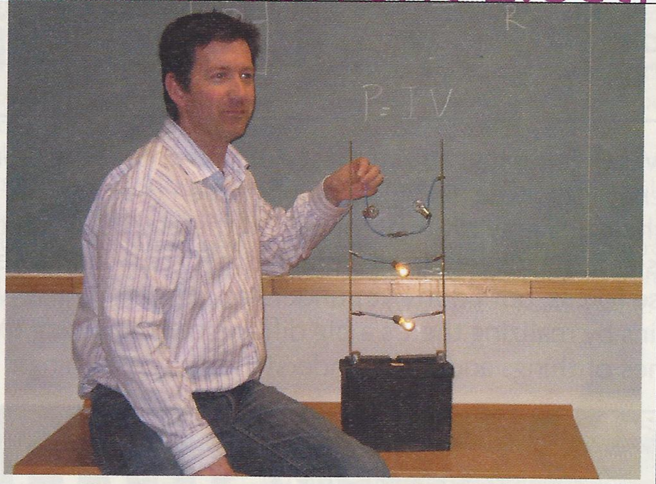
CHAPTER 10

Static and Current Electricity



New Zealand physics instructor David Housden constructs a parallel circuit by fastening lamps to extended terminals of a common battery. He asks his class to predict the relative brightnesses of two identical lamps in one wire about to be connected in parallel.

Electricity underlies 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. More than the physics we've studied thus far, an understanding of electricity requires a step-by-step approach, for one concept is the building block for the next. So please put in extra care in the study of this material. It can be difficult, confusing, and frustrating if you're hasty; but, with careful effort, it can be comprehensible and rewarding. We start with static electricity, electricity at rest, and complete the chapter with current electricity. Let's begin.

10.1 Electric Force and Charge

What if there were a universal force that, like gravity, varies inversely as the square of the distance but that is billions upon billions of times stronger? If there were such a force, and if it were an attractive force like gravity, the universe would be pulled together into a tight ball with all matter pulled as close together as physically possible. But suppose this force were a repelling force, with every bit of matter repelling every other bit of matter. What then? The universe would be an ever-expanding gaseous cloud. Suppose, however, that the universe consisted of two kinds of particles—say, positive and negative. Suppose positives repelled positives but attracted negatives, and that negatives repelled negatives but attracted positives. Like kinds repel and unlike kinds attract (Figure 10.1). Further, suppose there were equal numbers of each so that this strong force was perfectly balanced. What would the universe 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 *electrical force*.

The Physics Place
Electrostatics

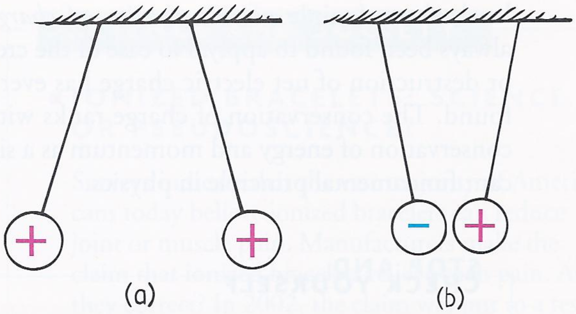


FIGURE 10.1
INTERACTIVE FIGURE

(a) Like charges repel. (b) Unlike charges attract.

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. The attractive force between these particles causes them to clump together into incredibly small units—atoms. (Atoms also contain neutral particles called *neutrons*.) We discussed atoms in Chapter 2. A review of some fundamental facts about atoms:

1. Every atom is composed of a positively charged nucleus surrounded by negatively charged electrons.
2. Each of the electrons in any atom has the same quantity of negative charge and the same mass. Electrons are identical to one another.
3. Protons and neutrons compose the nucleus. (The most common form of hydrogen atom, which has no neutrons, is the only exception.) Protons are about 1800 times more massive than electrons, but each one carries 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.

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

FIGURE 10.2
INTERACTIVE FIGURE

Model of a helium atom. The atomic nucleus is made up of two protons and two neutrons. The positively charged protons attract two negatively charged electrons. What is the net charge of this atom?

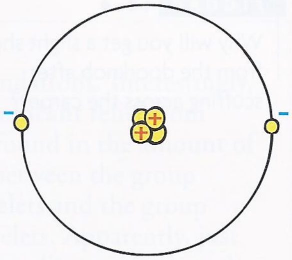


FIGURE 10.3

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

When an atom loses one or more electrons, it has a positive net charge, and when it gains one or more electrons, it has a negative net charge. A charged atom is called an *ion*. A *positive ion* has a net positive charge. A *negative ion*, with one or more extra electrons, has a net negative charge.

Material objects are made of atoms, which means they are composed of electrons and protons (and neutrons as well). Although the innermost electrons in an atom are attracted very strongly to the oppositely charged atomic nucleus, the outermost electrons of many atoms are attracted more loosely and can easily be dislodged. The amount of work required to pull an electron away from an atom varies for different substances. Plastic wrap becomes electrically charged as it is drawn from its container, which is why it is attracted to plastic containers. Electrons are held more firmly in rubber or plastic than in your hair, for example. Thus, when you rub a comb against your hair, electrons transfer from the hair to the comb. The comb then has an excess of electrons and is said to be *negatively charged*. Your hair, in turn, has a deficiency of electrons and is said to be positively charged. If you rub a glass or plastic rod with silk, you'll find that the rod becomes positively charged. The silk has a greater affinity for electrons than the glass or plastic rod. Electrons are rubbed off the rod and onto the silk.

FIGURE 10.4

Why will you get a slight shock from the doorknob after scuffing across the carpet?

So protons attract electrons and we have atoms. Electrons repel electrons and we have matter—because atoms don't mesh into one another. This pair of rules is the guts of electricity.

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

Conservation of Charge

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

Another basic rule 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.

STOP AND CHECK YOURSELF

If you walk across a rug and scuff electrons from your feet, are you negatively or positively charged?

CHECK YOUR ANSWER

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

10.2 Coulomb's Law

The electrical force, like gravitational force, decreases inversely as the square of the distance between charges. This relationship, which was discovered by Charles Coulomb in the eighteenth 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 them varies directly as the product of their charges and inversely as the square of the separation distance. The force acts along a straight line from one charge to the other. Coulomb's law can be expressed as

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

SCIENCE AND SOCIETY

ELECTRONICS TECHNOLOGY AND SPARKS

Electric charge can be dangerous. Two hundred years ago, young boys called powder monkeys ran barefoot 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 that landed 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.

SCIENCE AND SOCIETY

IONIZED BRACELETS: SCIENCE OR PSEUDOSCIENCE?

Surveys indicate that the vast majority of Americans today believe ionized bracelets can reduce joint or muscle pain. Manufacturers make the claim that ionized bracelets relieve such pain. Are they correct? In 2002, the claim was put to a test by researchers at Mayo Clinic in Jacksonville, Florida, who randomly assigned 305 participants to wear an ionized bracelet for 28 days and another 305 participants to wear a placebo bracelet for the same duration. The study volunteers were men and women 18 and older who had self-reported musculoskeletal pain at the beginning of the study.

Neither the researchers nor the participants knew which volunteers wore an ionized bracelet and which wore a placebo bracelet. Both types of bracelets were identical, were supplied by the manufacturer, and were worn according to the manufacturer's recommendations. Interestingly, both groups reported significant relief from pain. No difference was found in the amount of self-reported pain relief between the group wearing the ionized bracelets and the group wearing the placebo bracelets. Apparently, just believing that the bracelet relieves pain does the trick!

Interestingly, the brain initiates the creation of endorphins (which bind to opiate receptor sites) when the person expects to get relief from pain. The placebo effect is very real and measurable via blood titrations. So there's some merit in the old adage that wishing hard for something will make it come true. But this has nothing to do with the physics, chemistry, or biological interaction with the bracelet. Hence, ionized bracelets join the ranks of pseudoscientific devices.

In any society that thrives more on capturing attention than on informing, pseudoscience is big business.

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 second particle, and k is the proportionality constant.

There are about 10^{24} electrons in a penny, all repelling one another. Why don't these electrons fly off the coin?

The unit of charge is called 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 through a common 100-watt lightbulb in a little more than a second.

The proportionality constant k in Coulomb's law is similar to G in Newton's law of gravity. Instead of being a very small number, like G, k is a very large number, approximately

$$k = 9{,}000{,}000{,}000 \text{ N} \cdot \text{m}^2/\text{C}^2$$

In scientific notation, $k = 9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$. The unit $\text{N} \cdot \text{m}^2/\text{C}^2$ is not central to our interest here; it simply converts the right-hand side of the equation to the unit of force, the newton (N). What is important is the large magnitude of k. If, for example, a pair of like charges of 1 coulomb each were 1 meter apart, the force of repulsion between the two would be 9 billion newtons.[*] That would be about ten times the weight of a battleship! Obviously, such quantities of net charge do not usually exist in our everyday environment.

So Newton's law of gravitation for masses is similar to Coulomb's law for electrically charged bodies. 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.

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[*] 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, and differences in electrical forces between ordinary objects can be exceedingly huge. We don't sense them because the positives and negatives normally balance out, and, even for highly charged objects, the imbalance of electrons to protons is normally less than one part in a trillion trillion.

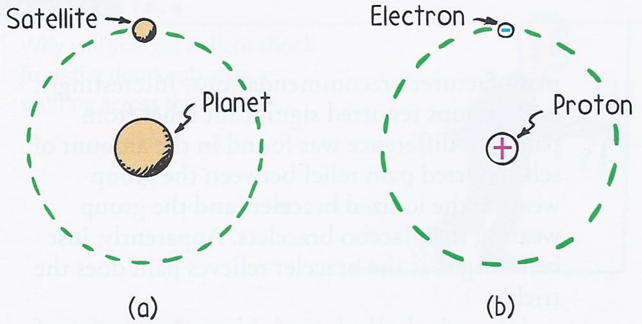

FIGURE 10.5

(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 electric charge exerts on another can be described as the interaction between one charge and the field set up by the other.

STOP AND CHECK YOURSELF

1. The proton is the nucleus of the hydrogen atom, and it attracts the electron that orbits it. Relative to this force, does the electron attract the proton with less force, more force, or 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 three times as distant from the particle? Five times as distant?
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. In accord with the inverse-square law, it decreases to 1/9 its original value. To 1/25 of its original value.
3. Positive.

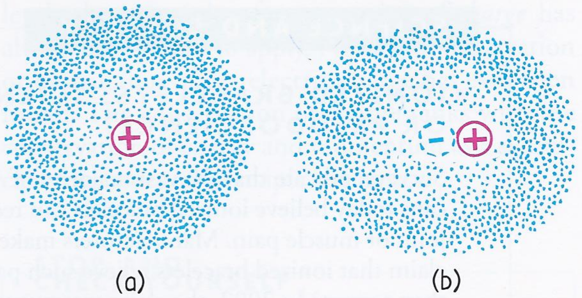

FIGURE 10.6

(a) The center of the negative "cloud" of electrons 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 electrically polarized.

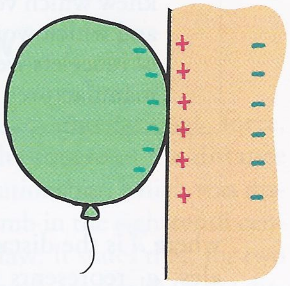

FIGURE 10.7

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

Charge Polarization

If you charge an inflated balloon by rubbing it on your hair and then place the balloon against a wall, it sticks. This is because the charge on the balloon alters the charge distribution in the atoms or molecules in the wall, effectively inducing an opposite charge on the wall. The molecules cannot move from their relatively stationary positions, but their "centers of charge" are moved. The positive part of the atom or molecule is attracted toward the balloon, whereas the negative part is repelled. This has the effect of distorting the atom or molecule (Figure 10.6). The atom or molecule is said to be electrically polarized.

STOP AND CHECK YOURSELF

You know that a balloon rubbed on your hair will stick to a wall. In a humorous vein, does it follow that your oppositely charged head would also stick to the wall?

CHECK YOUR ANSWER

No, unless you're an airhead (having a head mass about the same as that of an air-filled balloon). The force that holds a balloon to the wall cannot support your heavier head.

EVERYDAY APPLICATIONS

■ MICROWAVE OVEN

Imagine an enclosure filled with Ping-Pong balls among a few batons, all at rest. Now imagine that the batons suddenly rotate backward and forward, striking neighboring Ping-Pong balls. Almost immediately, most of the Ping-Pong balls are energized, vibrating in all directions. A microwave oven works similarly. The batons are water molecules made to rotate to and fro in rhythm with microwaves in the enclosure. The Ping-Pong balls are the other molecules that make up the bulk of material being cooked.

H_2O molecules are electrically polarized, with opposite charges on opposite sides. When an electric field is imposed on them, they align with the field like a compass needle aligns with a magnetic field. When the field is made to oscillate, the H_2O molecules oscillate also—and quite energetically when the frequency of the waves matches the natural rotational frequency of the H_2O. So food is cooked by converting H_2O molecules into flip-flopping energy sources that impart thermal motion to surrounding food molecules. Without polar molecules in the food, a microwave oven wouldn't work. That's why microwaves pass through foam, paper, or ceramic plates and reflect from metals with no effect. However, they do energize water molecules.

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.

10.3 Electric Field

Electrical forces, like gravitational forces, can act between things that are not in contact with each other. Both for electricity and gravity, a force field exists that influences distant charges and masses, respectively. The properties of space surrounding any mass are altered such that another mass introduced to this region experiences a force. This "alteration in space" is called its *gravitational field.* We can think of any other mass as interacting with the field and not directly with the mass that produces it. For example, when an apple falls from a tree, we say it is interacting with the mass of Earth, but we can also think of the apple as interacting with the gravitational field of Earth. It is common to think of distant rockets and the like as interacting with gravitational fields rather than bodies responsible for the fields. The field plays an intermediate role in the force between bodies. More important, the field stores energy. So similar to a gravitational field, the space around every electric charge is energized with an **electric field**—an energetic aura that extends through space.*

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

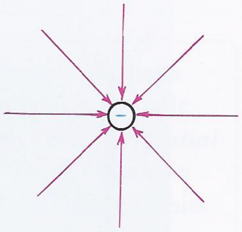

FIGURE 10.8
INTERACTIVE FIGURE

Electric field representations about a negative charge.

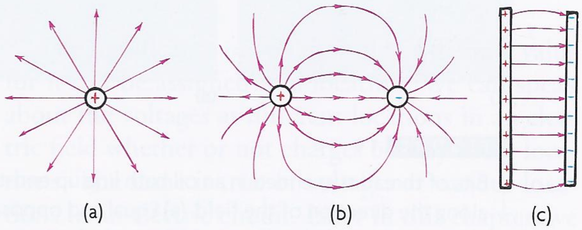

FIGURE 10.9
INTERACTIVE FIGURE

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

If you place a charged particle in an electric field, it will experience a force. The direction of the force on a positive charge is the same direction as the field. The electric field about a proton extends radially from the proton. About an electron, the field is in the opposite direction (Figure 10.8). As with

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* An electric field is a vector quantity, having both magnitude and direction. The magnitude of the field at any point is simply the force per unit of charge. If a charge q experiences a force F at some point in space, then the electric field E at that point is $E = F/q$.

electric force, the electric field about a particle obeys the inverse-square law. Some electric field configurations are shown in Figure 10.9, and photographs of field patterns are shown in Figure 10.10. In the next chapter, we'll see how bits of iron similarly align with magnetic fields.

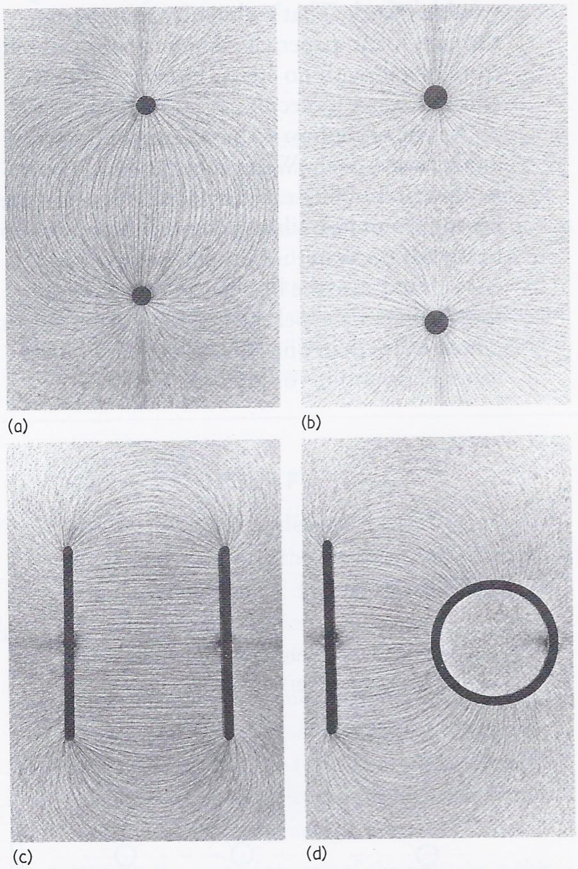

FIGURE 10.10

Bits of thread suspended in an oil bath line up end-to-end along the direction of the field. (a) Equal and opposite charges. (b) Equal like charges. (c) Oppositely charged plates. (d) Oppositely charged cylinder and plate.

Perhaps your instructor will demonstrate the effects of the electric field that surrounds the charged dome of a Van de Graaff generator (Figure 10.11). Charged objects in the field of the dome are either attracted or repelled, depending on their sign of charge.

Static charge on the surface of any electrically conducting surface will arrange itself such that the electric field inside the conductor will cancel to zero. Note the randomness of threads inside the cylinder of Figure 10.10d, where no field exists.

FIGURE 10.11

Both Lori and the spherical dome of the Van de Graaff generator are electrically charged.

fyi **Whatever the intensity of the electric field about a charged Van de Graaff generator, the electric field inside the dome cancels to zero. This is true for the interiors of all metals that carry static charge.**

STOP AND CHECK YOURSELF

Both Lori and the dome of the Van de Graaff generator in Figure 10.11 are charged. Why does Lori's hair stand out?

CHECK YOUR ANSWER

She and her hair are charged. Each hair is repelled by others around it—evidence that *like charges repel*. Even a small charge produces an electrical force greater than the weight of strands of hair. Fortunately, the electrical force is not great enough to make her arms stand out!

10.4 Electric Potential

In our study of energy in Chapter 4, 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

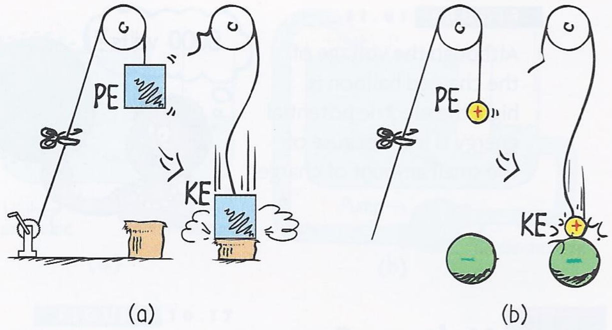

FIGURE 10.12

(a) The PE (gravitational potential energy) of a mass held in a gravitational field. (b) The PE of a charged particle held in an electric field. When the mass and particle are released, how does the KE (kinetic energy) acquired by each compare with the decrease in PE?

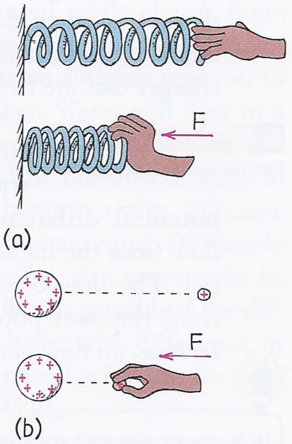

FIGURE 10.13

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

charged particle.* Similarly, work done in compressing a spring increases the potential energy of the spring (Figure 10.13a). Likewise, the work done in pushing a charged particle closer to the charged sphere in Figure 10.13b increases the potential energy of the charged particle. We call the energy possessed by the charged particle that is due to 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.

The Physics Place
Electric Potential

If we push a particle with twice the charge, we do twice as much work. Twice the charge in the same location has twice the electric potential energy; with three times the charge, there is three times as much potential energy; and so on. When working with electricity, rather than dealing with the total potential energy of a charged body, it is convenient to consider the electric potential energy *per charge*. We simply divide the amount of energy in any case by the amount of charge. The concept of potential energy per charge is called electric potential; that is,

$$\text{electric potential} = \frac{\text{electric potential energy}}{\text{amount of charge}}$$

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.

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

Thus, a 1.5-volt battery gives 1.5 joules of energy to every 1 coulomb of charge flowing through the battery. *Electric potential* and *voltage* are the same thing, and they are commonly used interchangeably.

In a nutshell: *electric potential* and *potential* mean the same thing—electrical potential energy per unit charge—in units of volts. On the other hand, *potential difference* is the same as *voltage*—the *difference* in electrical potential between two points—also in units of volts.

The significance of voltage is that a definite value for it can be assigned to a location. We can speak about the voltages at different locations in an electric field whether or not charges occupy those locations. The same is true of voltages at various locations in an electric circuit. Later in this chapter, we will see that the location of the positive terminal of a 12-volt battery is maintained at a voltage 12 volts higher than the location of the negative terminal. When a conducting medium connects this voltage difference, any charges in the medium will move between these locations.

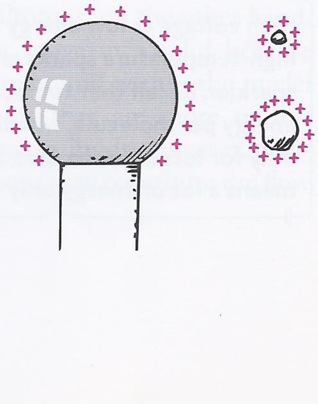

FIGURE 10.14

The larger test charge has more PE in the field of the charged dome, but the electric potential of any amount of charge at the same location is the same.

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

STOP AND CHECK YOURSELF

1. If there were twice as many coulombs in the test charge near the charged sphere in Figure 10.14, would the *electric potential energy* of the test charge relative to the charged sphere be the same, or would it be twice as great? Would the *electric potential* of the test charge be the same, or would it be twice as great?
2. What does it mean to say that the battery in your car is rated at 12 volts?

CHECK YOUR ANSWERS

1. The result of twice as many coulombs is twice as much *electric potential energy* because it takes twice as much work to put the charge there. But the *electric potential* would be the same. Twice the energy divided by twice the charge gives the same potential as one unit of energy divided by one unit of charge. Electric potential is not the same thing as electric potential energy. Be sure you understand this before you study further.
2. It means that one of the battery terminals is 12 V higher in potential than the other one. We'll soon learn that when a circuit is connected between these terminals, each coulomb of charge in the resulting current will be given 12 J of energy as it passes through the battery (and 12 J of energy "spent" in the circuit).

Rub a balloon on your hair, and 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 fairly respectable amount of charge. The charge on a balloon rubbed on hair is 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. Electrical potential energy differs from electric potential (or voltage).

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

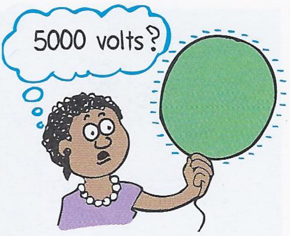

FIGURE 10.15
Although the voltage of the charged balloon is high, the electric potential energy is low because of the small amount of charge.

10.5 Voltage Sources

When the ends of a heat conductor 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. Any material having free charged particles that easily flow through it when an electric force acts on them is called an electric **conductor.** Both heat and electric conductors are characterized by electric charges that are free to move. Similar to heat flow, when the ends of an electrical conductor are at different electric potentials—when there is a **potential difference**—charges in the conductor flow from the higher potential to the lower potential. The flow of charge persists until both ends reach the same potential. Without a potential difference, no flow of charge will occur.

The Physics Place
Van de Graff Generator

A battery doesn't supply electrons to a circuit; it instead supplies energy to electrons that already exist in the circuit.

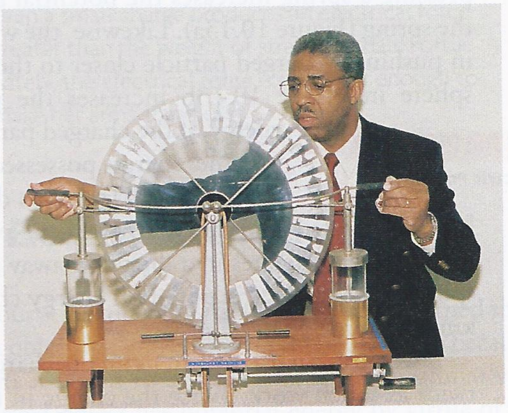

FIGURE 10.16
Although the Wimshurst machine can generate thousands of volts, it puts out no more energy than the work that Jim Stith puts into it by cranking the handle.