalt, and aluminum. In the rare earth metals such as gadolinium, the orbital motion is more significant.

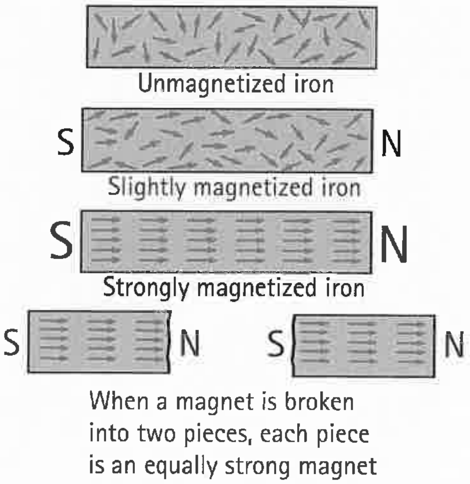

FIGURE 24.7

INTERACTIVE FIGURE

Pieces of iron in successive stages of magnetization. The arrows represent domains; the head is a north pole and the tail is a south pole. Poles of neighboring domains neutralize each other's effects, except at the two ends of a piece of iron.

fyi

- A magstripe on a credit card contains millions of tiny magnetic domains held together by a resin binder. Data are encoded in binary code, with zeros and ones distinguished by the frequency of domain reversals. It's quite amazing how quickly your name pops up when a clerk swipes your card.

CHECK POINT

How can a magnet attract a piece of iron that is not magnetized?

Check Your Answer

Domains in the unmagnetized piece of iron are induced into alignment by the magnetic field of the nearby magnet. See the similarity of this to Figure 22.13 back in Chapter 22. Like the pieces of paper that jump to the comb, pieces of iron will jump to a strong magnet when it is brought nearby. But, unlike the pieces of paper, they are not then repelled. Can you think of the reason why?

Electric Currents and Magnetic Fields

Since a moving charge produces a magnetic field, it follows that a current of charges also produces a magnetic field. The magnetic field that surrounds a current-carrying conductor can be demonstrated by arranging an assortment of compasses around a wire (Figure 24.8) and passing a current through it. The compass needles line up with the magnetic field produced by the current and they show the field to be a pattern of concentric circles about the wire. When the current reverses direction, the compass needles turn around, showing that the direction of the magnetic field changes also. This is the effect that Oersted first demonstrated in his classroom.

If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop (Figure 24.9). If the wire is bent into another loop, overlapping the first,

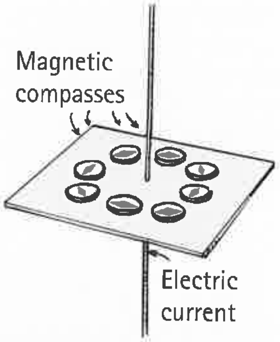

FIGURE 24.8

The compasses show the circular shape of the magnetic field surrounding the current-carrying wire.

Practicing Physics

Most iron objects around you are magnetized to some degree. A filing cabinet, a refrigerator, or even cans of food on your pantry shelf have north and south poles induced by Earth's magnetic field. If you bring a magnetic compass near the tops of iron or steel objects in your home, you will find that the north pole of the compass needle points to the tops of these objects, and the south pole of the compass needle points to their bottoms. This shows that the objects are magnets, having a south pole on top and a north pole on the bottom. Turn cans of food that have been in a vertical position upside down and see how many days it takes for the poles to reverse themselves!

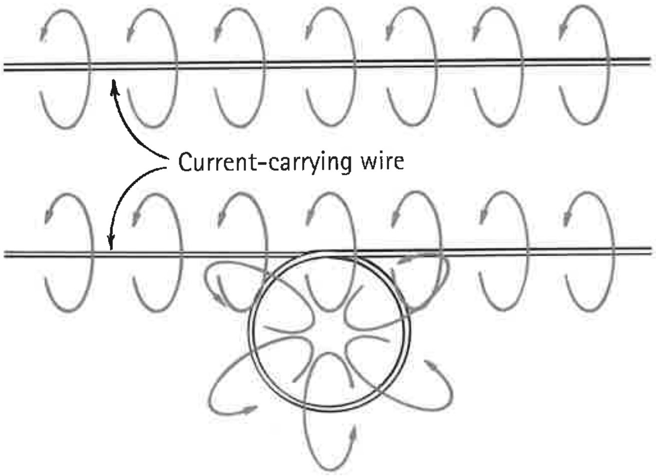

FIGURE 24.9
Magnetic field lines about a current-carrying wire crowd up when the wire is bent into a loop.

the concentration of magnetic field lines inside the loops is doubled. It follows that the magnetic field intensity in this region is increased as the number of loops is increased. The magnetic field intensity is appreciable for a current-carrying coil of many loops.

Electromagnets

A current-carrying coil of wire is an **electromagnet.** The strength of an electromagnet is increased by simply increasing the current through the coil and the number of turns in the coil. Industrial magnets gain additional strength by having a piece of iron within the coil. Electromagnets powerful enough to lift automobiles are a common sight in junkyards. Magnetic domains in the iron core are induced into alignment, adding to the field. For extremely strong electromagnets, such as those used to control charged-particle beams in high-energy accelerators, iron is not used, because, beyond a certain point, all of its domains are aligned. The magnet is said to be saturated and increasing the electric current flowing around the core no longer affects the magnetization of the core itself and it no longer adds to the field.

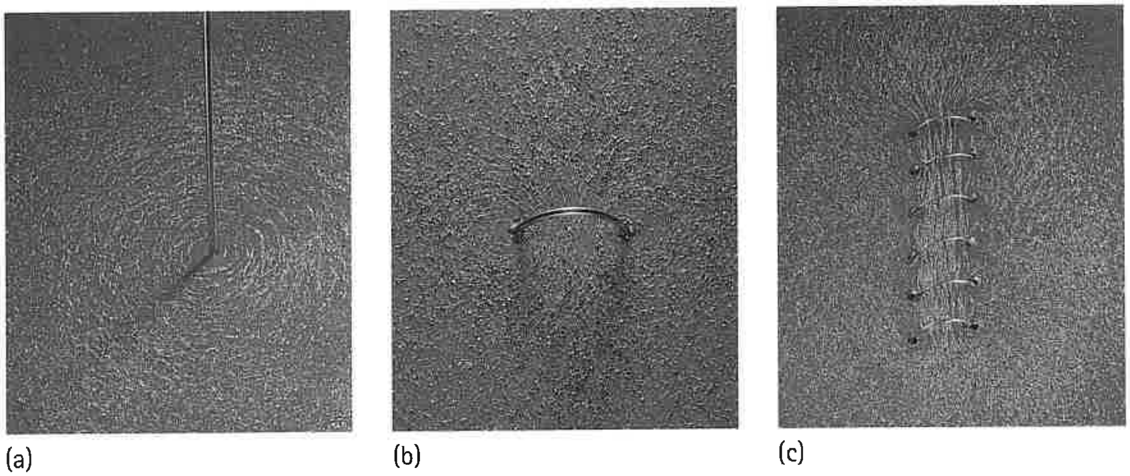
(a) (b) (c)

FIGURE 24.10
Iron filings sprinkled on paper reveal the magnetic field configurations about (a) a current-carrying wire, (b) a current-carrying loop, and (c) a current-carrying coil of loops.

Electromagnets need not have iron cores. Electromagnets without iron cores are used in magnetically levitated, or "maglev," transportation. Figure 24.11 shows a maglev train, which has no diesel or other conventional engine. Already operating in different countries, various designs are still being engineered. In one design already in commercial use, levitation is accomplished by magnetic coils that run along the track, called a guideway. The coils repel large magnets on the train's undercarriage. Once levitated a few centimeters, power is supplied to the coils within the guideway walls that propels the train. This is accomplished by continually alternating the electric current fed to the coils, which continually alternates their magnetic polarity. In this way a magnetic field pulls the vehicle forward, while a magnetic field farther back pushes. The alternating pushes and pulls produce a forward thrust. Since maglev trains float on a cushion of air, friction experienced by conventional trains is eliminated. Maglev speeds, about half that of commercial aircraft, are limited only by air friction and passenger comfort. Watch for expansion of this growing technology.

FIGURE 24.11

A magnetically levitated vehicle—a *magplane.* Whereas conventional trains vibrate as they ride on rails at high speeds, magplanes can travel vibration-free at high speeds because they levitate above the guideway.

SUPERCONDUCTING ELECTROMAGNETS

The most powerful electromagnets without iron cores use superconducting coils through which large electrical currents flow with ease. Recall, from Chapter 22, that there is no electrical resistance in a superconductor to limit the flow of electric charge and, therefore, no heating, even if the current is enormous. Electromagnets that utilize superconducting coils produce extremely strong magnetic fields—and they do so very economically because there are no heat losses (although energy is used to keep the superconductors cold). At the Large Hadron Collider in Geneva, Switzerland, superconducting magnets guide high-energy particles around an accelerator 17 miles in circumference. Superconducting magnets are used in magnetic resonance imaging (MRI) devices in hospitals.

Whether superconducting or not, electromagnets are part of everyday life. They're in sound systems, electric motors, in our automobiles, and even in shredded garbage recycling systems to remove metal bits. Cheers for electromagnets.

FIGURE 24.12

A permanent magnet levitates above a superconductor because its magnetic field cannot penetrate the superconducting material.

Magnetic Force on Moving Charged Particles

A charged particle at rest will not interact with a static magnetic field. But if the charged particle is moving in a magnetic field, the magnetic character of a charge in motion becomes evident. It experiences a deflecting force.[6] The force is greatest when the particle moves in a direction perpendicular to the magnetic field lines. At other angles, the force is less, and it becomes zero when the particles move parallel to the field lines. In any case, the direction of the force is always perpendicular to the magnetic field lines and to the velocity of the charged particle (Figure 24.13). So a moving charged particle is deflected when it crosses through a magnetic field, but, when it travels parallel to the field, no deflection occurs.

This deflecting force is very different from the forces that occur in other interactions, such as the gravitational forces between masses, the electric forces between charges, and the magnetic forces between magnetic poles. The force that acts on a moving charged

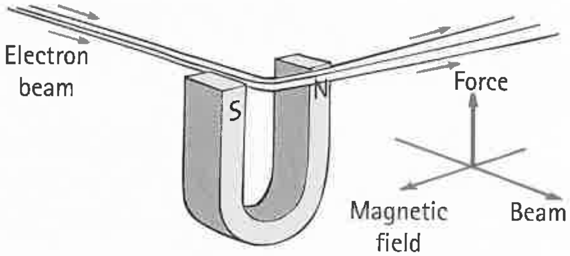

FIGURE 24.13

A beam of electrons is deflected by a magnetic field.

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[6] When particles of electric charge q and velocity v move perpendicularly into a magnetic field of strength B, the force F on each particle is simply the product of the three variables: $F = qvB$. For nonperpendicular angles, v in this relationship must be the component of velocity perpendicular to B.

particle does not act along the line that joins the sources of interaction but, instead, acts perpendicularly to both the magnetic field and the electron beam.

We are fortunate that charged particles are deflected by magnetic fields. Charged particles in cosmic rays are deflected by Earth's magnetic field. Although Earth's atmosphere absorbs most of these, cosmic ray intensity at Earth's surface would be much more intense without Earth's protective magnetic field.

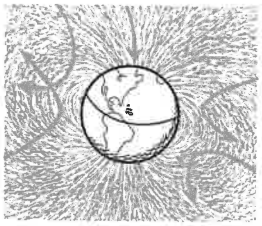

FIGURE 24.14
The magnetic field of Earth deflects many charged particles that make up cosmic radiation.

Magnetic Force on Current-Carrying Wires

Simple logic tells you that if a charged particle moving through a magnetic field experiences a deflecting force, then a current of charged particles moving through a magnetic field also experiences a deflecting force. If the particles are trapped inside a wire when they respond to the deflecting force, the wire will also be pushed (Figure 24.15).

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Video
Magnetic Forces on Current-Carrying Wires

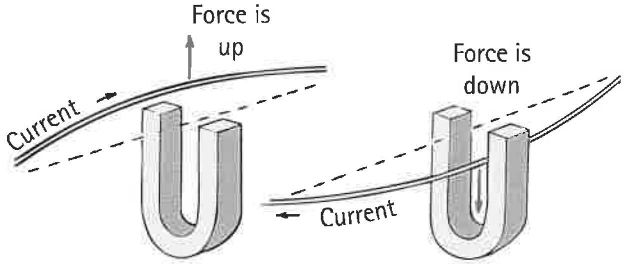
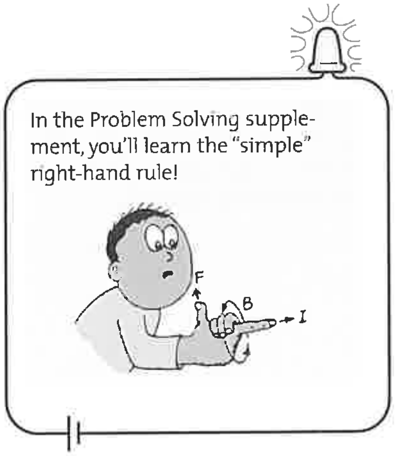


FIGURE 24.15
INTERACTIVE FIGURE
A current-carrying wire experiences a force in a magnetic field. (Can you see that this is a follow-up of what happens in Figure 24.13?)

If we reverse the direction of the current, the deflecting force acts in the opposite direction. The force is strongest when the current is perpendicular to the magnetic field lines. The direction of force is not along the magnetic field lines or along the direction of current. The force is perpendicular to both field lines and current. It is a sideways force.

We see that, just as a current-carrying wire will deflect a magnet such as a compass needle (again, as discovered by Oersted), a magnet will deflect a current-carrying wire. Discovering these complementary links between electricity and magnetism created much excitement, and people began harnessing the electromagnetic force for useful purposes almost immediately—with great sensitivity in electric meters and with great force in electric motors.


In the Problem Solving supplement, you'll learn the "simple" right-hand rule!

CHECK POINT

What law of physics tells you that if a current-carrying wire produces a force on a magnet, a magnet must produce a force on a current-carrying wire?

Check Your Answer

Newton's third law, which applies to *all* forces in nature.

ELECTRIC METERS

The simplest meter to detect electric current is a magnet that is free to turn—a compass. The next simplest meter is a compass in a coil of wires (Figure 24.16).

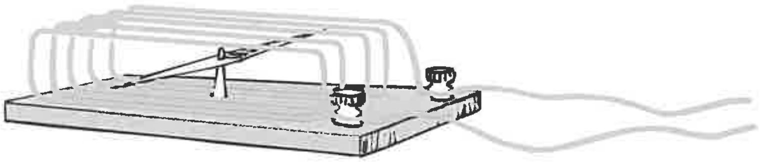


FIGURE 24.16
A very simple galvanometer.

When an electric current passes through the coil, each loop produces its own effect on the needle, so a very small current can be detected. A sensitive current-indicating instrument is called a *galvanometer,* named after Luigi Galvani, who in the 18th century discovered that dissimilar metals caused twitching in a frog's leg that he was dissecting.

A common galvanometer design is shown in Figure 24.17. It employs many loops of wire and is therefore more sensitive. The coil is mounted for movement, and the magnet is held stationary. The coil turns against a spring, so the greater the current in its windings, the greater its deflection. A galvanometer may be calibrated to measure current (amperes), in which case it is called an *ammeter*. Or it may be calibrated to measure electric potential (volts), in which case it is called a *voltmeter*.

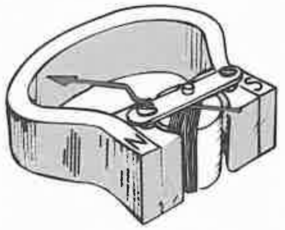


FIGURE 24.17

A common galvanometer design.

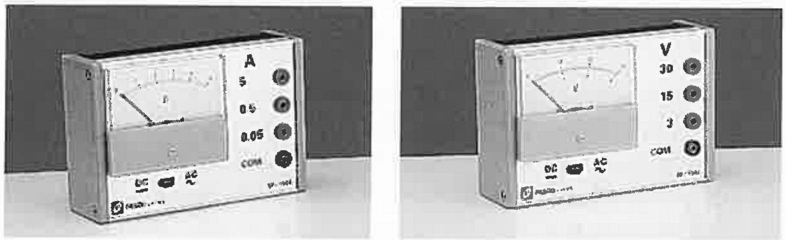


FIGURE 24.18

Both the ammeter and the voltmeter are basically galvanometers. (The electrical resistance of the instrument is made to be very low for the ammeter and very high for the voltmeter.)

Galvani's chance discovery of the twitching frog led him to invent the chemical cell and the battery. The next time you pick up a galvanized pail, think of Luigi Galvani in his anatomy laboratory.

ELECTRIC MOTORS

If we modify the design of the galvanometer slightly, so deflection makes a complete rather than a partial rotation, we have an *electric motor*. The principal difference is that in a motor, the current is made to change direction every time the coil makes a half rotation. After being forced to turn one-half rotation, the coil continues in motion just in time for the current to reverse, whereupon, instead of the coil reversing direction, it is forced to continue another half rotation in the same direction. This happens in cyclic fashion to produce continuous rotation, which has been harnessed to run clocks, operate gadgets, and lift heavy loads.

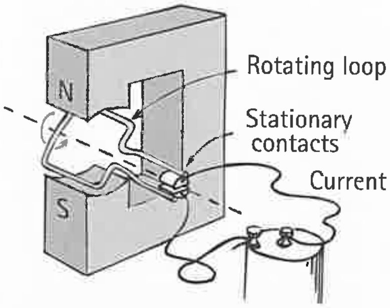


FIGURE 24.19

INTERACTIVE FIGURE

A simplified electric motor.

In Figure 24.19, we can see the principle of the electric motor in bare outline. A permanent magnet produces a magnetic field in a region in which a rectangular loop of wire is mounted to turn about the dashed axis shown. The current in the loop flips direction with each half-turn, and continuous rotation results.

Any current in the loop moves in one direction in the upper side of the loop and the opposite direction in the lower side (because charges flowing into one end of the loop must flow out the other end). If the upper side of the loop is forced to the left by the magnetic field, the lower side is forced to the right, as if it were a galvanometer. But, unlike the situation in a galvanometer, the current in a motor is reversed during each half-revolution by means of stationary contacts on the shaft. The parts of the wire that rotate and brush against these contacts are called *brushes*. In this way, the current in the loop alternates so that the forces on the upper and lower regions do not change directions as the loop rotates. The rotation is continuous as long as current is supplied.

A motor and a generator are actually the same device, with input and output reversed. The electrical device in a hybrid car is such a motor/generator combination.

We have described here only a very simple dc motor. Larger motors, dc or ac, are usually manufactured by replacing the permanent magnet with an electromagnet that is energized by the power source. Of course, more than a single loop is used. Many loops of wire are wound about an iron cylinder, called an *armature,* which then rotates when the wire carries current.

The advent of electric motors brought to an end much human and animal toil in many parts of the world. Electric motors have greatly changed the way people live.

CHECK POINT

What is the major similarity between a galvanometer and a simple electric motor? What is the major difference?

Check Your Answers

Both are similar, as coils are positioned in a magnetic field. A force produces rotation when current passes through the coils. The major difference is that the maximum rotation of the coil in a galvanometer is one half-turn, whereas, in a motor, the coil (wrapped on an armature) rotates through many complete turns—accomplished by alternating the current with each half-turn of the armature.

Earth's Magnetic Field

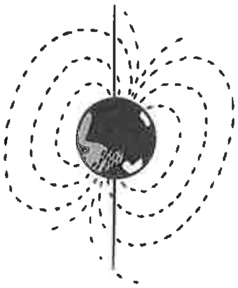


FIGURE 24.20
Earth is a magnet.

A suspended magnet or compass points northward because Earth itself is a huge magnet. The compass aligns with the magnetic field of Earth. The magnetic poles of Earth, however, do not coincide with the geographic poles—in fact, the magnetic and geographical poles are widely separated. The magnetic pole in the Northern Hemisphere, for example, is now located nearly 1800 kilometers from the geographic pole, somewhere in the Hudson Bay region of northern Canada. The other pole is located south of Australia (Figure 24.20). This means that compasses do not generally point to the true north. The discrepancy between the orientation of a compass and true north is known as the *magnetic declination.*

We do not know exactly why Earth itself is a magnet. The configuration of Earth's magnetic field is like that of a strong bar magnet placed near the center of Earth. But Earth is not a magnetized chunk of iron like a bar magnet. It is simply too hot for individual atoms to hold to a proper orientation. So the explanation likely involves electric currents deep in the interior. About 2000 kilometers below the outer rocky mantle (which itself is almost 3000 kilometers thick) lies the molten part that surrounds the solid center. Most Earth scientists think that moving charges looping around within the molten part of Earth create the magnetic field. Some Earth scientists speculate that the electric currents are the result of convection currents—from heat rising from the central core (Figure 24.21)—and that such convection currents combined with the rotational effects of Earth produce Earth's magnetic field. Because of Earth's great size, the speed of moving charges need only be about a millimeter per second to account for the field. A firmer explanation awaits more study.

Being certain about things is not science. The certitude responsible for disasters throughout history is absent in science. Scientists accept "not knowing" all the answers.

Whatever the cause, the magnetic field of Earth is not stable; it has wandered throughout geologic time. Evidence of this comes from the analysis of magnetic properties of rock strata. Iron atoms in a molten state are disoriented because of thermal motion, but a slight predominance of the iron atoms align with the magnetic field of Earth. When cooling and solidification occur, this predominance records the direction of Earth's magnetic field in the resulting igneous rock. It's similar for sedimentary rocks, where magnetic domains in grains of iron that settle in sediments tend to align themselves with Earth's magnetic field and become locked into the rock that forms. The slight magnetism that results can be measured with sensitive instruments. As samples of rock are tested from different strata formed throughout geologic time, the magnetic field of Earth for different periods can be charted. This evidence shows that there have been times when the magnetic field of Earth has diminished to zero, followed by reversal of the poles. More than 20 reversals have taken place in the past 5 million years. The most recent occurred 700,000 years ago. Prior reversals happened 870,000 and 950,000 years ago. Studies of deep-sea sediments indicate that the field was virtually switched off for 10,000 to 20,000 years just over 1 million years ago. We cannot predict when the next reversal will occur because the reversal sequence is not

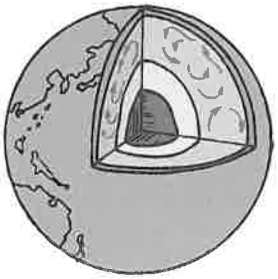


FIGURE 24.21
Convection currents in the molten parts of Earth's interior may drive electric currents to produce Earth's magnetic field.

regular. But there is a clue in recent measurements that show a decrease of more than 5% of Earth's magnetic field strength in the last 100 years. If this change is maintained, we may well have another reversal within 2000 years.

The reversal of magnetic poles is not unique to Earth. The Sun's magnetic field reverses regularly, with a period of 22 years. This 22-year magnetic cycle has been linked, through evidence in tree rings, to periods of drought on Earth. Interestingly enough, the long-known, 11-year sunspot cycle is just half the time during which the Sun gradually reverses its magnetic polarity.

Varying ion winds in Earth's atmosphere cause more rapid but much smaller fluctuations in Earth's magnetic field. Ions in this region are produced by the energetic interactions of solar ultraviolet rays and X-rays with atmospheric atoms. The motion of these ions produces a small but important part of Earth's magnetic field. Like the lower layers of air, the ionosphere is churned by winds. The variations in these winds are responsible for nearly all of the fast fluctuations in Earth's magnetic field. Interestingly, solar winds that reach Earth collide with Earth's magnetic field rather than with the atmosphere.

Like tape from a tape recorder, history of the ocean's bottom is preserved in a magnetic record.

COSMIC RAYS

The universe is a shooting gallery of charged particles. They are called **cosmic rays** and consist of protons, alpha particles, and other atomic nuclei stripped of electrons, as well as high-energy electrons. The protons may be remnants of the Big Bang; the heavier nuclei probably boiled off from exploding stars. In any event, they travel through space at fantastic speeds and make up the cosmic radiation that is hazardous to astronauts. This radiation is intensified when the Sun is active and contributes added energetic particles. Cosmic rays are also a hazard to electronic instrumentation in space; impacts of cosmic-ray nuclei can cause computer memory bits to "flip" or small microcircuits to fail. Fortunately for those of us on Earth's surface, most of these charged particles don't reach us due to the thickness of the atmosphere. Cosmic rays are also deflected away by the magnetic field of Earth. Some of them are trapped in the outer reaches of Earth's magnetic field and make up the Van Allen radiation belts (Figure 24.22).

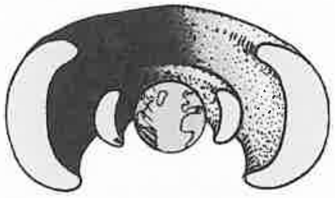


FIGURE 24.22

A cross section of the Van Allen radiation belts, shown here undistorted by the solar wind.

The Van Allen radiation belts consist of two doughnut-shaped rings about Earth, named after James A. Belts, who suggested their existence from data gathered by the U.S. satellite *Explorer I* in 1958.[7] The inner ring is centered about 3200 kilometers above Earth's surface, and the outer ring, which is a larger and wider doughnut, is centered about 16,000 kilometers overhead. Astronauts orbit at safe distances well below these belts of radiation. Most of the charged particles—protons and electrons—trapped in the outer belt probably come from the Sun. Storms on the Sun hurl charged particles out in great fountains, many of which pass near Earth and are trapped by its magnetic field. The trapped particles follow corkscrew paths around the magnetic field lines of Earth and bounce between Earth's magnetic poles high above the atmosphere. Disturbances in Earth's field often allow the ions to dip into the atmosphere, causing it to glow like a fluorescent lamp. This is the beautiful *aurora borealis* (or northern lights); in the Southern Hemisphere, it is an *aurora australis.*

The particles trapped in the inner belt probably originated from Earth's atmosphere. This belt gained newer electrons from high-altitude hydrogen-bomb explosions in 1962.

FIGURE 24.23

The aurora borealis lighting of the sky caused by charged particles in the Van Allen belts striking atmospheric molecules.

In spite of Earth's protective magnetic field, many "secondary" cosmic rays reach Earth's surface.[8] These are particles created when "primary" cosmic rays—those

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[7] Actually, humor aside, the name is James A. Van Allen (with his permission).

[8] Some biological scientists speculate that Earth's magnetic changes played a significant role in the evolution of life forms. One hypothesis is that in the early phases of primitive life, Earth's magnetic field was strong enough to shield the delicate life forms from high-energy charged particles. But, during periods of zero strength, cosmic radiation and the spilling of the Van Allen belts increased the rate of mutation of more robust life forms—not unlike the mutations produced by X-rays in the famous heredity studies of fruit flies. Coincidences between the dates of increased life changes and the dates of the magnetic pole reversals in the last few million years lend support to this hypothesis.

coming from outer space—strike atomic nuclei high in the atmosphere. Cosmic-ray bombardment is greatest at the magnetic poles, because charged particles that hit Earth there do not travel *across* the magnetic field lines but, rather, *along* the field lines and are not deflected. Cosmic-ray bombardment decreases away from the poles, and it is smallest in equatorial regions. At middle latitudes, about five particles strike each square centimeter each minute at sea level; this number increases rapidly with altitude. So cosmic rays are penetrating your body as you are reading this—and even when you aren't reading this!

Biomagnetism

Certain bacteria biologically produce single-domain grains of magnetite (a compound equivalent to iron ore) that they string together to form internal compasses. They then use these compasses to detect the dip of Earth's magnetic field. Equipped with a sense of direction, the organisms are able to locate food supplies. Amazingly, those bacteria that live south of the equator build the same single-domain magnets as their counterparts that live north of the equator, but they align them in the opposite direction to coincide with the oppositely directed magnetic field in the Southern Hemisphere! Bacteria are not the only living organisms with built-in magnetic compasses: Pigeons have multiple-domain magnetite magnets within their skulls that are connected with a large number of nerves to the pigeon brain. Pigeons have a magnetic sense, and not only can they discern longitudinal directions along Earth's magnetic field, they can also detect latitude by the dip of Earth's field. Magnetic material is also in the abdomens of bees, whose behavior is affected by small magnetic fields. Some wasps, Monarch butterflies, sea turtles, and fish join the ranks of creatures with a magnetic sense. Magnetite crystals that resemble the crystals found in magnetic bacteria have been found in human brains. No one knows if these are linked to our sensations. Like the creatures mentioned above, we may share a common magnetic sense.

MRI: Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a noninvasive way to provide high-resolution pictures of the tissues inside a body. Superconducting coils produce a strong magnetic field up to 60,000 times stronger than the intensity of Earth's magnetic field, which is used to align the protons of hydrogen atoms in the body of the patient.

Like electrons, protons have a "spin" property, so they will align with a magnetic field. Unlike a compass needle that aligns with Earth's magnetic field, the proton's axis wobbles about the applied magnetic field. Wobbling protons are slammed with a burst of radio waves tuned to push the proton's spin axis sideways, perpendicular to the applied magnetic field. When the radio waves pass and the protons quickly return to their wobbling pattern, they emit faint electromagnetic signals whose frequencies depend slightly on the chemical environment in which the proton resides. The signals, which are detected by sensors, are then analyzed by a computer to reveal varying densities of hydrogen atoms in the body and their interactions with surrounding tissue. The images clearly distinguish fluid and bone.

It is interesting to note that MRI was formerly called NMRI (nuclear magnetic resonance imaging), because hydrogen nuclei resonate with the applied fields. Because of public phobia of anything "nuclear," the devices are now called MRI scanners. Tell phobic friends that every atom in their bodies contains a nucleus!

SUMMARY OF TERMS

Magnetic force (1) Between magnets, it is the attraction of unlike magnetic poles for each other and the repulsion between like magnetic poles. (2) Between a magnetic field and a moving charged particle, it is a deflecting force due to the motion of the particle: The deflecting force is perpendicular to the velocity of the particle and perpendicular to the magnetic field lines. This force is greatest when the charged particle moves perpendicular to the field lines and is smallest (zero) when it moves parallel to the field lines.

Magnetic field The region of magnetic influence around a magnetic pole or a moving charged particle.

Magnetic domains Clustered regions of aligned magnetic atoms. When these regions themselves are aligned with one another, the substance containing them is a magnet.

Electromagnet A magnet whose field is produced by an electric current. It is usually in the form of a wire coil with a piece of iron inside the coil.

Cosmic rays Various high-speed particles that travel throughout the universe.

REVIEW QUESTIONS

Magnetism

1. By whom, and in what setting, was the relationship between electricity and magnetism discovered?

Magnetic Forces

2. The force between electrically charged particles depends on the magnitude of each charge, the distance of separation, and what else?
3. What is the source of magnetic force?

Magnetic Poles

4. Is the rule for the interaction between magnetic poles similar to the rule for the interaction between electrically charged particles?
5. In what way are *magnetic poles* very different from *electric charges?*

Magnetic Fields

6. How does magnetic field strength relate to the closeness of magnetic field lines about a bar magnet?
7. What produces a magnetic field?
8. What two kinds of rotational motion are exhibited by electrons in an atom?

Magnetic Domains

9. What is a magnetic domain?
10. At the micro level, what is the difference between an unmagnetized iron nail and a magnetized iron nail?
11. Why will dropping an iron magnet on a concrete sidewalk make it a weaker magnet?

Electric Currents and Magnetic Fields

12. In Chapter 22, we learned that the direction of the electric field about a point charge is radial to the charge. What is the direction of the magnetic field surrounding a current-carrying wire?
13. What happens to the direction of the magnetic field about an electric current when the direction of the current is reversed?
14. Why is the magnetic field strength greater inside a current-carrying loop of wire than about a straight section of wire?

Electromagnets

15. Why does a piece of iron in a current-carrying loop increase the magnetic field strength?
16. Why are the magnetic fields of superconducting magnets often stronger than those of conventional magnets?

Magnetic Force on Moving Charged Particles

17. In what direction relative to a magnetic field does a charged particle move in order to experience maximum deflecting force? Minimum deflecting force?

Magnetic Force on Current-Carrying Wires

18. What effect does Earth's magnetic field have on the intensity of cosmic rays striking Earth's surface?
19. What relative direction between a magnetic field and a current-carrying wire results in the greatest force?
20. How does a galvanometer detect electric current?
21. What is a galvanometer called when it has been calibrated to read current? When it has been calibrated to read voltage?
22. How often is current reversed in the loops of an electric motor?

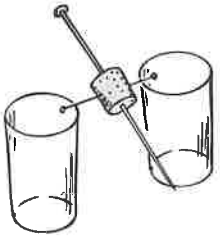
Earth's Magnetic Field

23. Why are there probably no permanently aligned magnetic domains in Earth's core?
24. What are *magnetic pole reversals?*

Biomagnetism

25. What is the cause of the aurora borealis (northern lights)?
26. Name at least six creatures that are known to harbor tiny magnets within their bodies.

PROJECTS



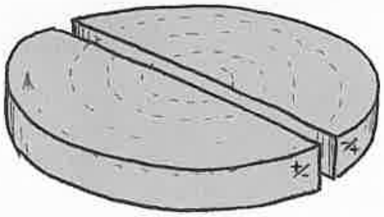
1. Find the direction and dip of Earth's magnetic field lines in your locality. Magnetize a large steel needle or a straight piece of steel wire by stroking it a couple of dozen times with a strong magnet. Run the needle or wire through a cork in such a way that, when the cork floats, your thin magnet remains horizontal (parallel to the water's surface). Float the cork in a plastic or wooden container of water. The needle will point toward the magnetic pole. Then press a pair of unmagnetized common pins into the sides of the cork. Rest the pins on the rims of a pair of drinking glasses so that the needle or wire points toward the magnetic pole. It should dip in line with Earth's magnetic field.
2. An iron bar can be easily magnetized by aligning it with the magnetic field lines of Earth and striking it lightly a few times with a hammer. This works best if the bar is tilted down to match the dip of Earth's field. The hammering jostles the domains so they are better able to fall into alignment with Earth's field. The bar can be demagnetized by striking it when it is oriented in an east-west direction.

EXERCISES

1. Many dry cereals are fortified with iron, which is added to the cereal in the form of small iron particles. How might these particles be separated from the cereal?
2. In what sense are all magnets electromagnets?
3. All atoms have moving electric charges. Why, then, aren't all materials magnetic?
4. To make a compass, point an ordinary iron nail along the direction of Earth's magnetic field (which, in the Northern Hemisphere, is angled downward as well as northward) and repeatedly strike it for a few seconds with a hammer or a rock. Then suspend it at its center of gravity by a string. Why does the act of striking magnetize the nail?
5. If you place a chunk of iron near the north pole of a magnet, attraction will occur. Why will attraction also occur if you place the same iron near the south pole of the magnet?
6. Do the poles of a horseshoe magnet attract each other? If you bend the magnet so that the poles get closer together, what happens to the force between the poles?
7. Why is it inadvisable to make a horseshoe magnet from a flexible material?
8. Your study buddy claims that an electron always experiences a force in an electric field, but not always in a magnetic field. Do you agree? Why or why not?
9. What kind of force field surrounds a stationary electric charge? What additional field surrounds it when it moves?
10. What is different about the magnetic poles of common refrigerator magnets and those of common bar magnets?
11. A friend tells you that a refrigerator door, beneath its layer of white-painted plastic, is made of aluminum. How could you check to see if this is true (without any scraping)?
12. Why will a magnet attract an ordinary nail or paper clip but not a wooden pencil?
13. Why aren't permanent magnets really permanent?
14. Will either pole of a magnet attract a paper clip? Explain what is happening inside the attracted paper clip. (*Hint:* Consider Figure 22.13.)
15. One way to make a compass is to stick a magnetized needle into a piece of cork and float it in a glass bowl full of water. The needle will align itself with the horizontal component of Earth's magnetic field. Since the north pole of this compass is attracted northward, will the needle float toward the north side of the bowl? Defend your answer.

16. A "dip needle" is a small magnet mounted on a horizontal axis so that it can swivel up or down (like a compass turned on its side). Where on Earth will a dip needle point most nearly vertically? Where on Earth will it point most nearly horizontally?
17. In what direction would a compass needle point, if it were free to point in all directions, when located near Earth's north magnetic pole in Canada?
18. What is the net magnetic force on a compass needle? By what mechanism does a compass needle align with a magnetic field?
19. Since the iron filings that align with the magnetic field of the bar magnet shown in Figure 24.2 are not solely little individual magnets, by what mechanism do they align themselves with the field of the magnet?
20. The north pole of a compass is attracted to the north magnetic pole of Earth, yet like poles repel. Can you resolve this apparent dilemma?
21. We know that a compass points northward because Earth is a giant magnet. Will the northward-pointing needle point northward when the compass is brought to the Southern Hemisphere?
22. Your friend says that, when a compass is taken across the equator, it turns around and points in the opposite direction. Your other friend says that this is not true, that people in the Southern Hemisphere use the south magnetic pole of the compass to point toward the nearest pole. You're on; what do you say?
23. In what position can a current-carrying loop of wire be located in a magnetic field so that it doesn't tend to rotate?
24. Magnet A has twice the magnetic field strength of magnet B (at equal distance) and, at a certain distance, it pulls on magnet B with a force of 50 N. With how much force, then, does magnet B pull on magnet A?
25. In Figure 24.15 we see a magnet exerting a force on a current-carrying wire. Does a current-carrying wire exert a force on a magnet? Why or why not?
26. A strong magnet attracts a paper clip to itself with a certain force. Does the paper clip exert a force on the strong magnet? If not, why not? If so, does it exert as much force on the magnet as the magnet exerts on it? Defend your answers.
27. A current-carrying wire is in a north-south orientation. When a compass needle is placed below or above it, in what direction does the compass needle point?

28. A loudspeaker consists of a cone attached to a current-carrying coil located in a magnetic field. What is the relationship between vibrations in the current and vibrations of the cone?
29. Will a superconducting magnet use less electric power than a traditional copper-wire electromagnet of the same field strength? Defend your answer.
30. When iron-hulled naval ships are built, the location of the shipyard and the orientation of the ship in the shipyard are recorded on a brass plaque permanently attached to the ship. Why?
31. A beam of electrons passes through a magnetic field without being deflected. What can you conclude about the orientation of the beam relative to the magnetic field? (Neglect any other fields.)
32. Can an electron at rest in a magnetic field be set into motion by the magnetic field? What if it were at rest in an electric field?
33. A proton moves in a circular path perpendicular to a constant magnetic field. If the field strength of the magnet is increased, does the diameter of the circular path increase, decrease, or remain the same?
34. A cyclotron is a device for accelerating charged particles to high speed as they follow an expanding spiral-like path. The charged particles are subjected to both an electric field and a magnetic field. One of these fields increases the speed of the charged particles, and the other field causes them to follow a curved path. Which field performs which function?



35. A magnet can exert a force on a moving charged particle, but it cannot change the particle's kinetic energy. Why not?
36. A beam of high-energy protons emerges from a cyclotron. Do you suppose that there is a magnetic field associated with these particles? Why or why not?
37. Two charged particles are projected into a magnetic field that is perpendicular to their velocities. If the particles are deflected in opposite directions, what does this tell you about them?
38. A magnetic field can deflect a beam of electrons, but it cannot do work on the electrons to change their speed. Why?
39. Inside a laboratory room there is said to be either an electric field or a magnetic field, but not both. What experiments might be performed to establish what kind of field is in the room?
40. Residents of northern Canada are bombarded by more intense cosmic radiation than residents of Mexico. Why is this so?
41. Why do astronauts keep to altitudes beneath the Van Allen radiation belts when doing space walks?
42. What changes in cosmic-ray intensity at Earth's surface would you expect during periods in which Earth's magnetic field passed through a zero phase while undergoing pole reversals?
43. In a mass spectrometer (Figure 34.14), ions are directed into a magnetic field, where they curve and strike a detector. If a variety of singly ionized atoms travel at the same speed through the magnetic field, would you expect them all to be deflected by the same amount, or would different ions be bent different amounts? Defend your answer.
44. One way to shield a habitat in outer space from cosmic rays is with an absorbing blanket of some kind, which would function much like the atmosphere that protects Earth. Speculate on a second way for shielding the habitat that would also be similar to Earth's natural shielding.
45. If you had two bars of iron—one magnetized and one unmagnetized—and no other materials at hand, how could you determine which bar was the magnet?

46. Historically, replacing dirt roads with paved roads reduced friction on vehicles. Replacing paved roads with steel rails reduced friction further. What recent step eliminates rail friction of vehicles? What friction remains after rail friction is eliminated?
47. Will a pair of parallel current-carrying wires exert forces on each other?
48. What is the magnetic effect of placing two wires with equal but oppositely directed currents close together or twisted about each other?
49. When a current is passed through a helically coiled spring, the spring contracts as if it's compressed. What's your explanation?
50. When preparing to undergo an MRI scan, why are patients advised to remove eyeglasses, watches, jewelry, and other metal objects?

CHAPTER 24 ONLINE RESOURCES

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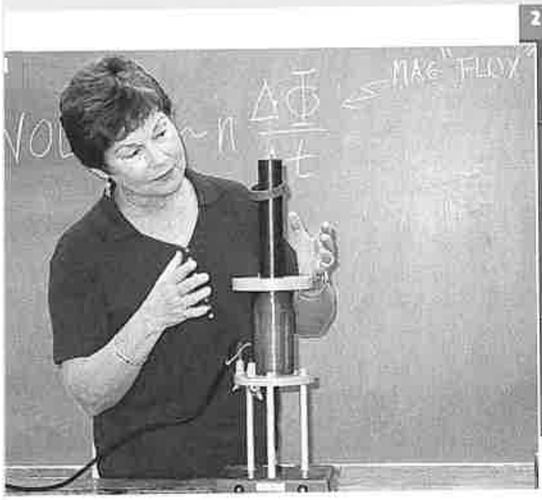
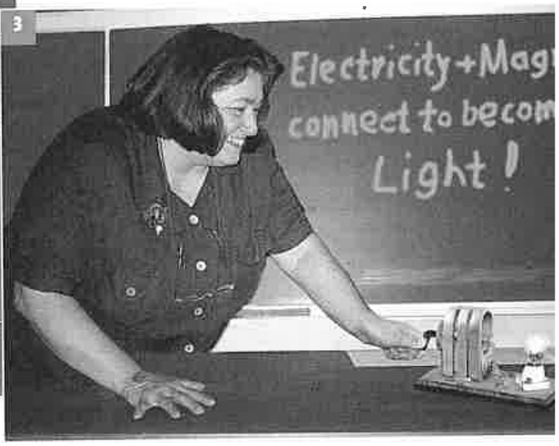
25 Electromagnetic Induction





1 Jean Curtis prompts a check-your-neighbor discussion to explain why the copper ring levitates about the iron core of the electromagnet. 2 A common neighborhood transformer typically steps 2400 volts down to 240 volts for houses and small businesses. The 240 volts can divide to safer 120 volts. 3 Sheron Snyder converts mechanical energy into electromagnetic energy, which in turn, converts to light.

In previous times, most great scientific contributors were men of financial means. People with little or no money were too busy making a living to spend the time required for serious scientific inquiry. Michael Faraday was an exception.

Michael Faraday was one of four children of James Faraday, a village blacksmith in Southeast London. Michael had only a basic school education and was largely self-educated. At the age of 13 he became an apprentice to a local bookbinder and, during his seven-year apprenticeship, he read many books in the bindery. He became very interested in science, especially electricity. In 1812, at the end of his apprenticeship and then 20 years old, Faraday attended lectures by the world-renowned English chemist Sir Humphry Davy of the Royal Institution and Royal Society. Faraday took detailed notes, put them in book form, and sent Davy a more-than-300-page book of the lectures. Davy was most impressed and congratulated Faraday, although at first he advised him to stay in the bookbinding business. But the next year, when Davy's assistant was fired for fighting, Davy invited Faraday to take his place.

Michael Faraday (1791–1867)

In the class-based English society of the time, Faraday was not considered a gentleman. When Davy went on an 18-month tour to the continent with his new wife, Faraday went along but traveled outside the coach and ate with the servants because Davy's wife refused to treat him as an equal. Faraday nevertheless had an opportunity to meet Europe's scientific elite and gain a host of stimulating ideas.

Faraday went on to be one of the most important experimental scientists of the time. He made significant discoveries in chemistry, electrolysis, and mainly electricity and magnetism. In 1831, he made his most remarkable discovery. When he moved a magnet into loops of wire, electric current was induced in them. This is *electromagnetic induction,* coincidentally discovered at about the same time in America by Joseph Henry (the insulation for Henry's wire loops was tearfully donated by his wife, who sacrificed part of the silk from her wedding gown to cover the wires). At this time the only way of producing substantial electric current was with batteries. Electromagnetic induction ushered in the age of electricity.

Faraday's mathematical abilities were limited to simple algebra and did not extend as far as trigonometry. As a result, he conveyed his ideas pictorially and with simple language. He visualized electric and magnetic effects being conveyed by "lines of force." We now call them lines of electric and magnetic fields, and they remain useful tools in science and engineering.

Faraday refused to participate in the production of chemical weapons for the Crimean War, citing ethical reasons. He was deeply religious and met his wife, Sarah Barnard, while attending church. They had no children. He was elected to membership in prestigious societies and enjoyed high scientific status in his later years. He rejected knighthood and twice refused to be President of the Royal Society. He put great effort into service projects for private companies and the British government—increasing the safety of coal mines, new ways of operating lighthouses, and controlling pollution. Faraday was an original "green."

The unit of electrical capacitance, the farad, is named after Faraday. He died at the age of 75 in 1867. Before his death he turned down future burial in Westminster Abbey. A memorial plaque for him is there, near Isaac Newton's tomb. He was, instead, buried in a plot at the church he attended.

Electromagnetic Induction

Faraday and Henry both discovered that electric current can be produced in a wire simply by moving a magnet in or out of loops of wire without an additional voltage source (Figure 25.1). No battery or other voltage source is needed—only the motion of a magnet in a wire loop. This phenomenon of inducing voltage by changing the magnetic field in loops of wire is called **electromagnetic induction.** Voltage is caused, or *induced,* by the relative motion between a wire and a magnetic field—that is, whether the magnetic field of a magnet moves near a stationary conductor or the conductor moves in a stationary magnetic field (Figure 25.2).

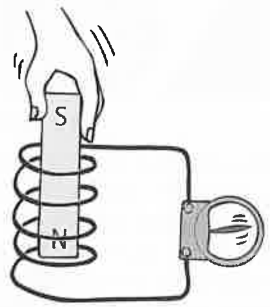


FIGURE 25.1

When the magnet is plunged into the coil, voltage is induced in the coil and charges in the coil are set in motion.

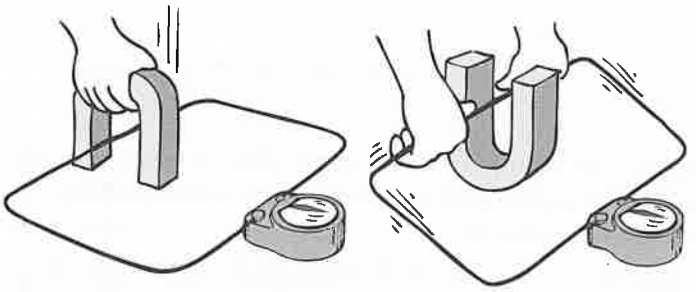


FIGURE 25.2

Voltage is induced in the wire loop either when the magnetic field moves past the wire or the wire moves through the magnetic field.

The greater the number of loops of wire that move in a magnetic field, the greater the induced voltage (Figure 25.3). Pushing a magnet into a coil with twice as many loops will induce twice as much voltage; pushing it into a coil with 10 times as many loops will induce 10 times as much voltage; and so on. It may seem that we get something (energy) for nothing simply by increasing the number of loops in a coil of wire. But, assuming that the coil is connected to a resistor or other energy-dissipating

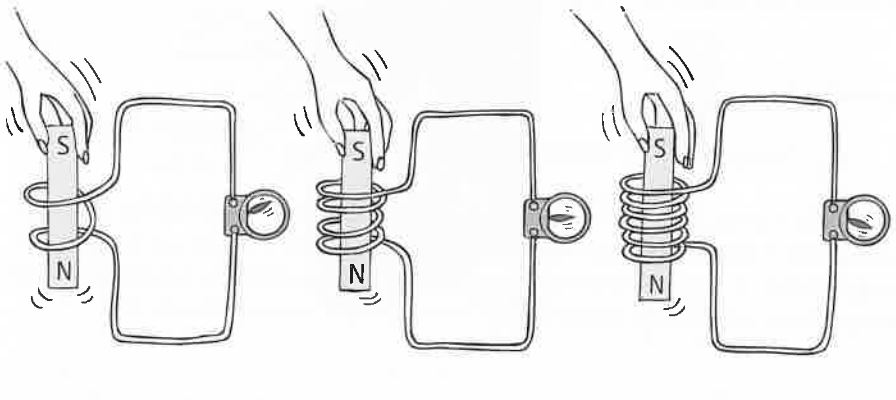


FIGURE 25.3

When a magnet is plunged into a coil of twice as many loops as another, twice as much voltage is induced. If the magnet is plunged into a coil with 3 times as many loops, then 3 times as much voltage is induced.

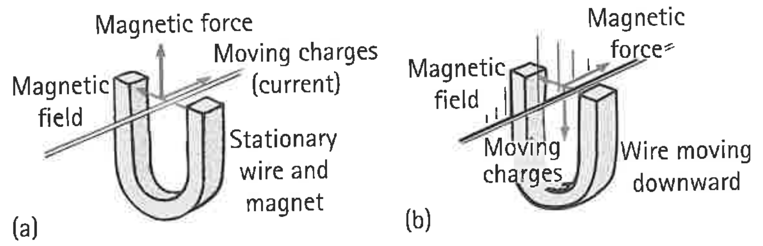


FIGURE 25.7

INTERACTIVE FIGURE

(a) Motor effect: When charge moves along the wire, there is a perpendicular upward force on the charge. Since there is no conducting path upward, the force on the charge tugs the wire upward. (b) Generator effect: When a wire with no initial current is moved downward, the charge in the wire experiences a deflecting force perpendicular to its motion. There is a conducting path in this direction, so the charge moves, constituting a current.

field they traverse (Figure 25.7). We will call the deflection of the wire (motion as a result of current) the *motor effect,* and we will call what happens as a result of the law of induction (current as a result of motion) the *generator effect.* These effects are summarized in (a) and (b) of the figure (where by convention, current and force arrows apply to positive charge). Study them. Can you see that the two effects are related?

We can see the electromagnetic induction cycle in Figure 25.8. Note that when the loop of wire is rotated in the magnetic field, there is a change in the number of magnetic field lines within the loop. When the plane of the loop is perpendicular to the field lines, the maximum number of lines is enclosed. As the loop rotates, it in effect chops the lines, so that fewer lines are enclosed. When the plane of the loop is parallel to the field lines, none are enclosed. Continued rotation increases and decreases the number of enclosed lines in cyclic fashion, with the greatest rate of change of field lines occurring when the number of enclosed field lines goes through zero. Hence, the induced voltage is greatest as the loop rotates through its parallel-to-the-lines orientation. Because the voltage induced by the generator alternates, the current produced is ac, an alternating current.[3] The alternating current in our homes is produced by generators standardized so that the current goes through 60 cycles of change each second—60 hertz.

When you step on the brakes in a hybrid car, the electric motor becomes a generator and charges a battery.

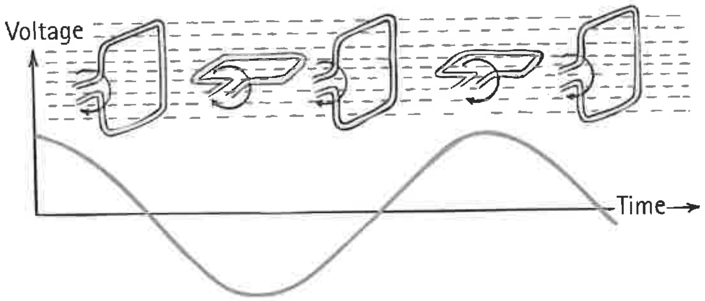


FIGURE 25.8

As the loop rotates, the induced voltage (and current) changes in magnitude and direction. One complete rotation of the loop produces one complete cycle in voltage (and in current).

CHECK POINT

When is work input necessary for energy output by electromagnetic induction?

Check Your Answer

Always.

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[3] With appropriate brushes and by other means, the ac in the loop(s) can be converted to dc to make a dc generator.

Power Production

Fifty years after Michael Faraday and Joseph Henry discovered electromagnetic induction, Nikola Tesla and George Westinghouse put those findings to practical use and showed the world that electricity could be generated reliably and in sufficient quantities to light entire cities.

TURBOGENERATOR POWER

Tesla built generators much like those in operation today, but quite a bit more complicated than the simple model we have discussed. Tesla's generators had armatures—iron cores wrapped with bundles of copper wire—that were made to spin within strong magnetic fields by means of a turbine, which, in turn, was spun by the energy of steam or falling water. The rotating loops of wire in the armature cut through the magnetic field of the surrounding electromagnets, thereby inducing alternating voltage and current.

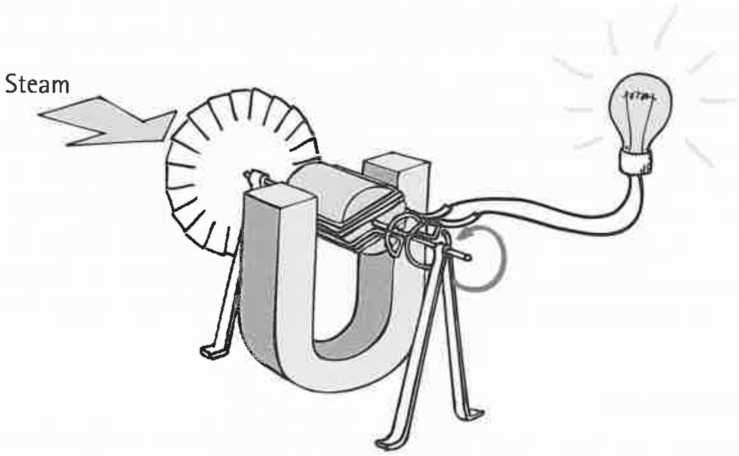

FIGURE 25.9

Steam drives the turbine, which is connected to the armature of the generator.

We can look at this process from an atomic point of view. When the wires in the spinning armature cut through the magnetic field, oppositely directed electromagnetic forces act on the negative and positive charges. Electrons respond to this force by momentarily swarming relatively freely in one direction throughout the crystalline copper lattice; the copper atoms, which are actually positive ions, are forced in the opposite direction. Because the ions are anchored in the lattice, however, they hardly move at all. Only the electrons move, sloshing back and forth in alternating fashion with each rotation of the armature. The energy of this electronic sloshing is tapped at the electrode terminals of the generator.

In making a great discovery, being at the right place at the right time is not enough—curiosity and hard work are also important.

MHD POWER

An interesting device similar to the turbogenerator is the MHD (magnetohydrodynamic) generator, which eliminates the turbine and spinning armature altogether. Instead of making charges move in a magnetic field via a rotating armature, a plasma of electrons and positive ions expands through a nozzle and moves at supersonic speed through a magnetic field. Like the armature in a turbogenerator, the motion of charges through a magnetic field gives rise to a voltage and flow of current in accordance with Faraday's law of induction. Whereas in a conventional generator "brushes" carry the current to the external load circuit, in the MHD generator the same function is performed by conducting plates, or *electrodes* (Figure 25.10). Unlike the turbogenerator, the MHD generator can operate at any temperature to which the plasma can be heated, either by combustion or nuclear processes.

The high temperature results in a high thermodynamic efficiency, which means more power for the same amount of fuel and less waste heat. Efficiency is further boosted when the "waste" heat is used to convert water into steam to run a conventional steam-turbine generator.

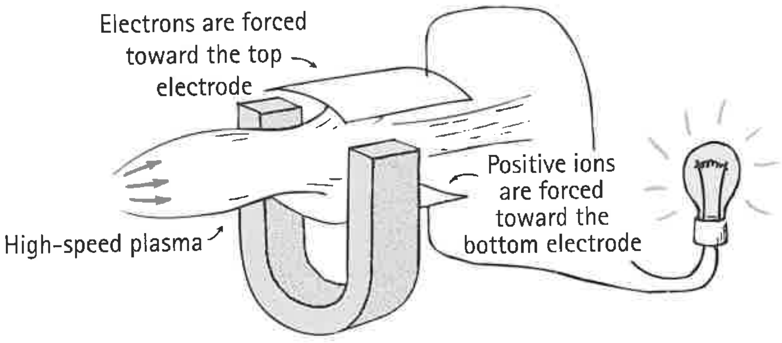

FIGURE 25.10

A simplified MHD generator. Oppositely directed forces act on the positive and negative particles in the high-speed plasma moving through the magnetic field. The result is a voltage difference between the two electrodes. Current then flows from one electrode to the other through an external circuit. There are no moving parts; only the plasma moves. In practice, superconducting electromagnets are used.

This substitution of a flowing plasma for rotating copper coils in a generator has become operational only since development of the technology to produce sufficiently high-temperature plasmas. Current plants use a high-temperature plasma formed by combustion of fossil fuels in air or oxygen.[4]

It's important to know that generators don't produce energy—they simply convert energy from some other form to electric energy. As we discussed in Chapter 7, energy from a source, whether fossil or nuclear fuel or wind or water, is converted to mechanical energy to drive the turbine. The attached generator converts most of this mechanical energy to electrical energy. Some people think that electricity is a primary source of energy. It is not. It is a carrier of energy that requires a source.

TRANSFORMERS

Electric energy can certainly be carried along wires, and now we'll see how it can be carried across empty space. Energy can be transferred from one device to another with the simple arrangement shown in Figure 25.11. Note that one coil is connected to a battery and the other is connected to a galvanometer. It is customary to refer to the coil connected to the power source as the *primary* (input) and to the other as the *secondary* (output). As soon as the switch is closed in the primary and current passes through its coil, a current occurs in the secondary also—even though there is no material connection between the two coils. Only a brief surge of current occurs in the secondary, however. Then, when the primary switch is opened, a surge of current again registers in the secondary, but in the opposite direction.

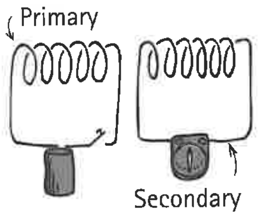

FIGURE 25.11

Whenever the primary switch is opened or closed, voltage is induced in the secondary circuit.

This is the explanation: A magnetic field builds up around the primary when the current begins to flow through the coil. This means that the magnetic field is growing (that is, *changing*) about the primary. But, since the coils are near each other, this changing field extends into the secondary coil, thereby inducing a voltage in the secondary. This induced voltage is only temporary, for when the current and the magnetic field of the primary reach a steady state—that is, when the magnetic field is no longer changing—no further voltage is induced in the secondary. But, when the switch is turned off, the current in the primary drops to zero. The magnetic field about the coil collapses, thereby inducing a voltage in the secondary coil, which senses the change. We see that voltage is induced whenever a magnetic field is *changing* through the coil, regardless of the reason.

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[4] Lower temperatures are sufficient when the electrically conducting fluid is liquid metal, usually lithium. A liquid-metal MHD power system is referred to as a LMMHD power system.

CHECK POINT

When the switch of the primary in Figure 25.11 is opened or closed, the galvanometer in the secondary registers a current. But when the switch remains closed, no current is registered on the galvanometer of the secondary. Why?

Check Your Answer

When the switch remains in the closed position, there is a steady current in the primary and a steady magnetic field about the coil. This field extends to the secondary, but unless there is a *change* in the field, electromagnetic induction does not occur.

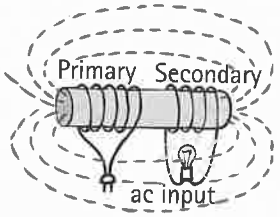
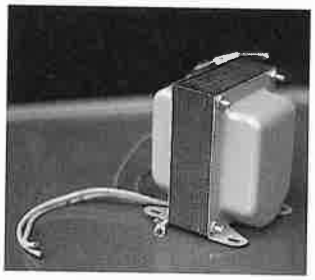


FIGURE 25.12
A simple transformer.



If you place an iron core inside the primary and secondary coils of the arrangement of Figure 25.11, the magnetic field within the primary is intensified by the alignment of magnetic domains. The field is also concentrated in the core and extends into the secondary, which intercepts more of the field change. The galvanometer will show greater surges of current when the switch of the primary is opened or closed. Instead of opening and closing a switch to produce the change of magnetic field, suppose that alternating current is used to power the primary. Then the frequency of periodic changes in the magnetic field is equal to the frequency of the alternating current. Now we have a **transformer** (Figure 25.12). A more efficient arrangement is shown in Figure 25.13.

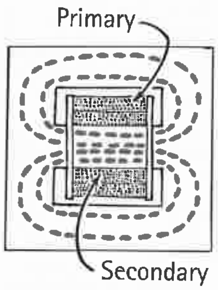


FIGURE 25.13
A practical and more efficient transformer. Both primary and secondary coils are wrapped on the inner part of the iron core (yellow), which guides alternating magnetic lines (green) produced by ac in the primary. The alternating field induces ac voltage in the secondary. Thus power at one voltage from the primary is transferred to the secondary at a different voltage.

If the primary and secondary have equal numbers of wire loops (usually called *turns*), then the input and output alternating voltages will be equal. But if the secondary coil has more turns than the primary, the alternating voltage produced in the secondary coil will be greater than that produced in the primary. In this case, the voltage is said to be *stepped up*. If the secondary has twice as many turns as the primary, the voltage in the secondary will be double that of the primary.

We can see this with the arrangements in Figure 25.14. First consider the simple case of a single primary loop connected to a 1-volt alternating source, and a single secondary loop connected to the ac voltmeter (a). The secondary intercepts the changing magnetic field of the primary, and a voltage of 1 V is induced in the secondary. If another loop is wrapped around the core so that the transformer has two secondaries (b), it intercepts the same magnetic field change. We see that 1 V is induced in it also. There is no need to keep both secondaries separate, for we could join them (c) and still have a total induced voltage of 1 V + 1 V, or 2 V. This is equivalent to saying that a voltage of 2 V will be induced in a single secondary that has twice the number of loops as the primary. If the secondary is wound with 3 times as many loops, then 3 times as much voltage will be induced. Stepped-up voltage may light a neon sign or send power over a long distance.

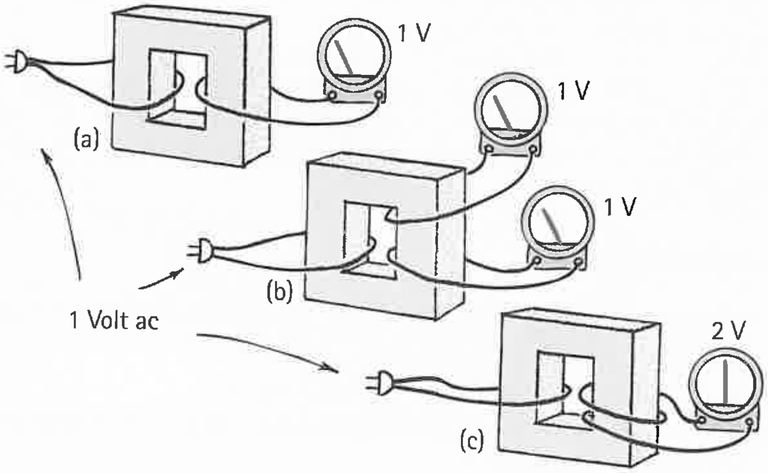


FIGURE 25.14
(a) The voltage of 1 V induced in the secondary equals the voltage of the primary. (b) A voltage of 1 V is also induced in the added secondary because it intercepts the same magnetic field change from the primary. (c) The voltages of 1 V each induced in the two one-turn secondaries are equivalent to a voltage of 2 V induced in a single two-turn secondary.

If the secondary has fewer turns than the primary, the alternating voltage produced in the secondary will be *lower* than that produced in the primary. The voltage is said to be *stepped down*. This stepped-down voltage may safely operate a toy electric train. If the secondary has half as many turns as the primary, then only half as much voltage is induced in the secondary. So electric energy can be fed into the primary at a given alternating voltage and taken from the secondary at a greater or lower alternating voltage, depending on the relative number of turns in the primary and secondary coil windings. The relationship between primary and secondary voltages with respect to the relative number of turns is given by

$$\frac{\text{Primary voltage}}{\text{Number of primary turns}} = \frac{\text{secondary voltage}}{\text{number of secondary turns}}$$

It might seem that we get something for nothing with a transformer that steps up the voltage. Not so, for energy conservation always regulates what can happen. When voltage is stepped up, current in the secondary is less than in the primary. The transformer actually transfers energy from one coil to the other. Make no mistake about this point: It can in no way step up energy—a conservation of energy no-no. A transformer steps voltage up or down without a change in energy. The rate at which energy is transferred is called *power*. The power used in the secondary is supplied by the primary. The primary gives no more than the secondary uses, in accord with the law of conservation of energy. If the slight power losses due to heating of the core are neglected, then

$$\text{Power into primary} = \text{power out of secondary}$$

Electric power is equal to the product of voltage and current, so we can say

$$(\text{Voltage} \times \text{current})_{\text{primary}} = (\text{voltage} \times \text{current})_{\text{secondary}}$$

We see that if the secondary has more voltage than the primary, it will have less current than the current in the primary. The ease with which voltages can be stepped up or down with a transformer is the principal reason that most electric power is ac rather than dc.

CHECK POINT

1. If 100 V of ac is put across a 100-turn transformer primary, what will be the voltage output if the secondary has 200 turns?
2. Assuming the answer to the previous question is 200 V, and the secondary is connected to a flood lamp with a resistance of 50 Ω, what will be the ac current in the secondary circuit?
3. What is the power in the secondary coil?
4. What is the power in the primary coil?
5. What is the ac current drawn by the primary coil?
6. The voltage has been stepped up, and the current has been stepped down. Ohm's law says that increased voltage will produce increased current. Is there a contradiction here, or does Ohm's law not apply to circuits that have transformers?

Check Your Answers

1. From $\frac{100\text{ V}}{100\text{ primary turns}} = \frac{x\text{ V}}{200\text{ secondary turns}}$, you should see that $x = 200$ V.
2. From Ohm's law, 200 V/50 Ω = 4 A.
3. Power = voltage × current = 200 V × 4 A = 800 W.
4. By the law of conservation of energy, the power in the primary is the same, 800 W.

5. 8 A, twice as much (100 V × ? A = 800 W).
6. Ohm's law remains alive and well. The voltage induced across the secondary circuit divided by the load (resistance) of the secondary circuit equals the current in the secondary circuit. In the primary circuit, on the other hand, there is no conventional resistance. What "resists" the current in the primary is the transfer of energy to the secondary.

Self-Induction

Current-carrying loops in a coil interact not only with loops of other coils but also with loops of the same coil. Each loop in a coil interacts with the magnetic field around the current in other loops of the same coil. This is *self-induction.* A self-induced voltage is produced. This voltage is always in a direction opposing the changing voltage that produces it and is commonly called the "back electromotive force," or simply "back emf."[5] We won't treat self-induction and back emfs here, except to acknowledge a common and dangerous effect.

Suppose that a coil with a large number of turns is used as an electromagnet and is powered with a dc source, perhaps a small battery. Current in the coil is then accompanied by a strong magnetic field. When we disconnect the battery by opening a switch, we had better be prepared for a surprise. When the switch is opened, the current in the circuit falls rapidly to zero and the magnetic field in the coil undergoes a sudden decrease (Figure 25.15). What happens when a magnetic field suddenly changes in a coil, even if it is the same coil that produced it? The answer is that a voltage is induced. The rapidly collapsing magnetic field with its store of energy may induce an enormous voltage, large enough to develop a strong spark across the switch—or to you, if you are opening the switch! For this reason, electromagnets are connected to a circuit that absorbs excess charge and prevents the current from dropping too suddenly. This reduces the self-induced voltage. This is also, by the way, why you should disconnect appliances by turning off the switch, not by pulling out the plug. The circuitry in the switch may prevent a sudden change in current.

FIGURE 25.15
When the switch is opened, the magnetic field of the coil collapses. This sudden change in the field can induce a huge voltage.

Power Transmission

Almost all electric energy sold today is in the form of ac, traditionally because of the ease with which it can be transformed from one voltage to another.[6] Large currents in wires produce heat and energy losses, so power is transmitted great distances at high voltages and correspondingly low currents (power = voltage × current). Power is generated at 25,000 V or less and is stepped up near the power station to as much as 750,000 V for long-distance transmission, then stepped down in stages at substations and distribution points to voltages needed in industrial applications (often 440 V or more) and for the home (240 and 120 V).

Note transformers on utility poles in your neighborhood. They are the go-between from power stations to individual consumers, often humming as they do their thing.

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[5] The opposition of an induced effect to an inducing cause is called *Lenz's law;* it is a consequence of the conservation of energy.

[6] Nowadays, power utilities can transform dc voltages using semiconductor technology. Keep an eye on the present advances in superconductor technology, and watch for resulting changes in power transmission.

FIGURE 25.16
Power transmission.

Energy, then, is transferred from one system of conducting wires to another by electromagnetic induction. It is but a short step further to find that the same principles account for eliminating wires and sending energy from a radio-transmitter antenna to a radio receiver many kilometers away. Extend these principles just a tiny step further to the transformation of the energy of vibrating electrons in the Sun to life energy on Earth. The effects of electromagnetic induction are very far-reaching.

Field Induction

Electromagnetic induction explains the induction of voltages and currents. Actually, the more basic *fields* are at the root of both voltages and currents. The modern view of electromagnetic induction states that electric and magnetic fields are induced. These, in turn, produce the voltages we have considered. So induction occurs whether or not a conducting wire or any material medium is present. In this more general sense, Faraday's law states:

200 years ago, people got light from whale oil. Whales should be glad that humans discovered how to harness electricity!

An electric field is induced in any region of space in which a magnetic field is changing with time.

There is a second effect, an extension of Faraday's law. It is the same except that the roles of electric and magnetic fields are interchanged. It is one of nature's many symmetries. This effect was advanced by the British physicist James Clerk Maxwell in about 1860 and is known as **Maxwell's counterpart to Faraday's law:**

A magnetic field is induced in any region of space in which an electric field is changing with time.

Electromagnetic waves scarcely ever interact with each other. The space around you is filled with radio waves, TV signals, cell-phone messages, and light, each "doing its own thing" and ignoring all the others. How fortunate for us.

In each case, the strength of the induced field is proportional to the rate of change of the inducing field. Induced electric and magnetic fields are at right angles to each other.

Maxwell saw the link between electromagnetic waves and light.[7] If electric charges are set into vibration in the range of frequencies that match those of light, waves are produced that *are* light! Maxwell discovered that light is simply electromagnetic waves in the range of frequencies to which the eye is sensitive.

Because of electromagnetic induction, the energy of elevated rivers has been harnessed, turned to electricity, and transported to distant cities. The advent of motors, generators, and transformers occurred at about the time the American Civil War was being fought. From a long view of human history, there can be little doubt that events such as the American Civil War will pale into provincial insignificance in comparison with the more significant event of the 19th century: the discovery and implementation of the electromagnetic laws.

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[7] On the eve of his discovery, story has it that Maxwell had a date with a young woman he was later to marry. While walking in a garden, his date remarked about the beauty and wonder of the stars. Maxwell asked how she would feel to know that she was walking with the only person in the world who knew what starlight really was. For it was true. At that time, James Clerk Maxwell was the only person in the world to know that light of any kind is energy carried in waves of electric and magnetic fields that continually regenerate each other.

SUMMARY OF TERMS

Electromagnetic induction The induction of voltage when a magnetic field changes with time. If the magnetic field within a closed loop changes in any way, a voltage is induced in the loop:

$$\text{Voltage induced} \sim \text{area of loop} \times \frac{\Delta \text{ magnetic field}}{\Delta \text{ time}}$$

This is a statement of Faraday's law. (If multiple loops are connected together in a coil, the voltage induced is multiplied by the number of loops.) The induction of voltage is actually the result of a more fundamental phenomenon: generally, the induction of an electric *field.*

Faraday's law An electric field is created in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. The direction of the induced field is at right angles to the changing magnetic field.

Generator An electromagnetic induction device that produces electric current by rotating a coil within a stationary magnetic field. A generator converts mechanical energy to electrical energy.

Transformer A device for transferring electric power from one coil of wire to another, by means of electromagnetic induction, for the purpose of transforming one value of voltage to another.

Maxwell's counterpart to Faraday's law A magnetic field is created in any region of space in which an electric field is changing with time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is at right angles to the changing electric field.

REVIEW QUESTIONS

Electromagnetic Induction

1. Exactly what did Michael Faraday and Joseph Henry discover?
2. What must change in order for electromagnetic induction to occur?

Faraday's Law

3. In addition to induced voltage, on what does the current produced by electromagnetic induction depend?
4. What are the three ways in which voltage can be induced in a wire?

Generators and Alternating Current

5. How does the frequency of induced voltage relate to how frequently a magnet is plunged in and out of a coil of wire?
6. What is the basic *similarity* between a generator and an electric motor? What is the basic *difference* between them?
7. Where in the rotation cycle of a simple generator is the induced voltage at a maximum?
8. Why does a generator produce alternating current?

Power Production

9. Who discovered electromagnetic induction, and who put it to practical use?
10. What is an armature?
11. What commonly supplies the energy input to a turbine?
12. What are the principal differences between an *MHD generator* and a *conventional generator?*
13. Does an MHD generator employ Faraday's law of induction?
14. Electric energy can certainly be carried along wires, but can it be carried across empty space? If so, how?
15. Why does a transformer require ac?
16. What name is given to the rate at which energy is transferred?
17. What is the principal advantage of ac over dc?

Self-Induction

18. When the magnetic field changes in a coil of wire, voltage in each loop of the coil is induced. Will voltage be induced in a loop if the source of the magnetic field is the coil itself?

Power Transmission

19. What is the purpose of transmitting power at high voltages over long distances?
20. Does the transmission of electric energy require electrical conductors between the source and receiver? Cite an example to defend your answer.

Field Induction

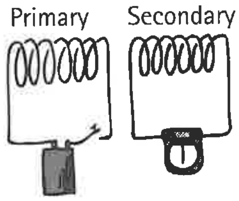
21. What is induced by the rapid alternation of a *magnetic field?*
22. What is induced by the rapid alternation of an *electric field?*

PROJECT

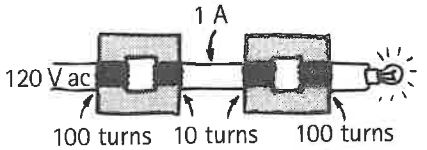
1. Drop a small magnet through a vertical plastic pipe, noting its speed of fall. Then do the same with a copper pipe. Explain why the magnet falls much slower in the copper pipe.
2. Write a letter to Grandma and tell her the answer to what has been a mystery for centuries—what light is. Tell her how light is related to electricity and magnetism.

EXERCISES

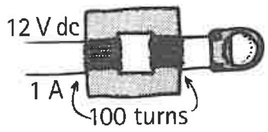
1. Why does the word *change* occur so frequently in this chapter?
2. A common pickup for an electric guitar consists of a coil of wire around a small permanent magnet, as described in Figure 25.5. Why will this type of pickup fail with nylon strings?
3. Why does an iron core increase the magnetic induction of a coil of wire?
4. Why are the armature and field windings of an electric motor usually wound on an iron core?
5. Why is a generator armature harder to rotate when it is connected to a circuit and supplying electric current?
6. Why does a motor also tend to act as a generator?
7. Will a cyclist coast farther if the lamp connected to the generator on his bicycle is turned off? Explain.
8. When an automobile moves over a wide, closed loop of wire embedded in a road surface, is the magnetic field of Earth within the loop altered? Is a pulse of current produced? Can you cite a practical application for this at a traffic intersection?
9. At the security area, people walk through a large coil of wire and through a weak ac magnetic field. What is the result of a small piece of metal on a person that slightly alters the magnetic field in the coil?
10. A piece of plastic tape coated with iron oxide is magnetized more in some parts than in others. When the tape is moved past a small coil of wire, what happens in the coil? What is a practical application of this?
11. Joseph Henry's wife donated part of her silk wedding gown to cover the wires of Joseph's electromagnets. What was the purpose of the silk covering?
12. A certain simple earthquake detector consists of a little box firmly anchored to Earth. Suspended inside the box is a massive magnet that is surrounded by stationary coils of wire fastened to the box. Explain how this device works, applying two important principles of physics—one studied in Chapter 2 and the other in this chapter.
13. How do the direction of the magnetic force and its effects differ between the motor effect and the generator effect, as shown in Figure 25.7?
14. When you turn the shaft of an electric motor by hand, what occurs in the interior coils of wire?
15. Your friend says that if you crank the shaft of a dc motor manually, the motor becomes a dc generator. Do you agree or disagree?
16. Does the voltage output increase when a generator is made to spin faster? Defend your answer.
17. If you place a metal ring in a region in which a magnetic field is rapidly alternating, the ring may become hot to your touch. Why?
18. An electric saw operating at normal speed draws a relatively small current. But if a piece of wood being sawed jams and the motor shaft is prevented from turning, the current dramatically increases and the motor overheats. Why?
19. A magician places an aluminum ring on a table with a hidden electromagnet underneath. When the magician says "abracadabra" (and pushes a switch that starts current flowing through the coil under the table), the ring jumps into the air. Explain his "trick."
20. In the chapter-opening photograph, Jean Curtis asks her class why the copper ring levitates about the iron core of the electromagnet. What is the explanation, and does it involve ac or dc?
21. How could a lightbulb near an electromagnet, but not touching it, be lit? Is ac or dc required? Defend your answer.
22. A length of wire is bent into a closed loop and a magnet is plunged into it, inducing a voltage and, consequently, a current in the wire. A second length of wire, twice as long, is bent into two loops of wire, and a magnet is similarly plunged into it. Twice the voltage is induced, but the current is the same as that produced in the single loop. Why?
23. Two separate but similar coils of wire are mounted close to each other, as shown. The first coil is connected to a battery and has a direct current flowing through it. The second coil is connected to a galvanometer.



    a. How does the galvanometer respond when the switch in the first circuit is closed?
    b. After being closed, how does the meter respond when the current is steady?
    c. How does the meter respond when the switch is opened?
24. Why will more voltage be induced with the apparatus shown above if an iron core is inserted in the coils?
25. Why will a transformer not work if you are using dc?
26. How does the current in the secondary of a transformer compare with the current in the primary when the secondary voltage is twice the primary voltage?
27. In what sense can a transformer be considered an electrical lever? What does it multiply? What does it *not* multiply?
28. What is the principal difference between a step-up transformer and a step-down transformer?
29. Why can a hum usually be heard when a transformer is operating?
30. Why doesn't a transformer work with direct current? Why is ac required?
31. Why is it important that the core of a transformer pass through both coils?
32. Are the primary and secondary coils in a transformer physically linked, or is there space between the two? Explain.
33. In the circuit shown, how many volts are impressed across the lightbulb and how many amps flow through it?



34. In the circuit shown, how many volts are impressed across the meter and how many amps flow through it?



35. How would you answer the previous question if the input were 12 V ac?
36. Your friend says that according to Ohm's law, high voltage produces high current. Then your friend asks, "So how can power be transmitted at high voltage and *low* current in a power line?" What is your illuminating response?

37. Can an efficient transformer step up energy? Defend your answer.

38. If a bar magnet is thrown into a coil of high-resistance wire, it will slow down. Why?

39. Your physics instructor drops a magnet through a long vertical copper pipe and it moves slowly compared with the drop of a nonmagnetized object. Provide an explanation.

40. This exercise is similar to the previous one. Why will a bar magnet fall slower and reach terminal velocity in a vertical copper or aluminum tube but not in a cardboard tube?

41. Although copper and aluminum are not magnetic, why is a sheet of either metal more difficult to pass between the pole pieces of a magnet than a sheet of cardboard?

42. A metal bar, pivoted at one end, oscillates freely in the absence of a magnetic field. But when it oscillates between the poles of a magnet, its oscillations are quickly damped. Why? (Such magnetic damping is used in a number of practical devices.)

43. The metal wing of an airplane acts like a "wire" flying through Earth's magnetic field. A voltage is induced between the wing tips, and a current flows along the wing, but only for a short time. Why does the current stop even though the airplane continues flying through Earth's magnetic field?

44. What is wrong with this scheme? To generate electricity without fuel, arrange a motor to operate a generator that will produce electricity that is stepped up with transformers so that the generator can operate the motor and simultaneously furnish electricity for other uses.

45. We know that the source of a sound wave is a vibrating object. What is the source of an electromagnetic wave?

46. With no magnets in the vicinity, why will current flow in a large coil of wire waved around in the air?

47. What does an incident radio wave do to the electrons in a receiving antenna?

48. How do you suppose the frequency of an electromagnetic wave compares with the frequency of the electrons it sets into oscillation in a receiving antenna?

49. A friend says that changing electric and magnetic fields generate one another and that this gives rise to visible light when the frequency of change matches the frequencies of light. Do you agree? Explain.

50. Would electromagnetic waves exist if changing magnetic fields could produce electric fields, but changing electric fields could not, in turn, produce magnetic fields? Explain.

PROBLEMS

1. The primary coil of a step-up transformer draws 100 W. How much power is provided by the secondary coil?

2. An ideal transformer has 50 turns in its primary and 250 turns in its secondary. 12 V ac is connected to the primary.
  a. Find the volts ac available at the secondary.
  b. Show that a 10-Ω device connected to the secondary draws a current of 6 A.
  c. How much power is supplied to the primary?

3. A model electric train requires 6 V to operate. If the primary coil of its transformer has 240 windings, how many windings should the secondary have if the primary is connected to a 120-V household circuit?

4. Neon signs require about 12,000 V for their operation. What should be the ratio of the number of loops in the secondary to the number of loops in the primary for a neon-sign transformer that operates from 120-V lines?

• **5.** 100 kW (10^5 W) of power is delivered to the other side of a city by a pair of power lines between which the voltage is 12,000 V.
  a. How much current is carried in the lines?
  b. Each of the two lines has a resistance of 10 Ω. What is the voltage difference between the two ends of each line? (Think carefully. This voltage is not that between the two lines.)
  c. What power is wasted as heat in both lines together (distinct from power delivered to customers)? How does this compare with the power being delivered?

Remember, review questions provide you with a self check of whether or not you grasp the central ideas of the chapter. The exercises, rankings, and problems are extra "pushups" for you to try after you have at least a fair understanding of the chapter and can handle the review questions.

CHAPTER 25 ONLINE RESOURCES

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- 25.6, 25.7

Videos

- Faraday's Law
- Application of E&M Induction

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PART FIVE MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. The electrical force of attraction between an electron and a proton is greater on the
   (a) proton.
   (b) electron.
   (c) Neither; both are the same.
2. When you brush your hair and scrape electrons from your hair, the charge of your hair becomes
   (a) positive.
   (b) negative.
   (c) Both of these.
   (d) Neither of these.
3. According to Coulomb, a pair of charged particles placed twice as close to each other experience a force
   (a) twice as strong.
   (b) 4 times as strong.
   (c) 1/2 as strong.
   (d) 1/4 as strong.
4. When you buy a pipe in a hardware store, the water isn't included. When you buy copper wire, electrons
   (a) must be supplied by you.
   (b) are included in the wire.
   (c) may fall out; hence, insulation.
   (d) None of these.
5. Immediately after two separated charged particles are released from rest, both increase in *speed*. The sign of charge of the particles is therefore
   (a) the same.
   (b) opposite.
   (c) Either of these.
   (d) Need more information.
6. Immediately after two separated charged particles are released from rest, both increase in *acceleration*. The sign of charge of the particles is therefore
   (a) the same.
   (b) opposite.
   (c) Either of these.
   (d) Need more information.
7. The electric field between a pair of oppositely charged parallel plates
   (a) gets weaker with distance inside the plates.
   (b) follows the inverse-square law.
   (c) Both of these.
   (d) Neither of these.
8. A capacitor can store
   (a) charge.
   (b) energy.
   (c) Both of these.
   (d) Neither of these.
9. The electric field inside the dome of a Van de Graaff generator is zero when the dome is
   (a) charged.
   (b) uncharged.
   (c) Either of these.
   (d) Neither of these.
10. The potential energy of a compressed spring and the potential energy of a charged object both depend on
    (a) the work done on them.
    (b) motion.
    (c) Both of these.
    (d) Neither of these.
11. To receive an electric shock there must be a
    (a) current in one direction.
    (b) presence of moisture.
    (c) high voltage and low body resistance.
    (d) voltage difference across part or all of your body.
12. A 10-Ω resistor carries 10 A. The voltage across the resistor is
    (a) 0.
    (b) more than 0 but less than 10 V.
    (c) 10 V.
    (d) more than 10 V.
13. If the current in the filament of a lamp is 3 A, the current in the connecting wire is
    (a) less than 3 A.
    (b) 3 A.
    (c) more than 3 A.
    (d) Not enough information to say.
14. The difference between dc and ac in electrical circuits is that in dc, charges flow
    (a) steadily in one direction.
    (b) in one direction.
    (c) to and fro.
    (d) All of these.
15. As more lamps are connected to a series circuit, the current in the power source
    (a) increases.
    (b) decreases.
    (c) remains the same.
    (d) None of these.
16. In a series circuit, if the current in one lamp is 2 A, the current in the lamp next to it is
    (a) half, 1 A.
    (b) 2 A.
    (c) Depends on which lamp is closer to the battery.
    (d) Not enough information to say.
17. As more lamps are connected in parallel in a circuit, the current in the power source
    (a) increases.
    (b) decreases.
    (c) remains the same.
    (d) Not enough information to say.
18. In a circuit of two lamps in parallel, if the current in one lamp is 2 A, the current in the other lamp is
    (a) about 1 A.
    (b) 2 A.
    (c) Depends on which lamp is closer to the battery.
    (d) Not enough information to say.
19. An electron can be speeded up by
    (a) an electric field.
    (b) a magnetic field.
    (c) Both of these.
    (d) Neither of these.
20. The magnetic field lines about a current-carrying wire form
    (a) circles.
    (b) radial lines.
    (c) eddy currents.
    (d) energy loops.
21. A magnetic force can act on an electron even when it
    (a) is at rest.
    (b) moves parallel to magnetic field lines.
    (c) Both of these.
    (d) Neither of these.
22. A magnetic force acting on a beam of electrons can change its
    (a) direction.
    (b) energy.
    (c) Both of these.
    (d) Neither of these.
23. A galvanometer can be calibrated to read electric
    (a) current.
    (b) voltage.
    (c) Either of these.
    (d) Neither of these.
24. A motor and a generator are
    (a) similar devices.
    (b) very different devices.
    (c) forms of transformers.
    (d) energy sources.
25. The metal detectors people walk through at airports operate via
    (a) Ohm's law.
    (b) Faraday's law.
    (c) Coulomb's law.
    (d) Newton's laws.
26. If you change the magnetic field in a closed loop of wire, what is created in the loop is a(n)
    (a) current.
    (b) voltage.
    (c) electric field.
    (d) All of these.
27. A voltage will be induced in a wire loop when the magnetic field within that loop
    (a) changes.
    (b) aligns with the electric field.
    (c) is at right angles to the electric field.
    (d) converts to magnetic energy.
28. A step-up transformer in an electrical circuit can step up
    (a) voltage.
    (b) energy.
    (c) Both of these.
    (d) Neither of these.
29. Compared with power input, the power output of an ideal transformer is
    (a) greater.
    (b) less.
    (c) the same.
    (d) Any of these.
30. Electricity and magnetism connect to form
    (a) mass.
    (b) energy.
    (c) ultra-high-frequency sound.
    (d) light.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.