CHAPTER 10

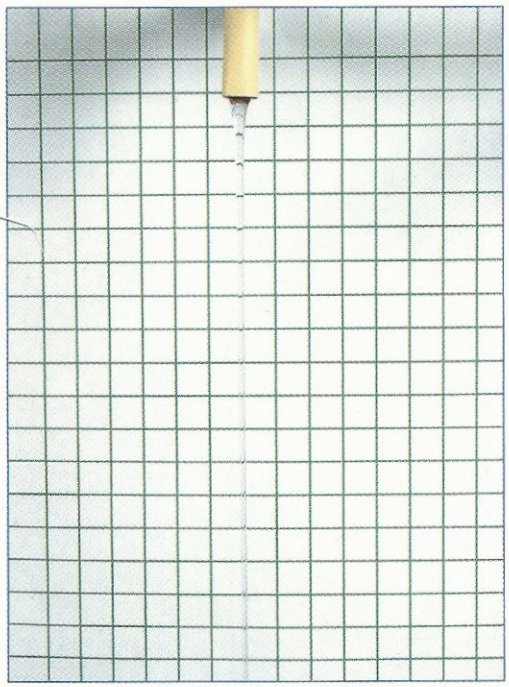
Electricity

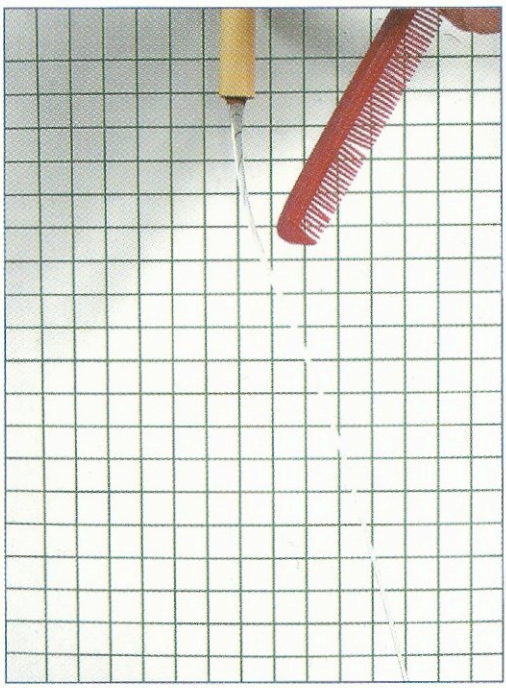
While it's hard to see the electric charges that are responsible for electricity, it's easy to see their effects. They're all around us: in the sparks and shocks of a cold winter day, the imaging process of a xerographic copier, and the illumination of a flashlight when you turn on its switch. Although we often take electricity for granted, it clearly underlies many aspects of our modern world.

Just imagine what life would be like if there were no electric charges and no electricity. For starters, we'd probably be sitting around campfires at night, trying to think of things to do without television, cell phones, or computer games. But before you remark on just how peaceful such a pre-electronic-age existence would be, let me add one more sobering thought: we wouldn't exist either. Whether it's motionless as static charge or moving as electric current, electricity really does make the world go 'round.

EXPERIMENT: Moving Water without Touching It

Unlike gravity, which always pulls objects toward one another, electric forces can be either attractive or repulsive. You can experiment with electric forces using a thin stream





Courtesy Lou Bloomfield

of water and an electrically charged comb. First, open a water faucet slightly so that the flow of water forms a thin but continuous strand below the mouth of the faucet. Next, give your rubber or plastic comb an electric charge by passing it rapidly through your hair or rubbing it vigorously against a wool sweater. Finally, hold the comb near the stream of water, just below the faucet, and watch what happens to the stream. Is the electric force that you're observing attractive or repulsive? Why does this force change the path of the falling water?

Rubbing the comb through your hair makes it electrically charged. What other objects can acquire and hold a charge when you rub them across hair or fabric? Which works better: a metal object or one that's an insulator? Why?

Chapter Itinerary

Although we often experience electric forces and currents as novelties or nuisances, there are also many devices that depend on them. In this chapter, we'll examine the mysteries of (1) *static electricity* and study two modern devices that are based on electricity: (2) *xerographic copiers* and (3) *flashlights*. In *static electricity*, we'll look at how clothes and other objects acquire charges and how they exert forces on one another as a result. In *xerographic copiers*, we'll see how these same electric forces work together with light to control the placement of black powder in order to reproduce images on sheets of paper. In *flashlights*, we'll look at how a current of electric charges conveys power from batteries to a lightbulb. For a more complete preview of the chapter, turn ahead to the Chapter Summary at the end of the chapter.

Although this chapter concentrates on electricity and its charges, we will see in Chapter 11 that magnetism and its poles are closely related. While we'll leave the relationships between electricity and magnetism for that chapter, you may already begin seeing similarities between those two seemingly separate phenomena as you read Chapter 10.

SECTION 10.1 Static Electricity

Electricity may be difficult to see, but you can easily observe its effects. How often have you found socks clinging to a shirt as you remove them from a hot dryer or struggled to throw away a piece of plastic packaging that just won't leave your hand or stay in the trash can? The forces behind these familiar effects are electric in nature and stem from what we commonly call "static electricity." Static electricity does more than just push things around, however, as you've probably noticed while reaching for a doorknob or a friend's hand on a cold, dry day. In this section, we'll examine static electricity and the physics behind its intriguing forces and often painful shocks.

Questions to Think About: *How does a dryer produce static electricity, and why do some clothes cling while others repel? Why does walking across a carpet on a cold, dry day put you at great risk of a shock as you reach for a doorknob? Why do you get only a single, brief shock from that knob and not a long, sustained one? When touching a friend results in a shock, did one of you cause that shock or are you both responsible? If rubbing is required to develop static electricity, why does the plastic wrap produce so much of it when you open a new CD? Why do moist air and antistatic chemicals reduce static electricity?*

Experiments to Do: *You can study static electricity by rubbing a toy balloon vigorously through your hair or against a wool sweater. Though its appearance won't change, the*

balloon will begin to attract other things, particularly your hair. What has happened to the balloon? To your hair? Why does the balloon also attract things that weren't rubbed?

Try to get rid of the balloon's attractiveness by letting a thick stream of water flow over its surface. Why does this process return the balloon to normal? What did you "wash" off the balloon? Now rub two identical balloons through your hair and see whether they attract or repel one another. Does the result make sense?

Finally, draw two long strips of transparent tape from a dispenser without rubbing them on anything and see if they attract or repel. Is rubbing essential to the development of static electricity?

Although best remembered for his political activities, American statesman and philosopher Benjamin Franklin (1706–1790) was also the preeminent scientist in the American colonies during the mid-1700s. His experiments, both at home and in Europe, contributed significantly to the understanding of electricity and electric charge. In addition to demonstrating that lightning is a form of electric discharge, Franklin invented a number of useful devices, including the Franklin stove, lightning rods, and bifocals.

Electric Charge and Freshly Laundered Clothes

Unless you have always lived in a damp climate and avoided synthetic materials, you have experienced the effects of static electricity. Seemingly ordinary objects have pushed or pulled on one another mysteriously, and you've received shocks while reaching for light switches, car doors, or friends' hands. Static electricity is more than an interesting nuisance, though; it's a simple window into the inner workings of our universe and worthy of a serious look. It will take some time to lay the groundwork, but soon you'll be able to explain most of the effects of static electricity and even to control it to some extent.

The existence of static electricity has been known for several thousand years. About 600 B.C., the Greek philosopher Thales of Miletus (ca 624–546 B.C.) observed that when amber is rubbed vigorously with fur, it attracts light objects such as straw and feathers. Known in Greek as *elektron*, amber is a fossil tree resin with properties similar to those of modern plastics. The term "static electricity," like many others in this chapter, derives from that Greek root.

Static electricity begins with **electric charge**, an intrinsic property of matter. Electric charge is present in many of the **subatomic particles** from which matter is constructed, and these particles incorporate their charges into nearly everything. No one knows why charge exists; it's simply one of the basic features of our universe and something that people discovered through observation and experiment. Because electric charge has so much influence on objects that contain it, we'll sometimes refer to those objects as **electric charges** or simply as **charges**.

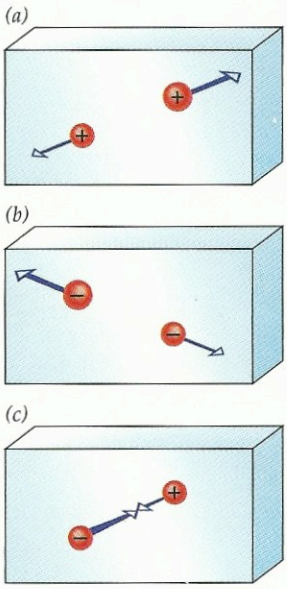


Fig. 10.1.1 (*a*) Two positive charges experience equal but oppositely directed forces exactly away from one another. (*b*) The same effect occurs for two negative charges. (*c*) Two opposite charges experience equal but oppositely directed forces exactly toward one another.

Charges exert forces on one another, and it is these forces that you observe with static electricity. Next time you're doing laundry, experiment with your clothes as they come out of the dryer. You'll find that some electrically charged garments attract one another while others repel. Evidently, there are two different types of charge. But although this dichotomy has been known since 1733, when it was discovered by French chemist Charles-François de Cisternay du Fay [1698–1739], it was Benjamin Franklin who finally gave the two charges their present names. Franklin called what appears on glass when it's rubbed with silk "positive charge" and what appears on hard rubber when it's rubbed with animal fur "negative charge."

Two like charges (both positive or both negative) push apart, each experiencing a repulsive force that pushes it directly away from the other (Figs. 10.1.1*a* and *b*). Two opposite charges (one positive and one negative) pull together, each experiencing an attractive force that pulls it directly toward the other (Fig. 10.1.1*c*). These forces between stationary electric charges are called **electrostatic forces**.

When you find that two freshly laundered socks push apart, it's because they both have the same type of charge. Whether that charge is positive or negative depends on

the fabrics involved (more on that later), so let's just suppose that the dryer has given each sock a negative charge. Since like charges repel, the socks push apart. What does it mean for the dryer to give each sock a negative charge?

The answer to that question has several parts. First, the dryer didn't create the negative charge that it gave to a sock. Like momentum, angular momentum, and energy, electric charge is a conserved physical quantity—it cannot be created or destroyed, only transferred. The negative charge that the dryer gave to the sock must have come from something else, perhaps a shirt.

Second, positive charge and negative charge aren't actually separate entities—they're just positive and negative amounts of the same physical quantity: electric charge. Positive charges have positive amounts of electric charge, while negative charges have negative amounts. Like most physical quantities, we measure charge in standard units. The SI unit of electric charge is the **coulomb** (abbreviated C). Small objects rarely have a whole coulomb of charge, and your sock's charge is only about -0.0000001 C.

Third, the sock's negative charge refers to the sock as a whole, not to its internal pieces. As with all ordinary matter, the sock contains an enormous number of positively and negatively charged particles. Each of the sock's atoms consists of a dense central core or **nucleus**, containing positively charged **protons** and uncharged **neutrons**, surrounded by a diffuse cloud of negatively charged **electrons**. The electrostatic forces between those tiny charged particles hold together not only the atoms, but also the entire sock. However, in giving the sock a negative charge, the dryer saw to it that the sock's **net electric charge**—the sum of all its positive and negative amounts of charge—is negative. With its negative net charge, the sock behaves much like a simple, negatively charged object.

Finally, the sock became negatively charged when it contained more electrons than protons. Underlying that seemingly simple statement is a great deal of painstaking scientific study. To begin with, experiments have shown that electric charge is **quantized**: charge always appears in integer multiples of the **elementary unit of electric charge**. This elementary unit of charge is extremely small, only about 1.6×10^{-19} C, and is the magnitude of the charge found on most subatomic particles. An electron has -1 elementary unit of charge, while a proton has $+1$ elementary unit of charge. Since the only charged subatomic particles in normal matter are electrons and protons, the sock becomes negatively charged simply by having more electrons than protons.

Returning to the original question, we now know what the dryer did in order to give a sock a negative charge. Assuming the sock was electrically **neutral** to start—it had zero net charge—the dryer must have added electrons to the sock or removed protons from the sock or both. These transfers of charge upset the sock's charge balance and gave it a negative net charge.

In keeping with our convention regarding conserved quantities, all unsigned references to charge in this book imply a positive amount. For example, if the dryer gave charge to a jacket, we mean it gave a positive amount of charge to that jacket. We follow this same convention with money: when you say that you gave money to a charity, we assume that you gave a positive amount.

Finally, Franklin's charge-naming scheme was brilliant in concept but unlucky in execution. Although it reduced the calculation of net charge to a simple addition problem, it required Franklin to choose which type of charge to call "positive" and which to call "negative." Unfortunately, his seemingly arbitrary choice made electrons, the primary constituents of electric current in wires, negatively charged. By the time physicists had recognized the mistake, it was too late to fix. Scientists and engineers have had to deal with negative amounts of charge flowing through wires ever since. Imagine the

■ In 1781, after a career as a military engineer in the West Indies, French physicist Charles-Augustin de Coulomb (1736–1806) returned to his native Paris in poor health. There he conducted scientific investigations into the nature of forces between electric charges and published a series of memoirs on the subject between 1785 and 1789. His research came to a close in 1789 when he was forced to leave Paris because of the French Revolution.

awkwardness of having to carry out business using currency printed only in negative denominations!

Check Your Understanding #1: In Charge of Opening Gifts

The gift you are about to unwrap is electrically neutral. You tear off the clingy wrapper and find that it has a large negative charge. What charge does the gift itself have, if any?

Answer: It has a large positive charge equal in amount to the wrapper's negative charge.

Why: Since charge is a conserved physical quantity, the wrapper and gift must remain neutral overall even after you separate them. The wrapper's negative charge must be balanced by the gift's positive charge.

Coulomb's Law and Static Cling

Although your sock and shirt pull together strongly when they're only inches apart, you can put on your shirt and go to the movies without fear of being attacked by your sock from the other side of town. Evidently, the forces between charges weaken with distance.

Over two centuries ago, French physicist Charles-Augustin de Coulomb ■ studied electrostatic forces experimentally and determined that the forces between two electric charges are inversely proportional to the square of their separation (Fig. 10.1.2). For example, doubling the separation between your shirt and sock reduces their attraction by a factor of four, which explains your uneventful night out on the town.

Coulomb's experiments also showed that the forces between electric charges are proportional to the amount of each charge. That means that doubling the charge on either your shirt or your sock doubles the force each garment exerts on the other. Finally, changing the sign of either charge turns attractive forces into repulsive ones or vice versa. If both garments were either positively charged or negatively charged, they'd repel instead of attracting.

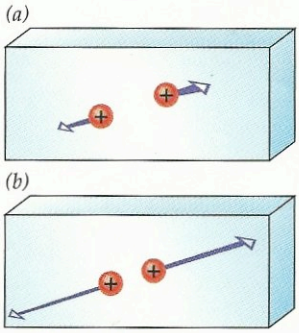


Fig. 10.1.2 The electrostatic forces between two charges increase dramatically as they become closer. As the distance separating two positive charges decreases by a factor of 2 between (*a*) and (*b*), the forces those two charges experience increase by a factor of 4.

These ideas can be combined to describe the forces acting on two charges and written as a word equation:

$$\text{force} = \frac{\text{Coulomb constant} \cdot \text{charge}_1 \cdot \text{charge}_2}{(\text{distance between charges})^2}, \qquad (10.1.1)$$

in symbols:

$$F = \frac{k \cdot q_1 \cdot q_2}{r^2},$$

and in everyday language:

When there are enough like charges packed close together on your hair, it'll stand up.

The force on charge_1 is directed toward or away from charge_2, and the force on charge_2 is directed toward or away from charge_1.

This relationship is called **Coulomb's law**, after its discoverer. The **Coulomb constant** is about $8.988 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$ and is one of the physical constants found in

nature. Consistent with Newton's third law, the force that charge_1 exerts on charge_2 is equal in amount but oppositely directed from the force that charge_2 exerts on charge_1.

Coulomb's Law

The magnitudes of the electrostatic forces between two objects are equal to the Coulomb constant times the product of their two electric charges divided by the square of the distance separating them. If the charges are like, then the forces are repulsive. If the charges are opposite, then the forces are attractive.

In addition to protecting you from distant charged socks, this relationship between electrostatic forces and distance gives rise to another intriguing feature of laundry static: charged clothes can cling to objects that are electrically neutral! For example, a negatively charged sock can stick to a neutral wall.

The origin of this attraction is a subtle rearrangement of charges within the wall. Even though the wall has zero net charge, it still contains both positively and negatively charged particles. When the negatively charged sock is near the wall, it pulls the wall's positive charges a little closer and pushes the wall's negative charges a little farther away (Fig. 10.1.3). Although each individual charge shifts just a tiny distance, the wall contains so many charges that together they produce a dramatic result. The wall develops an **electric polarization**—it remains neutral overall, but has a positively charged region nearest the sock and a negatively charged one farthest from the sock.

The wall's positive region attracts the sock while its negative region repels the sock. Though you might expect those two opposing forces to balance, Coulomb's law says otherwise. Since electrostatic forces grow weaker with distance, the sock is attracted more strongly to the nearer positive region than it is repelled by the more distant negative region. Overall, there is a net electrostatic attraction between the charged sock and the polarized wall, so the sock clings to the wall!

Check Your Understanding #2: Wrapper Recycling

After opening your gift, you try to throw away its negatively charged wrapper. However, the wrapper keeps returning to your hand. What attracts it to your electrically neutral hand?

Answer: Its negative charge polarizes your hand and is then attracted to your hand's nearby positive charge.

Why: Although your hand is neutral, its charges rearrange in response to the nearby wrapper's negative charge. Positive charge in your hand shifts toward the wrapper and attracts it.

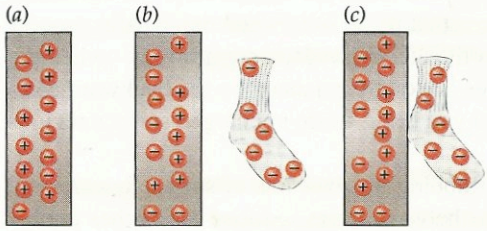


Fig. 10.1.3 (*a*) A neutral wall contains countless positive and negative charges. (*b*) As a negatively charged sock approaches the wall, the positive charges move toward it and the negative charges move away. (*c*) The polarized wall continues to attract the sock and holds it in place.

Check Your Figures #1: Moving Out

You have two positively charged balls, each of which is experiencing a force of 1 N away from the other. If you halve the distance separating the balls, what force will each exert on the other?

Answer: 4 N.

Why: According to Coulomb's law, the force on each charge varies inversely with the square of their separation. By halving that separation, you increase the electrostatic force by a factor of 4.

Transferring Charge: Sliding Friction or Contact?

While it's clear that the dryer transfers charge between the clothes, why does that charge move and what determines which garments gain charge and which lose it?

You might suppose that sliding friction is responsible for the transfer—that the dryer rubs the clothes together and somehow wipes charge from one garment to the other. After all, friction seems to help you charge a balloon as you rub it through your hair or against a wool sweater. However, be careful—there are other cases of charge transfer that don't involve rubbing at all. For example, the plastic wrap you remove from a store package can acquire a charge no matter how careful you are not to rub it against its contents. And an antique car can build up enough charge to give you a nasty shock even when its pale rubber tires never skid across the pavement.

Charge transfer is less the result of rubbing than it is of contact between dissimilar surfaces. When two different materials touch one another, a few electrons normally shift from one surface to the other. That transfer results from the chemical differences between the two touching surfaces and the associated change in an electron's potential energy when it shifts. In effect, some surfaces are "hungrier" for electrons than others, and whenever two dissimilar surfaces touch, the hungrier surface steals a few electrons from its less hungry partner.

The physics behind this theft has to do with chemical potential energy—energy stored in the chemical forces that bind together a material's constituent atoms and electrons. To hold onto its electrons, a surface reduces their chemical energies to less than zero, meaning that it would take additional energy to free those electrons from the surface. However, some surfaces reduce the electron chemical potential energies more than others and thus bind their electrons more tightly. If an electron on one surface can reduce its chemical potential energy by shifting to the other surface, it will accelerate toward that "hungrier" surface and eventually stick there. You can picture the electron as "rolling downhill" from a chemical "valley" on one surface to an even deeper valley on the other surface.

This transfer of electrons is self-limiting. As electrons accumulate on the lower energy surface, they begin to repel any electrons that try to follow and the transfer process soon grinds to a halt. It stops altogether when the electrons reach equilibrium—when the forward chemical force an electron experiences is exactly balanced by the backward electrostatic force. The transfer won't resume until you bring fresh, uncharged surface regions into contact.

That's where rubbing enters the picture. Rubbing involves lots of surface contact and almost endless opportunities for charge transfer between those surfaces. As clothes tumble

about in the dryer, touching one another and often rubbing, some fabrics steal electrons and become negatively charged while other fabrics lose electrons and become positively charged.

That said, you should be aware that the details of contact charging are messy. For starters, the surfaces that actually touch one another are neither chemically pure nor free of microscopic defects. Although it's generally true that whichever fabric binds electrons most tightly is the one most likely to develop a negative net charge, surface contamination and defects can change the outcome radically. Even your choice of laundry detergent may affect the fabric's surface chemistry and thus how it charges. Furthermore, water molecules cling to most surfaces and influence the contact charging process. Finally, while we've concentrated on the exchange of electrons, it's also possible for certain surfaces to exchange **ions**—that is, electrically charged atoms, molecules, or small particles—along with electrons and acquire net charges as a result.

Check Your Understanding #3: Sticky Tape

When you peel a piece of adhesive tape off a glass window, you find that the tape is attracted toward the spot it left behind. How did the tape and glass acquire electric charges?

Answer: While the tape and glass were in contact, charge was unevenly distributed between their surfaces. Removing the tape merely made that imbalance more obvious.

Why: The tape and glass have different chemical affinities for electrons and become oppositely charged whenever they touch. In fact, the tape's stickiness itself comes from electrostatic attraction.

Separating Your Clothes: Producing High Voltages

The dryer stops and you take out your favorite shirt. It has several socks clinging to it, so you begin to remove them. As you separate the garments, they crackle and spark. Their attraction is obviously due to opposite charges, but why does separating them make them spark?

To answer that question, let's think about energy as you pull the negatively charged sock steadily away from the positively charged shirt. Since the sock would accelerate toward the shirt if you let go, you are clearly exerting a force on the sock. And because that force and the sock's movement are in the same direction, you are also doing work on the sock. You are transferring energy to it.

That energy is stored in the electrostatic forces—the shirt and sock accumulate **electrostatic potential energy**. Electrostatic potential energy is present whenever opposite charges have been pulled apart or like charges have been pushed together. With the negatively charged sock now far from the positively charged shirt, both attraction and repulsion contribute to the electrostatic potential energy: opposite charges are separated on the two garments and like charges are assembled together on each garment.

The total electrostatic potential energy in the shirt and sock is the work you did to separate them. However, that potential energy isn't divided equally among the individual charges on these garments. Depending on their locations, some charges have more electrostatic potential energy than others and are therefore more important when it comes to sparks. In recognition of those differences, we need a proper way to characterize the electrostatic potential energy available to a charge at a particular location. The measure

we're seeking is **voltage**—the electrostatic potential energy available per unit of electric charge at a given location, or

$$\text{voltage} = \frac{\text{electrostatic potential energy}}{\text{charge}}.$$

Voltage is a difficult quantity to conceptualize because you can't see charge or sense its stored energy. To help you understand voltage, we'll use a simple analogy. In this analogy, the role of charge will be played by water and the role of voltage will be played by altitude. Where voltage is high, visualize water far above you. Where voltage is low, picture water at a lesser height. Just as water tends to flow from higher altitude to lower altitude, so charge tends to flow from higher voltage to lower voltage.

This analogy works well because both voltage and altitude measure the energy in a unit of something. Voltage is the electrostatic potential energy per unit of charge, and altitude can be construed as the gravitational potential energy per unit of weight. Though thinking of altitude this way may seem strange, both water at high altitude and charge at high voltage are loaded with energy per unit and likely to cause trouble!

Since the SI unit of energy is the joule and the SI unit of electric charge is the coulomb, the SI unit of voltage is the joule-per-coulomb, more commonly called the **volt** (abbreviated V). Where the voltage is positive, (positive) charge can release electrostatic potential energy by escaping to a distant neutral place. Charge at positive voltage is analogous to water on a hill, which can release gravitational potential energy by flowing down to a distant level place. Where the voltage is negative, charge needs energy to escape to a distant neutral place. Charge at negative voltage is analogous to water in a valley, which needs energy in order to flow up to a distant level place.

As you can see, this voltage–altitude analogy is quite a boon. But while you should find it helpful now and throughout this book, please remember that the ups and downs in altitude that you're using to visualize voltage occur only in your mind's eye and not in the real world. Your clothes don't necessarily move up or down as their voltages change!

Returning to those clothes, you'll find that each point on the shirt or sock has its own voltage. You can determine that voltage by taking a tiny amount of (positive) charge at that point—a "test charge"—and moving it to a distant neutral place. The point's voltage is simply the electrostatic potential energy the test charge releases during that trip divided by the amount of its charge. If the point you examine is on the positively charged shirt, you'll obtain a large positive voltage—probably several thousand volts. If it's on the negatively charged sock, you'll obtain a negative voltage of similar magnitude. Whether positive or negative, these high voltages tend to cause sparks.

We'll look at the physics of sparks and discharges soon, but you can already see why oppositely charged clothes spark as you separate them: that's when the high voltages develop. As long as your sock is clinging tightly to your shirt, there isn't much electrostatic potential energy available. But as soon as you begin to separate them, watch out!

Check Your Understanding #4: High Altitude Voltage

Although any cloud may contain opposite charges, only the violent updrafts inside thunderheads are able to separate those charges and produce lightning. Why does such separation lead to lightning?

Answer: That separation takes work, which appears as electrostatic potential energy in the separated charges. The positively charged regions of the thunderhead acquire huge positive voltages, and the negatively charged regions acquire huge negative voltages.

Why: When opposite charges are nearby, they don't necessarily have much electrostatic potential energy per charge and the voltages may be small. Separating those charges to great distances dramatically increases their stored energy and produces high voltages.

Accumulating Huge Static Charges

We've seen that touching two different materials together causes a small transfer of charge from one surface to the other and that separating those oppositely charged surfaces produces elevated voltages and perhaps sparks. However, the quiet crackling and snapping of items in your laundry basket is nothing compared to the miniature lightning bolts you can unleash after walking across a carpet on a dry winter day, stepping out of an antique car, or playing with a static generator. To get a really big spark, you need to separate lots of charge, and that usually requires repeated effort.

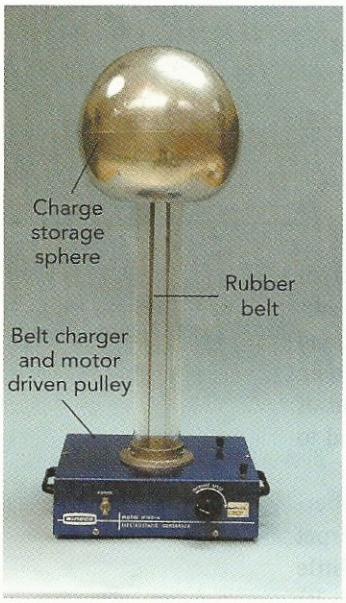
Walking across a carpet is just such a repetitive process. Each time your rubber-soled shoe lands on an acrylic carpet, some (positive) charge shifts from the carpet to your shoe. Although the transfer is brief and self-limiting, you now have a little extra charge on your shoe. When you lift that shoe off the carpet, you do work on its newfound charge, and your shoe's voltage surges to a high positive value. High voltage charge tends to leak from one place to another, and the shoe's charge quickly spreads to the rest of your body. By the time your foot lands again on a fresh patch of carpet, the shoe has given away most of its charge and is ready to begin the process all over again.

Each time your foot lands on the carpet, it picks up some charge. Each time it lifts off the carpet, that charge spreads out on your body. By the time you finally reach for the doorknob, you are covered with charge and have an enormous positive voltage. As your hand draws close to the doorknob, it begins to influence the doorknob's charges—pulling the doorknob's negative charges closer and pushing its positive charges away. You are polarizing the doorknob.

As we saw while separating your freshly laundered sock from your shirt, oppositely charged objects that are close but not touching can have both large electrostatic potential energies and strong electrostatic forces. That's the situation here. The closer your hand gets to the doorknob, the stronger the electrostatic forces become until finally the air itself cannot tolerate the forces and a spark forms. In an instant, most of your accumulated electrostatic potential energy is released as light, heat, and sound. And that doesn't include any screams.

As good as walking is at building up charge, though, an antique car is even better. Its pale rubber tires gather negative charge when they touch the pavement and develop large negative voltages as they roll away from it. This charge migrates onto the car body so that after a few seconds of driving, the car accumulates enough charge to give anyone who touches it a painful shock. Collecting tolls used to be hazardous work! Fortunately, modern tires are formulated to allow this negative charge to return safely to the pavement, so that cars rarely accumulate much charge. Instead, most shocks associated with cars now come from sliding across the seat as you step in or out.

While cars try to avoid static charging, there are machines that deliberately accumulate separated charge to produce extraordinarily high voltages. The most famous of these static machines is the Van de Graaff generator (Fig. 10.1.4). It uses a rubber belt to lift positive or negative charges onto a metal sphere until the magnitude of that sphere's voltage reaches hundreds of thousands or even millions of volts.



Courtesy Lou Bloomfield

Fig. 10.1.4 Static electricity can be produced by mechanical processes. In this Van de Graaff generator, a moving rubber belt transfers negative charges from the base to the shiny metal sphere. This negative charge creates dramatic sparks as it returns through the air toward the positive charge it left behind.

A typical classroom Van de Graaff generator uses a motor-driven rubber belt to carry negative charges from its base to its spherical metal top. Once inside the sphere, the belt's negative charges flow outward onto the sphere's surface, where they can be as far apart as possible. There they remain until something releases them.

Suspended at the top of a tall, insulating column, the Van de Graaff generator's sphere can accumulate an enormous negative charge. You may hear the motor struggling as it pushes the belt's negative charges up to the sphere, a reflection of how much negative voltage the sphere is developing. Eventually it releases its negative charge via an immense spark.

Even without sparks, the Van de Graaff generator is an interesting novelty. If you isolate yourself from the ground and touch the metal sphere while it's accumulating negative charges, some of those negative charges will spread onto you as well. If your hair is long and flexible, and permits the negative charges to distribute themselves along its length, it may stand up, lifted by the fierce repulsions between those like charges.

Check Your Understanding #5: Stop the Presses!

The paper in some printing presses moves through the rollers at half a kilometer per minute. If no care is taken, dangerous amounts of static charge can accumulate on parts of the press. How does the moving paper contribute to that charging process?

Answer: Contact between dissimilar materials puts charge on the paper, which then carries that charge with it to isolated parts of the press. Enough charge can accumulate on those parts to be dangerous.

Why: Nonconductive paper is an excellent transporter of electric charge. Once the paper picks up a static charge by touching a dissimilar material, it can carry that charge with it as it moves through the press. Not surprisingly, printing presses use various tools to suppress this static charging.

Controlling Static Electricity: Fabric Softeners and Conditioners

Now that we've seen what static electricity is and how to produce it, we're ready to see how to tame it. Static cling, flyaway hair, and electrifying handshakes aren't everyone's cup of tea. The basic solution to static charge is mobility: if charges can move freely, they'll eliminate static electricity all by themselves. Opposite charges attract, so any separated positive and negative charges will join up as soon as they're allowed to move.

Materials such as metals that permit free charge movement are called **electrical conductors**. Those such as plastic, hair, and rubber that prevent free charge movement are called **electrical insulators**. Since charge movement eliminates static electricity, our troubles with static electricity stem mostly from insulators. If you wore metal clothing, you wouldn't have static problems with your laundry.

The simplest way to reduce static electricity is to turn the insulators into conductors. Even slight conductors, ones that just barely let charges move, will gradually get

rid of any accumulations of separated charge. That's one of the main goals of fabric softeners, dryer sheets, and hair conditioners. They all turn insulating materials—fabrics and hair—into slight electrical conductors. The result is the near disappearance of static electricity and all its fashion inconveniences.

How these three items work is an interesting tale. They all employ roughly the same chemical: a positively charged detergent molecule. A detergent molecule is a long molecule that is electrically charged at one end and electrically neutral at the other end. Its charged end clings electrostatically to opposite charges and is chemically "at home" in water. Its neutral end is oil-like, slippery, and "at home" in oils and greases. This dual citizenship is what makes detergents so good for cleaning.

While it might seem that positively and negatively charged detergent molecules would clean equally well, however, that's not the case. Since cleaning agents shouldn't cling to the materials they're cleaning, it's important that the two not have opposite charges. Fabrics and hair generally become negatively charged when wet—another example of a charge shift when two different materials touch—so negatively charged detergent molecules clean much better than positively charged ones.

Positively charged detergents are still useful, however, although you mustn't apply them until after you've cleaned your clothes or hair. Because they cling so well to wet fibers, these slippery detergent molecules will remain in place long after washing and give fabrics and hair a soft, silky feel. They'll also allow those materials to conduct electricity, albeit poorly, so as to virtually eliminate static electricity!

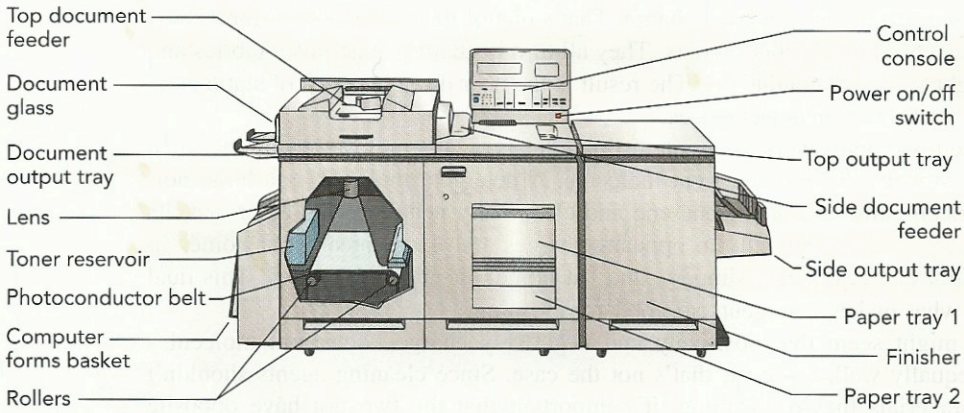
This conductivity is due principally to their tendency to attract moisture. Water is a slight electrical conductor, and damp surfaces allow charges to move around. That's why moist air decreases static electricity. By making fabrics and hair almost imperceptibly damp, the positively charged detergents allow separated charges to get back together and do away with static hair problems and laundry cling. That's why they're the main ingredients in fabric softeners, dryer sheets, hair conditioners, and even many antistatic sprays.

Check Your Understanding #6: **No Lightning at Work**

The conveyor belts used to move flammable materials often have metal threads woven into their fabric. Why are such conducting belts important for fire safety?

Answer: An insulating conveyor belt can separate enormous amounts of charge, leading to high voltages, sparks, and possibly fire. A conductive belt can't carry charge with it as it moves, so no charge accumulates.

Why: When an insulating belt has charge on its surface, that charge must move with the belt. However, charges are mobile in a conductive belt and don't normally move with it.



SECTION 10.2 Xerographic Copiers

The days of carbon paper and mimeograph machines are long gone. What modern office could operate without a xerographic copier? Advertisements for copiers are everywhere, and although each manufacturer claims to make the best copiers, that's mostly just salesmanship. In reality, all xerographic copiers are based on the same principles, discovered in 1938 by Chester Carlson. In this section, we'll examine xerographic copiers and the ideas that make them possible.

Questions to Think About: *How could you use static electricity to position black powder on a sheet of paper? How would you put that static electricity on the paper? In order for characters to appear on the sheet, how should its static electricity be distributed? In a copier, what should light do to the static electricity to produce a copy of the original? How can a device spray static electricity onto a surface?*

Experiments to Do: *To get a feel for how a copier works, cut a small sheet of paper into tiny squares, about 1 mm on a side. Put the squares on a table and suspend a thin plate of clear plastic above them, a few millimeters away. The top of a clear plastic box will do. Now run a plastic comb through your hair or against a sweater several times and touch it to the top of the plastic plate. Squares of paper will leap off the table and stick to the plastic plate. What's holding the squares against the plastic? If the paper were black, how could you form letters on the surface of the plastic?*

■ Impoverished as a youth, American inventor Chester F. Carlson (1906–1968) supported his family by washing windows and cleaning offices after school. His work in a print shop as a teenager started him thinking about copying, and he began to experiment with electrophotography. After attending Caltech (the California Institute of Technology), he worked for Bell Laboratories but was laid off during the Depression. While attending law school, he continued his experiments and invented the xerographic copying process in 1937–1938. Development of commercial copiers was slow, and it wasn't until 1960 that Haloid Xerox Corporation produced its first successful copier, Model 914. Carlson became extremely wealthy but gave most of his money away anonymously.

Xerography: Using Light to Print Copies

The image that a xerographic copier prints on a sheet of paper begins as a pattern of tiny black particles or *toner* on a smooth, light-sensitive surface. The copier uses static electricity and light reflected from the original document to arrange this toner on the surface and then carefully transfers the toner to the paper (Fig. 10.2.1). Invented in 1938 by Chester Carlson ■, this process is basically our old friend static electricity doing something useful.

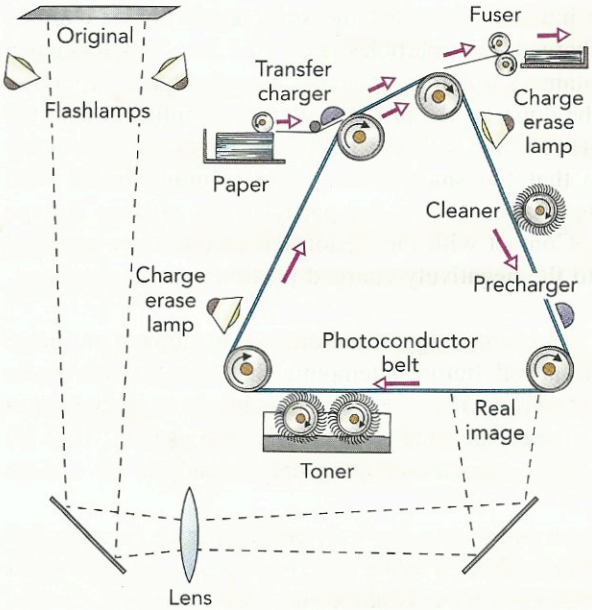


Fig. 10.2.1 This xerographic copying machine uses a photoconductor belt to form black-and-white images of an original document. The copying process begins with the precharger, which coats the photoconductor with charge. The optical system then forms a real image on a flat region of the photoconductor belt, producing a charge image. After the charge image picks up toner particles, the first charge erase lamp eliminates the charge image and weakens the toner's attachment to the belt. The toner is then transferred and fused to the paper.

At the heart of the xerographic copier is a thin, light-sensitive surface made from a **photoconductor**—a normally insulating material that becomes a conductor while exposed to light. Although the darkened photoconductor can keep positive and negative charges apart, these charges quickly draw together when light hits the photoconductor (Fig. 10.2.2). That flexibility allows light from the original document to determine the pattern of static electricity on the photoconducting surface and consequently the placement of toner on the piece of paper.

Each copying cycle begins in the dark with the copier spraying negative charges onto its photoconductor. On the other side of the photoconductor is a grounded metal surface—grounded in the sense that it's electrically connected to the earth so that charges are free to flow between the two. As negative charges land on the open surface of the photoconductor, they attract positive charges onto the metal surface beneath it. When the charge-spraying process is complete, the open surface of the photoconductor is uniformly coated with negative charges while the underlying metal surface is uniformly coated with positive charges (Fig. 10.2.3*a*).

After this precharging, the copier uses a lens to cast a sharp image of the original document onto the photoconducting surface. We'll examine lenses and the formation of images when we study cameras in Chapter 15. For now, what matters is that light hits the photoconductor only in certain places, corresponding to white parts of the original document.

There are two standard techniques for exposing the photoconductor to light. Some copiers illuminate the whole original document with the brilliant light of a flash lamp and cast a complete image onto a flattened portion of a photoconductor belt. In other copiers, a moving lamp or mirror illuminates the original a little at a time and the image is cast as a moving stripe on a rotating photoconductor drum. Either way, charges move through any regions of the photoconductor that are exposed to light, leaving these regions electrically neutral (Fig. 10.2.3*b*). The result is a *charge image*—a pattern of electric charge on the photoconductor's surface that exactly matches the pattern of ink on the original document (Fig. 10.2.3*c*).

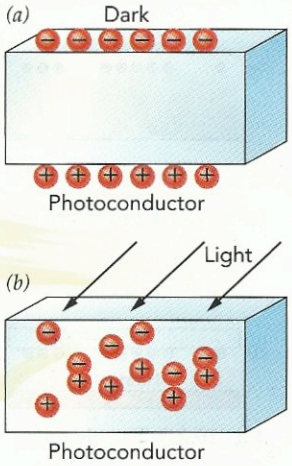


Fig. 10.2.2 (*a*) In the dark, a photoconductor is an electrical insulator, so that separated electric charges on its surfaces remain there indefinitely. (*b*) When the photoconductor is exposed to light, it becomes an electrical conductor and the opposite electric charges soon join one another.

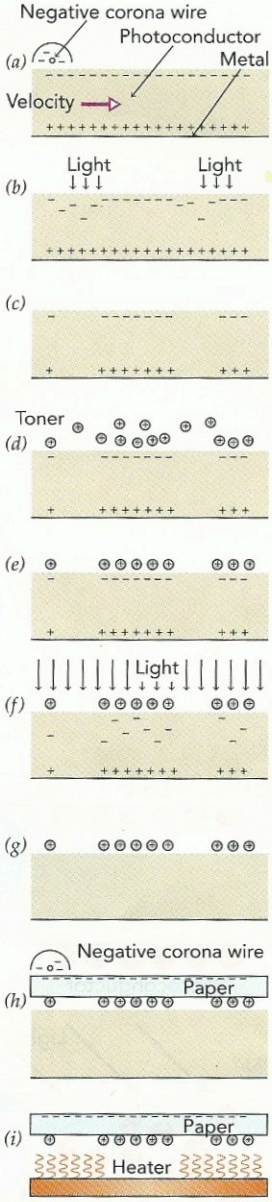


Fig. 10.2.3 The photoconductor is first coated (*a*) with a uniform layer of negative charge. Exposure to light (*b*) erases some charge to form a charge image (*c*). The charge image attracts (*d*) positively charged toner particles (*e*). The charge image is erased (*f*) to release the toner particles (*g*). The toner is transferred to the negatively charged paper (*h*) and fused to the paper with heat (*i*).

To develop this charge image into a visible one, the xerographic copier exposes the photoconductor to positively charged toner particles (Fig. 10.2.3*d*). This toner is a fine, insulating plastic powder containing a colored pigment, usually black. Applying toner to the photoconductor must be done gently, and it's often accomplished with the help of Teflon-coated iron balls. These tiny balls are held together in long filaments by a rotating magnetic shaft, so that the shaft resembles a spinning brush with extraordinarily soft bristles. These bristles wipe toner particles out of their storage tray and onto the photoconductor. Contact with the Teflon leaves the toner particles positively charged, so they stick to the negatively charged portions of the photoconductor (Fig. 10.2.3*e*).

The photoconductor now carries a black image of the original document, an image that the copier must transfer to the paper. Before attempting that transfer, the copier first weakens the photoconductor's grip on the toner by exposing it to light from a charge erase lamp. This light eliminates the photoconductor's charge (Fig. 10.2.3*f*) and leaves the positively charged toner particles clinging only loosely to its surface (Fig. 10.2.3*g*).

The copier then transfers the toner image to a blank sheet of paper by pressing that paper lightly against the photoconductor while spraying negative charge onto the paper's back (Fig. 10.2.3*h*). The positively charged toner is attracted to the negatively charged paper, and the two leave the photoconductor together. The copier then heats and presses the copy, permanently fusing the toner onto the paper (Fig. 10.2.3*i*). Once the image has been transferred to the paper, the copier cleans its photoconducting surface in preparation for the next copy: a second charge erase lamp eliminates any remaining charge, and a brush or squeegee mops up any residual toner.

With that introduction to xerography, you can already explain many things about copiers. For example, while fixing a copier jam, you may find that you have removed unfinished copies—ones bearing toner images that haven't yet been fused onto the paper. The toner of an unfused copy comes off on your hand because it's held in place only by electrostatic forces. When you replace the "toner cartridge" in a personal copier, in addition to adding new toner, you're also installing a new precharge system, photoconductor drum, and toner applicator (Fig. 10.2.4).

However, we've glossed over three important physics issues. Two we'll leave for later chapters: why a photoconductor becomes conducting when exposed to light (Chapter 12, Electronics) and how a lens projects an image of the document onto the photoconductor (Chapter 15, Optics). The third issue is relevant now, and so we'll examine it carefully: how the copier sprays charges onto surfaces.

Fig. 10.2.4 This xerographic copier places the photoconductor drum, toner supply, and a corona wire inside a disposable cartridge. After the paper passes through the cartridge, toner is fused onto its surface and it leaves the copier.

Courtesy Lou Bloomfield

Check Your Understanding #1: Sticky Copies

When the copies emerge from a xerographic copier, they tend to stick to things and attract lint. What causes this effect?

Answer: The charge that was placed on the paper to attract the toner isn't always removed completely. Moreover, the toner itself is charged.

Why: The final transfer process, lifting the toner particles from the photoconductor to the paper, is done by charging the paper, and some of this charge remains on the paper when it leaves the copier. Copier transparencies are particularly clingy because plastic retains charge so well.

Discharges and Electric Fields

At the start of the copy cycle, the xerographic copier coats its photoconducting surface uniformly with electric charges. Because this precharging process is done in the dark, while the surface is an electrical insulator, the charges must be sprayed onto it like paint. The copier's charge sprayer is a **corona discharge**—a gentle, sustained spark that forms in the air near a needle or fine wire that's maintained at high voltage.

It's a type of **discharge**—a flow of electric charge through a gas. Air is normally an insulator because its atoms and molecules are neutral and can't convey charge from one place to another. However, by seeding air liberally with individual charged particles, the copier manages to turn that air into a conductor and then to produce a discharge in it. How does the copier seed the air with charges and produce its discharge? And how does it use that discharge to coat its photoconducting surface? To answer those questions, we'll need to know more about electrostatic forces and voltages, and about a related concept: electric fields.

Because free charges are hard to come by in the air, the copier begins with just a few charged particles and uses them to generate more. The idea is simple: the copier uses electrostatic forces to accelerate those initial charges to enormous speeds and lets them smash into air's neutral particles. When hit hard enough, a neutral air particle breaks into oppositely charged fragments and thus adds two more free charges to the air. These new charges join the mix, accelerating, colliding, and breaking up still more air particles. A cascade of collisions ensues and the air "breaks down"—transforming from an insulator to a conductor. The copier then uses this conducting air to spray the photoconductor with charges.

Where do those initial charges come from? Surprisingly, they're already there, the products of cosmic rays and natural radioactivity! Every cubic centimeter of ordinary air contains almost 2000 charged particles, roughly half positive and half negative. Considering that this same volume of air contains almost 3×10^{19} neutral particles, that's not many charges, but it's enough to get the discharge started.

To parlay those initial charges into the vast numbers it needs, the copier must accelerate them aggressively. The neutral air particles are so densely packed that it's difficult for the charged ones to pick up much speed before they hit something and slow down. To give each initial charge a good shot at breaking the first neutral particle it hits, the copier must accelerate that charge very quickly.

The copier accelerates its free charges using electrostatic forces. Up until now, we've associated electrostatic forces with pairs of charges, each charge pushing or pulling on the other. Since the individual forces on an object sum to give the net force on that object, it's easy to figure out how three charges affect one another, or four, or five. . . . However,

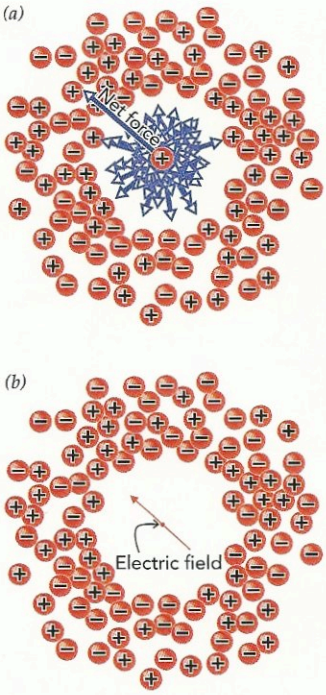


Fig. 10.2.5 (*a*) When a charge interacts with many other charges, adding up the individual electrostatic forces on that charge to obtain the net force on it becomes a daunting task. (*b*) It is often simpler to introduce an electric field as an intermediary. The other charges produce this electric field, which in turn exerts an electrostatic force on the charge (omitted for clarity). The electric field arrow passing through the red dot indicates the magnitude and direction of the force a positive test charge would experience at the dot's location.

in the copier's wires and discharge, there are so many individual charges that adding up their forces is virtually impossible. We need some other way to characterize the overall electrostatic force on a particular charge.

Instead of thinking about the many interactions between that charge and all the other charges around it (Fig. 10.2.5*a*), we can view the electrostatic force on our charge as the result of its one interaction with something local: an **electric field**—an attribute of space that exerts an electrostatic force on a charge (Fig. 10.2.5*b*). From this new perspective, our charge accelerates forward because it interacts with the local electric field, a field that's created by all of the surrounding electric charges.

This electric field appears to be nothing more than an intermediary: the surrounding charges produce the electric field, and this electric field pushes on our charge. In later sections, we'll see that an electric field is more than that, more than a seemingly unnecessary fiction. That's because an electric field truly exists in space, independent of the charges that produce it. In fact, electric fields are often created by things other than charges and can influence things other than charges as well.

The copier's electric field varies with location, meaning that the electrostatic force on our charge depends on where it is. This force is equal to the product of the charge times the electric field and points in the direction of that electric field. We can write this relationship as a word equation:

$$\text{force} = \text{charge} \cdot \text{electric field}, \tag{10.2.1}$$

in symbols:

$$\mathbf{F} = q\mathbf{E},$$

and in everyday language:

Charged lint accelerates quickly in a region full of static electricity,

where the force is in the direction of the electric field. Note, however, that a particle carrying a negative amount of charge (e.g., an electron) experiences a force opposite the electric field. The SI unit of electric field is the **newton-per-coulomb** (abbreviated N/C).

The copier employs a very strong electric field to "break down" the air so that it can operate its discharge. That field accelerates charges so rapidly that collision cascades occur and fill the air with free charges. Unfortunately, you can't sense electric fields directly, so it's hard to visualize a strong one. We'll work on that problem, but for now just remember that strong electric fields can initiate discharges in air. That's how thunderstorms produce lightning!

Check Your Understanding #2: **Medical Electrons**

A medical linear accelerator uses a strong electric field to accelerate electrons forward and give them enormous kinetic energies. These high-energy electrons enter the patient and kill cancer cells. In which direction does the accelerator's electric field point?

Answer: It points backward, away from the patient.

Why: Since electrons are negatively charged, they accelerate in the direction opposite to the field. Since the accelerator must push the electrons forward, toward the patient, its field must point away from the patient.

Check Your Figures #1: Lint Floats

A piece of charged lint refuses to fall because an electric field is exactly supporting its weight. If the lint weighs 10^{-8} N and has a positive charge of 10^{-11} C, what electric field is supporting it?

Answer: The lint is supported by an electric field of 1000 N/C in the upward direction.

Why: The electric field is equal to the force it exerts divided by the charge, or 10^{-8} N divided by 10^{-11} C. It must point upward to support the positively charged lint against the downward pull of gravity.

Conductors and Voltage Gradients

A copier's precharging system uses the gentle corona discharge that develops in the strong electric field just outside a fine, high-voltage wire. This discharge ferries charges to the photoconductor surface and coats it uniformly. To understand why a strong electric field exists outside a fine, high-voltage wire and why the discharge it produces is "gentle," we need some background. Let's start by looking at electric fields inside and outside electrical conductors.

Consider the simplest conducting object: a solid metal ball. If you release some positive charges inside that ball (Fig. 10.2.6*a*), what happens to them? Because they repel one another, those charges accelerate outward and move apart. In fact, they'd leave the ball altogether if they weren't chemically bound to its metal. After spending a moment or two ridding themselves of extra electrostatic potential energy, principally as heat, the charges settle down in stable equilibria on the ball's surface (Fig. 10.2.6*b*). At its

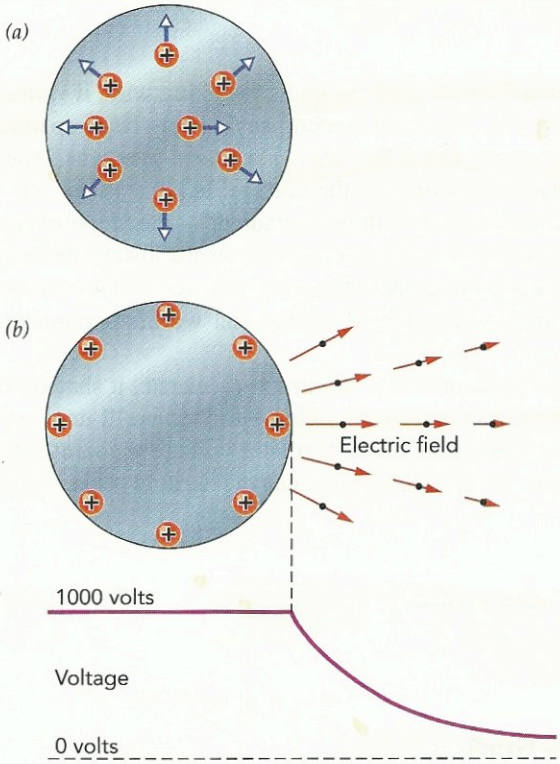


Fig. 10.2.6 (*a*) When like charges are placed inside a conducting sphere, they repel one another and accelerate toward the sphere's surface. (*b*) When those charges have reached equilibrium on the sphere's surface, the sphere has a single, uniform voltage and zero electric field inside it. Outside the sphere, the voltage decreases toward zero and there is an electric field.

equilibrium point, the outward electrostatic force each charge experiences from its fellow charges is perfectly balanced by the inward chemical force it experiences from the metal. The net force on it is zero.

At equilibrium, each charge has also minimized its total potential energy. After all, it can't stop accelerating until there is no direction in which it can move to lower its potential energy further. What's amazing about how the charges arrange themselves on the ball's surface is that each one ends up with the *same* total potential energy. That's because if one of them had less total potential energy than the rest, the other charges would accelerate toward it to lower their total potential energies as well!

Since the only potential energy that significantly affects charges in our small, homogeneous ball is electrostatic potential energy, every charge in our ball has essentially the same electrostatic potential energy. Because voltage is the electrostatic potential energy per unit of charge, equal potential energies on equal charges means equal voltages—the entire ball has a single, uniform voltage! In our voltage↔altitude analogy, this observation is analogous to the fact that, at equilibrium, the water level in a swimming pool has a single, uniform altitude.

Because of the ball's perfect symmetry, charges in equilibrium are spread evenly on its surface. Had we chosen a less symmetric conducting object, such as the copier's fine metal wire, charges in equilibrium would not be spread so evenly. Nonetheless, those charges would still be on the outside of the object and it would still have a single, uniform voltage.

Voltage and Charge on a Conducting Object
With its charges at equilibrium, a homogeneous conducting object has a single, uniform voltage and the net charge anywhere in its interior is zero.

Although the voltage is uniform *in* and *on* the copier's fine conducting wire, it varies rapidly with position *outside* that wire (Fig. 10.2.6*b*). Accompanying this large spatial variation in voltage is a strong electric field, officially called a **voltage gradient**. You can think of a spatial variation in voltage as a "slope" in the voltage. In our voltage–altitude analogy, a voltage gradient is analogous to an "altitude gradient"—the slope of an ordinary hill. Just as water accelerates swiftly down a steep slope toward lower altitude, so charge accelerates swiftly down a large voltage gradient toward lower voltage. Both are examples of the accelerations toward lower potential energy that we first examined in Chapter 2.

Since both electric fields and voltage gradients cause charges to accelerate, it shouldn't surprise you to learn that a voltage gradient *is* an electric field. Although we'll uncover a second source of electric fields in the next chapter, we'll treat a voltage gradient and an electric field as equivalent for now. Their relationship can be written as a word equation:

$$\text{electric field} = \text{voltage gradient} = \frac{\text{voltage drop}}{\text{distance}}, \tag{10.2.2}$$

in symbols:

$$\mathbf{E} = \mathbf{Gradient}(V),$$

and in everyday language:

Charges rush down steep drops in voltage, much as bicycles rush down steep drops in height,

where the electric field points in the direction of the most rapid voltage decrease.

This relationship gives us a second way to look at an electric field. In addition to being the electrostatic force exerted per unit of charge, electric field is also the voltage drop per unit of distance. The SI unit of electric field therefore has a second form: the **volt-per-meter** (abbreviated V/m). The V/m is exactly the same unit as the N/C. As an example of an electric field produced by a voltage drop, consider the top of a normal 9 V battery. With its two terminals separated by just 0.005 m and a voltage drop of 9 V between them, the space between those terminals contains an electric field of about 1800 V/m, pointing toward the negative terminal.

Check Your Understanding #3: **Don't Get Out of a Hot Car!**

During a thunderstorm, a lightning strike places a huge static charge on your car. Why don't you notice this charge as long as you remain inside the car?

Answer: The accumulated charge is all on the outside of the conducting car, so it will only affect you if you step outside and offer it a conducting path to the ground.

Why: Since the car body is an electrical conductor and its charges are in equilibrium, the car has a uniform voltage and there is no electric field inside the car. Outside the car, however, there is a substantial electric field. If your body provides a conducting path to the ground, that electric field will push charges through you and you will experience a shock. Similarly, if electric power lines ever fall on your car during a storm, stay inside the car to avoid a potentially lethal shock.

Check Your Figures #2: **Riding the Field**

An electric field pushes charged particles through the tube of a fluorescent lamp, allowing it to produce light. To operate properly, a typical fluorescent tube needs an electric field of about 100 V/m. If the average voltage difference between the two ends of a tube is 120 volts, how long can that fluorescent tube be?

Answer: It can be about 1.2 m (4 ft).

Why: With a voltage difference of 120 volts between its ends and a length of 1.2 meters, the tube's electric field will be 120 V divided by 1.2 m, or about 100 V/m. This result explains why so many fluorescent lamps in the United States are about 1.2 m (4 ft) long.

Fine Wires and High Voltages: Corona Discharges

Ordinary air breaks down in an electric field of about 3×10^6 volts-per-meter or, in customary units, about 30,000 volts-per-centimeter. At that field, free charges accelerate so rapidly that a cascade of charge-freeing collisions suddenly transforms air from a nearly perfect insulator into a reasonably good conductor.

Courtesy Lou Bloomfield

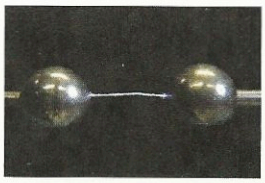


Fig. 10.2.7 These two metal spheres are 1 cm apart. When their difference in voltage is about 30,000 V, the air between them breaks down and forms a spark.

You can produce such a strong field all by yourself. On a dry winter day, you can coat yourself with positive charges and raise your voltage to about 30,000 volts simply by scuffing your rubber-soled shoes across an acrylic carpet. As you then approach a grounded doorknob at 0 volts, the voltage difference between the doorknob and your hand will be 30,000 volts. When your hand is about 1 cm from the doorknob, the electric field will reach 30,000 volts-per-centimeter, and the air will break down with a brilliant spark (Fig. 10.2.7).

Because your hand and the doorknob are similar in size and shape, the voltage changes smoothly between them (Fig. 10.2.8*a*). It varies steadily from 0 volts on the doorknob to 30,000 volts on your hand, so the voltage gradient or electric field is nearly uniform. When two objects differ significantly in size, however, the larger object dominates voltages in the space between them. For example, if you hold a long pin in your hand as you approach the doorknob, the doorknob will control the voltage most of the way to the pin and nearly all the increase in voltage will occur just outside the pin's point (Fig. 10.2.8*b*). Rather than being uniform, the voltage gradient or electric field will be strongest near that point.

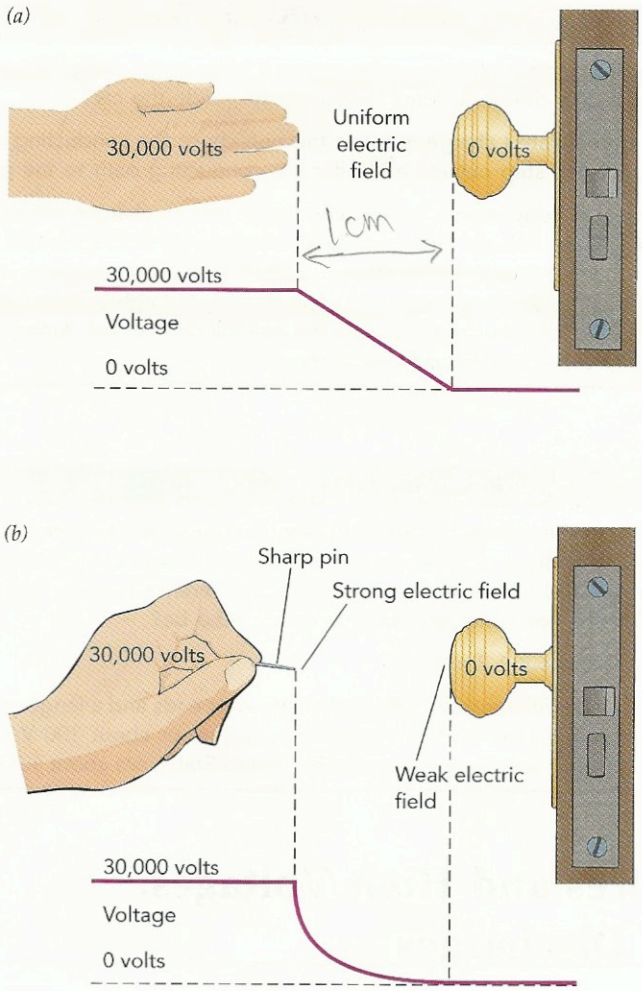


Fig. 10.2.8 Your voltage is 30,000 V when you reach for the 0-V doorknob. (*a*) Since your hand and the doorknob are similar in size, the voltage decreases steadily between them and the electric field is uniform. (*b*) When you hold out a pin, the voltage plummets near its sharp point and the electric field there is extremely strong.

The copier makes good use of this nonuniform field. Its fine, high-voltage wire is nearly surrounded by a much larger metal shroud. The wire is so thin that its influence fades just a hair's breadth from its surface and the grounded shroud dominates voltage almost all the way to the wire. Although the wire's negative voltage is only –3000 volts and it's about 1 cm from the shroud, the voltage changes so rapidly in the air just outside this wire that the electric field there easily exceeds 30,000 volts-per-centimeter and breaks down the air.

The discharge that forms near the fine wire is a special, self-regulating one—a corona discharge (Fig. 10.2.9). While most discharges can't control how many free charges they produce, a corona discharge automatically maintains a steady production. Because free charges form only in the strong electric field near its thin conductor, their production rate is very sensitive to changes in that conductor's effective thickness. If there are too many free charges in the air near the conductor, their ability to conduct electricity effectively thickens the conductor, weakens the electric field, and slows the production of free charges. The discharge is correcting its own mistake.

Because of this stabilizing effect, the air in a corona discharge maintains a steady electrical conductivity that's ideal for charging a copier's photoconductor. However, corona discharges were common long before copiers. They often occur spontaneously near sharp points or fine wires at high voltages, leading to charge leakage from power transmission lines and occasionally producing a glow called St. Elmo's fire on the masts and rigging of sailing ships (see ■).

Courtesy Lou Bloomfield

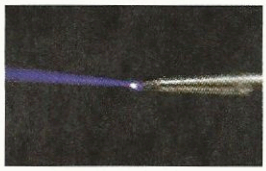


Fig. 10.2.9 The electric field near this sharp, high-voltage pin is so strong that it breaks down the air and forms a corona discharge. The resulting glow is produced by air particles that receive energy from the discharge.

■ Contrary to popular belief, lightning rods don't simply attract lightning strikes so as to protect the surrounding roof. Instead, they produce corona discharges that diminish any local buildups of electric charge. By neutralizing the local electric charge, the lightning rod reduces the chances that lightning will strike the house. Similar devices, called static dissipaters, are found near the tips of airplane wings and protect planes from lightning strikes.

Check Your Understanding #4: A Safety Pin

You could avoid the shock of static electricity by holding out a sharp needle as you reach for a metal doorknob or wall. How does that needle protect you from static electricity?

Answer: The needle emits charge into the air via a corona discharge.

Why: The needle acts as your personal lightning rod. When you are carrying a net electric charge, some of that charge settles onto the needle. The strong electric field near the needle's tip initiates a corona discharge, and much of your accumulated charge leaves through it. This discharge limits your net electric charge and thus the size of any shock you experience.

Getting Ready to Copy: Charging by Induction

A corona discharge does more than just turn air into a conductor; it also produces an outward spray of electric charges. Those charges are pushed outward by the electric field surrounding the corona wire. Since the copier's corona wire has a negative voltage, the surrounding electric field points toward that wire. Because negative charges accelerate opposite an electric field, the copier's corona produces a shower of outgoing negative charges. They spray onto the photoconducting surface as it moves steadily past the corona, and the photoconductor thus acquires a uniform coating of negative charges.

As each negative charge lands, it draws a positive charge onto the grounded metal surface beneath the photoconductor, and the attraction between those two opposite charges holds them firmly in place. While the photoconductor's open surface is acquiring its

uniform negative charge, the metal layer underneath is acquiring an equivalent positive charge (Fig. 10.2.3*a*). This process, whereby a grounded conductor acquires a charge through the attraction of nearby opposite charge, is called "charging by induction."

The induced positive charge on the metal side of the photoconductor is important to the xerographic process for several reasons. First, it lowers the electrostatic potential energy of the negative charge so that the surface's negative voltage isn't as enormous. Second, without that positive layer nearby, repulsion between like charges would tend to push negative charges on the open surface toward the edges of the photoconductor and distort the resulting images.

Most significantly, however, the positive charge layer gives the negative charge layer somewhere to go when the photoconductor is exposed to light! Wherever light from the original document turns a patch of photoconductor into a conductor, the negative and positive charge layers rush together and cancel. The resulting uncharged portion of photoconductor subsequently attracts no toner and produces a white patch on the finished copy.

Having come full circle, we can now see how the copier achieves its goal. It uses a corona discharge to coat a photoconducting surface with negative charge and then selectively erases portions of that charge layer with light from the original document. The remaining charged patches on the photoconductor attract positively charged black toner, which is then transferred permanently to the paper.

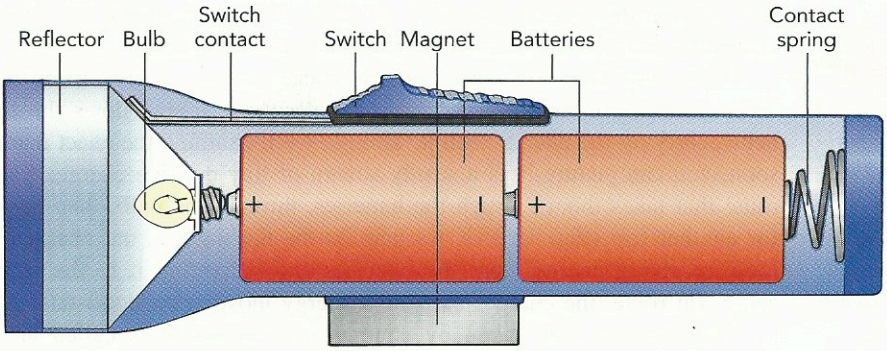
The only additional detail worth mentioning is that, for technical reasons, some copiers precoat their photoconductors with positive rather than negative charges and then use that charge to attract negatively charged toner. These copiers put high positive voltages on their fine wires so that their coronas spray positive charges.

Check Your Understanding #5: **Hot Rod**

A thick wire connects the lightning rod on the courthouse steeple to the ground and normally ensures that the rod is electrically neutral. However, when a negatively charged cloud floats overhead, what charge does that rod acquire?

Answer: The rod becomes positively charged.

Why: The lightning rod charges by induction—the cloud's negative charge attracts positive charge up the wire and onto the rod. The rod's sharp point initiates a corona discharge, spraying positive charge toward the cloud and gradually decreasing the cloud's charge. In that fashion, the lightning rod acts to suppress lightning strikes.



SECTION 10.3 Flashlights

There isn't much to a typical flashlight; you can see what few parts it has when you open it to replace its batteries. A flashlight isn't a mechanical device, though, it's an electrical one: it contains an electric circuit, and most of its components are involved in the flow of electricity. Understanding how a flashlight works means understanding how an electric circuit works and how electricity carries power from batteries to a bulb. As we'll see, flashlights aren't as simple as they appear.

Questions to Think About: *Why are some flashlights brighter than others? Why is it important that all of the batteries point in the same direction? What is the difference between old batteries and new? What makes a flashlight suddenly become dim or bright when you shake it?*

Experiments to Do: *Find a flashlight that uses two or more removable batteries. Turn it on. What did the switch do to make the flashlight produce light? With the flashlight turned on, slowly open the battery compartment. The lamp will probably become dark. You should be able to turn the flashlight on and off by opening and closing the battery compartment. Why does this method work?*

Replace the flashlight's batteries with older or newer ones and compare its brightness. Turn one or more of the batteries around backward and see how that change affects the flashlight. What happens when you put a piece of paper or tape between two of the batteries? What happens when you carefully clean the metal surfaces of each battery with a pencil eraser before putting them in the flashlight?

Electricity and the Flashlight's Electric Circuit

A basic flashlight has just three components—a battery, a bulb, and a switch—connected together by metal strips. When the switch is on, the strips transfer energy from the batteries to the bulb. How does energy move through the strips, and why does the switch

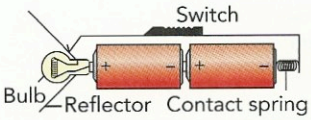


Fig. 10.3.1 A flashlight contains one or more batteries, a lightbulb, a switch, and several metal strips to connect them all together. When the switch is turned on (as shown), the components in the flashlight form a continuous loop of conducting materials. Electrons flow around this loop counterclockwise.

start or stop that energy transfer? To answer these questions, we must first understand electricity and electric circuits, so that's where we'll begin.

When you turn on a flashlight, electricity conveys energy from the batteries to the bulb. An **electric current**—a current of electric charges—flows through these components, carrying the energy with it. Though we'll examine the exact nature of this current soon, you can picture it as a steady stream of tiny positive charges following a circular route that takes them through the batteries, through the bulb, then back to the batteries for another trip (Fig. 10.3.1). As long as the flashlight is on, charges flow around this loop, receiving energy from the batteries and delivering it to the bulb, over and over again. En route, the charges carry this energy mostly as electrostatic potential energy.

The looping path taken by charges in a flashlight is called an **electric circuit**. Because a circuit has no beginning or end, charges can't accumulate in one place, where their mutual repulsion would eventually stop them from flowing. Circuits are present in virtually all electric devices and explain the need for at least two wires in the power cord of any home appliance: one wire carries charges to the appliance to deliver energy, and the other wire carries those charges back to the power company to receive some more.

What role does the switch play in all of this? As part of one conducting path between the batteries and bulb, the switch can make or break the flashlight's circuit (Fig. 10.3.2). When the flashlight is on, the switch completes the loop so that charges can flow continuously around the **closed circuit** (Fig. 10.3.2*a*). A closed circuit appears on the left side of Fig. 10.3.3.

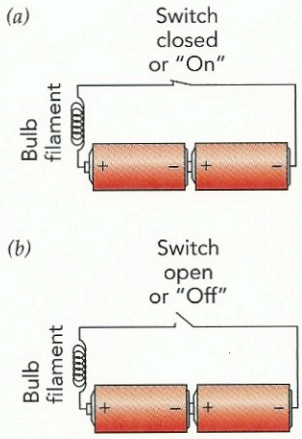
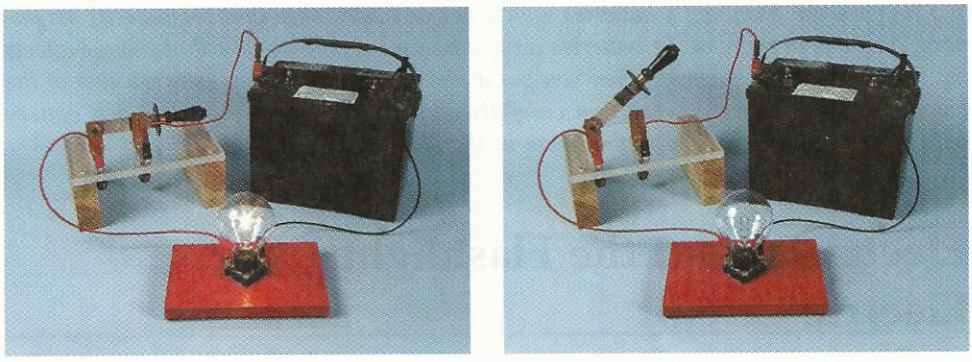


Fig. 10.3.2 (*a*) When the flashlight's switch is on, it closes the circuit so that current can flow continuously from the batteries, through the bulb's filament, and back through the batteries. It follows this circuit over and over again. (*b*) When the flashlight's switch is off, it opens the circuit so that current stops flowing.

However, when you turn off the flashlight, the switch breaks the loop to form an **open circuit** (Fig. 10.3.2*b*). Although one conducting path still connects the batteries and bulb, the loop now has a gap in it and can no longer carry a continuous current. Instead, charges accumulate at the gap and current stops flowing through the flashlight. Since energy can no longer reach the bulb, it goes dark. An open circuit appears on the right side of Fig. 10.3.3.

There's one other type of circuit worth mentioning. A **short circuit** forms when the two separate paths connecting the batteries to the bulb accidentally touch one another (Fig. 10.3.4). This unintended contact creates a new, shorter loop around which the charges can flow. Because the bulb is supposed to extract energy from the charges, it's designed to impede their flow and to convert their electrostatic potential energy into thermal energy and light. This opposition to the flow of electricity is called **electrical resistance**. Since the shortened loop offers little resistance, most of the charges flow through it and bypass the bulb. The bulb dims or goes out altogether.



Courtesy Lou Bloomfield

Fig. 10.3.3 When the switch is on (*left*), current flows around the closed circuit and carries power from the battery to the lightbulb. When the switch is off (*right*), no current flows through the open circuit.

Since the bulb is the only part of the flashlight that's designed to get hot, a short circuit leaves the charges without a safe place to get rid of their electrostatic potential energies. They deposit it dangerously in the batteries and the metal paths, making them hot. Since short circuits can start fires, flashlights and other electric equipment try to avoid them.

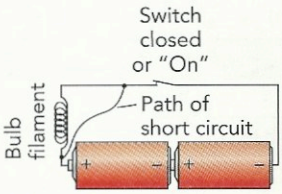


Fig. 10.3.4 When an unwanted conducting path allows current to bypass the flashlight's filament, it forms a short circuit. Because it has no proper place for electrons to deposit their energy, the short circuit becomes hot.

Check Your Understanding #1: Cutting the Power

If you remove just one of the wires from an automobile's battery, the vehicle will not start at all. Why doesn't the other wire supply any energy?

Answer: Removing a single wire from the battery breaks the circuit and prevents a steady flow of electric current through the car's electric system.

Why: Neither the battery nor the rest of the car can accumulate charges indefinitely. Without one wire to carry charges from the battery to the car and a second wire to return those charges from the car to the battery, accumulation will occur and charge movement will stop.

The Electric Current in the Flashlight

Each of the tiny charged particles flowing through the flashlight's circuit carries with it just a single elementary unit of electric charge and a miniscule amount of electrostatic potential energy. However, because those charges flow in astonishing numbers, they convey a considerable amount of energy per second—the quantity we know as power (see Section 2.2) and measure in watts (abbreviated W). The bulb needs a certain amount of power to keep its filament glowing brightly, and you can determine how much power is reaching the bulb by multiplying the number of elementary charges passing through the bulb each second by the amount of energy each one delivers.

There are too many elementary charges to count, though. You'll do much better to measure the circuit's **current**—that is, the amount of charge passing a particular point in the circuit per unit of time. The SI unit of current is the **ampere** (abbreviated A) and corresponds to 1 C (1 coulomb) of charge passing by the designated point each second. One coulomb is roughly 6.25×10^{18} or 6,250,000,000,000,000,000 elementary charges, so even a 1-A current involves a tremendous flow of elementary charges.

Using electric current instead of counting charges, you can determine how much power is reaching the bulb by multiplying that current by its electrostatic energy per coulomb—the quantity we already know as voltage. For example, a current of 2 amperes (2 coulombs-per-second) at a voltage of 3 volts (3 joules-per-coulomb) would bring 6 watts of power (6 joules-per-second) to the bulb. Brighter flashlights involve larger currents, greater voltages, or both.

Current has a direction, pointing along the route of positive charge flow. When you turn on the flashlight in Fig. 10.3.1, charge flows around the circuit clockwise—from the battery chain's positive terminal, through the bulb's filament, through the switch, and into the battery chain's negative terminal. However, it's time to address an awkward issue: the positive charges that flow clockwise around this circuit are fictitious. In reality, the electric current is actually carried by negatively charged electrons heading in the opposite direction!

This issue dates back to Franklin's unfortunate choice of which charge to call positive and which to call negative. By the time scientists discovered the electron and realized that

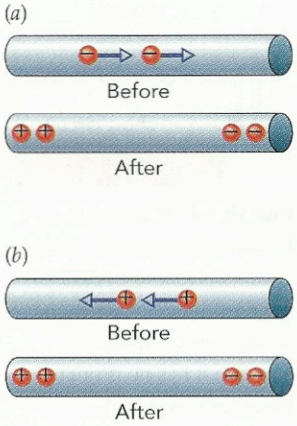


Fig. 10.3.5 A current of negatively charged particles flowing to the right through a piece of wire (*a*) can't easily be distinguished from a current of positively charged particles flowing to the left (*b*). The end result of both processes is an accumulation of positive charge on the left end of the wire and negative charge on its right end.

these negatively charged particles carry currents in wires, current had already been defined as pointing in the direction of positive charge flow. Since it was far too late to make current and electron-flow point in the same direction, scientists and engineers simply pretend that current is carried by fictitious positive charges heading in the current's direction.

This fiction works extremely well, as illustrated by a simple example. When negatively charged electrons flow to the right through a neutral piece of wire, the wire's right end becomes negatively charged and its left end becomes positively charged (Fig. 10.3.5*a*). But exactly the same thing would happen if a current of fictitious positively charged particles were to flow to the left through that same piece of wire (Fig. 10.3.5*b*). Without sophisticated equipment, you can't tell whether negative charges are flowing to the right or positive charges are flowing to the left because the end results are essentially indistinguishable.

We, too, adopt this fiction and pretend that current is the flow of positively charged particles. In this and subsequent chapters, we'll stop thinking about electrons and imagine that electricity is carried by positive charges moving in the direction of the current. There are only a few special cases in which the electrons themselves are important, and we'll consider those situations separately when they arise.

Check Your Understanding #2: Don't Touch That Pipe

A walk across wool carpeting in rubber-soled shoes has left you covered with negative charges. If you bring your hand near a large piece of metal, the negative charges will leap through the air as a spark in order to reach the metal. Which way is current flowing in this spark?

Answer: The current flows from the metal toward your hand.

Why: Because current is defined as the flow of positive charges, it points in the direction opposite the flow of negative charges. Thus the current flows from the metal toward your hand. These charges move only briefly because there is no circuit. For the charges to move continuously they would have to be recycled and a circuit would be essential.

Batteries, . . .

While a battery is basically a portable source of electric power, here are two other interesting ways to think of it. The first is rather abstract: a battery is a type of pump. It "pumps" charge from low voltage to high voltage, much as a water pump pumps water from low altitude to high altitude. Once again, our voltage↔altitude analogy is helpful. Each of these pumps moves something against its natural direction of flow, pushing it forward and doing work on it in the process. The battery increases a charge's electrostatic potential energy by pushing it up a voltage gradient, while the water pump increases water's gravitational potential energy by pushing it up an altitude gradient.

The second perspective on batteries is more mechanical: a battery is a chemically powered machine. It uses chemical forces to transfer charges from its negative terminal to its positive terminal. As positive charges accumulate on the battery's positive terminal, the voltage there rises, and as negative charges accumulate on the battery's negative terminal, the voltage there drops. Since the battery does work transferring charges from low voltage to high voltage, it is converting its chemical potential energy into electrostatic potential energy in these separated charges.

A battery's rated voltage reflects its chemistry, specifically the amount of chemical potential energy it has available for each charge transfer. As the voltage difference between its terminals increases, so does the energy required for each charge transfer. Eventually, the chemicals can't do enough work on a charge to pull it away from the negative terminal and push it onto the positive terminal, so the transfers stop. The battery is then in equilibrium—the electrostatic forces opposing the next charge transfer exactly balance the chemical forces promoting it. A typical alkaline battery reaches this equilibrium when the voltage of its positive terminal is 1.5 V above the voltage of its negative terminal. Lithium batteries, with their more energetic chemistries, can achieve voltage differences of 3 V or more.

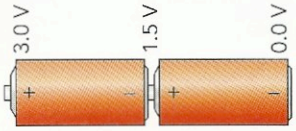


Fig. 10.3.6 When two 1.5-V batteries are connected in a chain, their voltages add so that the chain's positive terminal has a voltage that is 3.0 V higher than the chain's negative terminal. If the chain's negative terminal is chosen to be at 0 V, then the chain's positive terminal is at 3.0 V.

When you turn on the flashlight, you upset its equilibrium by allowing charges to leave the battery's positive terminal for its negative terminal. With fewer separated charges now on its terminals, the battery's voltage difference decreases slightly and it begins pumping charges again. That renewed charge transport replenishes the terminals' separated charges and opposes any further decrease in the battery's voltage. In this manner, a 1.5-V alkaline battery maintains a nearly steady voltage difference of 1.5 V between its terminals, whether its flashlight is on or off.

That alkaline battery is powered by an electrochemical reaction in which powdered zinc at its negative terminal reacts with manganese dioxide paste at its positive terminal. This reaction resembles controlled combustion. In effect, the battery "burns" zinc to obtain the energy it needs to pump charges from its negative terminal to its positive terminal. However, as the battery consumes its chemical potential energy, its ability to pump charges diminishes. When its chemicals are nearly exhausted, the battery's increasing disorder reduces its voltage. An aging battery can pump less current than a fresh one and provides that current with less voltage. Ultimately, less power reaches the flashlight's bulb and it goes dim.

Courtesy Lou Bloomfield

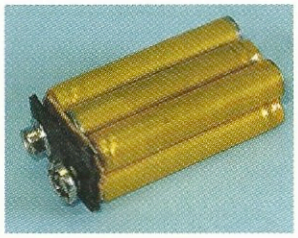


Fig. 10.3.7 A 9-V battery actually contains six small 1.5-V cells, connected in a chain. Positive charges that enter the chain at the battery's negative terminal pass through all six cells before arriving at the battery's positive terminal.

Most flashlights use more than one battery. When two alkaline batteries are connected together in a chain, so that the positive terminal of one battery touches the negative terminal of the other, the two batteries work together to pump charges from the chain's negative terminal to its positive terminal (Fig. 10.3.6). Each battery pumps charges until its positive terminal is 1.5 V above its negative terminal, so the chain's positive terminal is 3.0 V above its negative terminal. Because charges never leave the flashlight's circuit, only relative voltages matter in that circuit. We'll find it convenient to ignore the flashlight's absolute voltages and define the voltage of the battery chain's negative terminal to be 0 V (Fig. 10.3.6). With that choice, the voltage of its positive terminal becomes 3.0 V.

The more batteries in the flashlight's chain, the more energy a charge receives overall and the more the voltage will increase from the chain's negative terminal to its positive terminal. A flashlight that uses six alkaline batteries in its chain has a positive terminal that is 9 V above its negative terminal. A typical 9-V battery actually contains a chain of six miniature 1.5-V batteries, arranged so that their voltages add up to 9 V (Fig. 10.3.7).

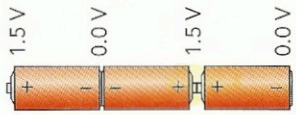


Fig. 10.3.8 When one battery in a chain of three is reversed, the reversed battery's voltage is subtracted from the sum of the others. The chain's positive terminal has a voltage only 1.5 V higher than its negative terminal. The reversed battery recharges.

If you reverse one of the batteries in a chain, the reversed battery will extract energy from any charge passing through it (Fig. 10.3.8). While the chain may still pump charge from its negative terminal to its positive terminal, its overall voltage will be reduced, because instead of adding 1.5 V to the chain's overall voltage, the reversed battery will subtract that amount. If the chain has three batteries, two will add energy to the charge while one will subtract it, and the chain's overall voltage will be only 1.5 V.

As the reversed battery extracts energy from the charges passing through it, at least some of that extracted energy is converted into chemical potential energy. The reversed battery is recharging! Battery chargers follow that concept, pushing current backward through a battery—from its positive terminal to its negative terminal—to restore the chemical potential energy in a rechargeable battery. However, normal alkaline batteries

are "nonrechargeable," meaning that they turn most of the recharging current's energy into thermal energy instead of chemical potential energy. Nonrechargeable batteries may overheat and explode during recharging.

Check Your Understanding #3: Car Batteries

A lead–acid automobile battery provides 12 V between its negative terminal and its positive terminal. It actually contains six individual batteries, connected in a chain. How much voltage does each individual battery provide?

Answer: Each individual battery provides 2 V.

Why: The voltages of the individual batteries add so that it takes six of the 2-V batteries to yield a 12-V chain. If one of the batteries becomes weak, through damage, loss of fluid, or consumption of its chemical potential energy, the voltage of the chain will drop below 12 V. Pushing current backward through a lead–acid battery recharges it.

. . . Bulbs, and Metal Strips

Whereas a battery gives charges electrostatic potential energy by pushing them *up* a voltage gradient, a bulb releases that electrostatic potential energy by letting charges slide *down* another voltage gradient. Those two devices make a perfect pair: the battery provides electric power and the bulb consumes it. The bulb uses this power to heat its tungsten filament so hot that it glows yellow-white—but how does electricity heat the filament?

We'll consider a flashlight with two alkaline batteries (Fig. 10.3.9*a*). The bulb's filament is a fine wire, and its two ends are electrically connected to the battery chain's terminals. With one end at 3.0 V and the other at 0.0 V, the filament has a voltage gradient across it and therefore an electric field. How is that possible? While discussing copiers, we observed that a conductor has a uniform voltage throughout. Isn't the filament violating that rule?

No, it isn't. While a conductor has a uniform voltage *when its charges are in equilibrium*, the charges in the bulb are only in equilibrium when the flashlight is off. When you switch the flashlight on, you impose a 3.0-V difference between the two ends of the filament, and the filament's charges immediately begin accelerating down the voltage gradient toward the 0.0-V end.

In our voltage↔altitude analogy, it's as though you suddenly tilted a level field to create a hill, and water that was lying motionless on that field now accelerates downhill. However, a better analog to the individual charges that we're considering at the moment would be bicyclists: picture hundreds of bicyclists on a level field that suddenly tilts to form a hill. All the bicyclists that were at equilibrium on the level field now accelerate downhill.

If the filament were a perfect conductor of electricity, each charge would accelerate steadily down the voltage gradient and convert its electrostatic potential energy into kinetic energy. However, the filament has a large electrical resistance and significantly impedes the flow of electric current. Each charge bounces its way down the voltage gradient, colliding frequently with the filament's tungsten atoms and giving up kinetic energy with each collision (Fig. 10.3.9*b*). What began as ordered electrostatic potential energy in the charges becomes thermal energy in the tungsten atoms, and the filament glows brightly. Referring again to our voltage↔altitude analogy, picture the bicyclists riding down a rough hill strewn with rocks and trees (Fig. 10.3.9*c*). They pick up bruises instead of speed.

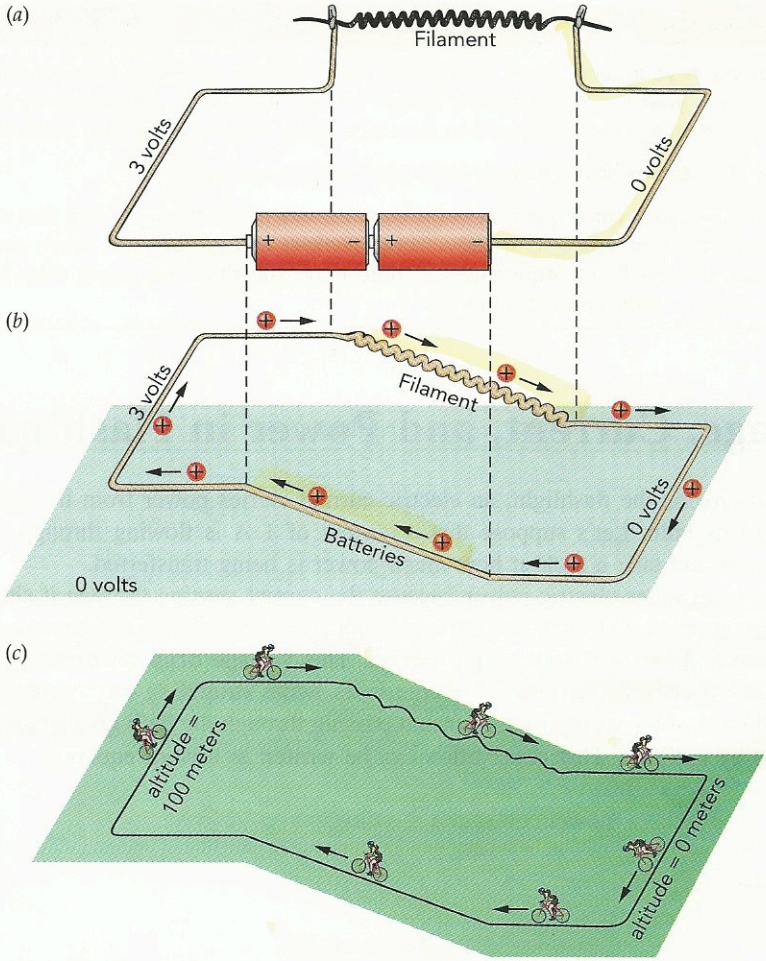


Fig. 10.3.9 (*a*) Current in a flashlight's circuit conveys power from the batteries and to the filament. (*b*) Its voltage rises in the batteries and decreases in the filament. Despite an electric field inside the filament that pushes the charges forward, they travel at constant velocity because of collisions. (*c*) This behavior is analogous to bicyclists pedaling up a smooth hill and then rolling down a rough one at constant velocity.

What about the metal strips connecting the flashlight's batteries and bulb? These thick conductors have small electrical resistances and carry current easily. Charges emerge from a strip with nearly as much electrostatic potential energy as they had when they entered it, so the voltages at the strip's ends are almost equal. In general, the less electrical resistance in the wires carrying current to and from the bulb, the less power is wasted en route and the more power reaches the bulb. That's why it's so important to use thick metal strips or even the flashlight's metal case in the connections.

A poor connection anywhere in the circuit can spoil this efficient transfer of power. If there is dirt or grease on a battery terminal or worn materials in the switch, the current will have to pass through a large electrical resistance and waste power. Improving that connection, either by shaking the flashlight or by cleaning the metal surfaces, will increase the current flow through the circuit, reduce the wasted power, and brighten the flashlight.

Check Your Understanding #4: You Get What You Pay For

The battery in your car is dead, so you use cheap jumper cables to connect the electric system in your car to the electric system in your friend's car. When you try to start your car, too little power reaches it to start its engine. What's wrong with those cables?

Answer: The cables have relatively large electrical resistances.

Why: Starting your car requires a huge current, and the wires supplying that current must not limit it or waste its energy. Cheap jumper cables have too much electrical resistance to fulfill those requirements. There is no substitute for good, thick jumper cables—they're worth the extra money.

Voltage, Current, and Power in Flashlights

When you turn on the flashlight, an electric current carries power from its two alkaline batteries to its bulb. Let's suppose that a current of 1 A is flowing through the flashlight's circuit and take a look at how much power is being transferred.

A bulb consumes electric power because the current passing through it slides down the voltage gradient and there is a drop in voltage between where the current arrives at the filament and where it leaves the filament. This **voltage drop** measures the electrostatic potential energy each unit of charge loses while struggling through the filament. Multiplying the voltage drop by the current passing through the bulb gives you the power consumed by the bulb. This observation can be written as a word equation:

$$\text{power consumed} = \text{voltage drop} \cdot \text{current}, \tag{10.3.1}$$

in symbols:

$$P = V \cdot I,$$

and in everyday language:

A large electric current dropping from high voltage to low voltage is like the torrent of water dropping from high to low over Niagara Falls: both release a lot of power.

Since the voltage drop across the bulb is 3.0 V and the current passing through it is 1.0 A, it's consuming 3.0 W of power.

A battery chain produces electric power because the current passing through it is pushed up a voltage gradient and there is a rise in voltage between where the current arrives at the battery chain and where it leaves the battery chain. This **voltage rise** measures the electrostatic potential energy each unit of charge gains while being pumped through the batteries. Multiplying the voltage gain by the current passing through the batteries gives you the power provided by the batteries. This observation can be written as a word equation:

$$\text{power provided} = \text{voltage rise} \cdot \text{current}, \tag{10.3.2}$$

in symbols:

$$P = V \cdot I,$$

and in everyday language:

Raising a large current from low voltage to high voltage is like pumping a huge stream of water from low to high to fight a fire at the top of a skyscraper: both require a lot of power.

Since the voltage rise across the chain is 3.0 V and the current passing through it is 1.0 A, it's providing 3.0 W of power.

Check Your Understanding #5: **Current Trends in Music**

A large battery powers your portable radio. Current enters the radio through one wire and leaves through another. Which wire has a higher voltage?

Answer: The wire through which current enters the radio.

Why: The radio is consuming power, so the current passing through it is experiencing a voltage drop. The current has a higher voltage when it enters the radio than when it leaves.

Check Your Figures #1: **When You Turn the Ignition Key**

When you first start your car, its cold engine is difficult to turn and a 200-A current flows through its starter motor. If there is a voltage drop of 12 V between where the current enters the starter and where it leaves the starter, how much power is being consumed?

Answer: 2400 W of power is being consumed.

Why: The voltage drop across the starter motor is 12 V (each coulomb of charge loses 12 J of energy in passing through it) and the current through it is 200 A (200 C of charge pass through it each second). We can use Eq. 10.3.1 to determine the power the motor is consuming:

$$\begin{aligned}\text{power consumed} &= \text{voltage drop} \cdot \text{current} \\ &= 12\,\text{V} \cdot 200\,\text{A} = 2400\,\text{W}.\end{aligned}$$

Check Your Figures #2: **When You Turn the Ignition Key Again**

When you restart the car, its warm engine is easier to turn, and a smaller current of 150 A flows through the car's starter motor. The battery is supplying power to this current, and there is a voltage rise of 12 V between where the current arrives at the battery and where it leaves the battery. How much power is the battery providing?

Answer: It is providing 1800 W of power.

Why: The voltage rise across the battery is 12 V (each coulomb of charge gains 12 J of energy in passing through it) and the current through it is 150 A (150 C of charge pass through it each second). We can use Eq. 10.3.2 to determine the power the battery is providing:

$$\begin{aligned}\text{power provided} &= \text{voltage rise} \cdot \text{current} \\ &= 12\,\text{V} \cdot 150\,\text{A} = 1800\,\text{W}.\end{aligned}$$

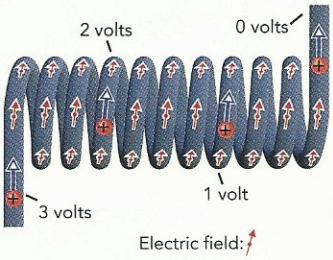


Fig. 10.3.10 This filament has a voltage drop of 3 V between its two ends. Charges moving through this filament are pushed forward by the resulting electric field. They maintain a constant speed despite frequent collisions with tungsten atoms.

Choosing the Bulb: Ohm's Law

Our flashlight's bulb is designed to operate properly with a voltage drop of 3.0 V. Subjected to that voltage drop, it will carry a current of 1 A and thus consume 3 W of electric power: just enough to make it glow properly. If you were to use the wrong bulb in this flashlight, one designed for a different voltage drop, its filament would carry the wrong amount of current and receive the wrong amount of power. Too much power would quickly burn out its filament, while too little power would make the filament glow dimly.

The bulb's filament must clearly match the flashlight, particularly the voltage of flashlight's battery chain. For example, flashlights that use many batteries require bulb filaments that are designed to operate with large voltage drops. Why is the current carried by a particular bulb filament related to the voltage drop across it, and why do different bulbs respond differently to a particular voltage drop?

The relationship between current and voltage drop is the result of collisions. Charges effectively stop each time they crash into tungsten atoms, so they need the push of an electric field to keep them moving forward (Fig. 10.3.10). Doubling that electric field doubles each charge's average speed and, because the number of mobile charges in the filament is fixed, also doubles the overall current flowing through the filament. Since the electric field that propels this current is the filament's voltage gradient, doubling the voltage drop through the filament doubles the current as well.

In our voltage–altitude analogy, picture bicyclists riding on extremely rocky terrain without pedaling. These lazy bicyclists effectively stop each time they crash into rocks, so they need the push of a slope to keep them moving forward. Doubling the slope's altitude gradient—the altitude drop per meter of downhill travel—doubles each bicyclist's average speed and, because the number of bicyclists who can fit on the hill at once is fixed, also doubles the overall current of bicyclists rolling down the hill. Since the slope that propels this bicyclist current is the hill's altitude gradient, doubling the hill height doubles the current of bicyclists as well.

The influence of filament choice on current flow reflects the different electrical resistances of those filaments. Anything that increases the number of mobile electric charges across the filament's width or allows those charges to maintain a higher average speed for a given voltage drop will decrease the filament's electrical resistance and increase the current flowing through it. In fact, electrical resistance is defined as the voltage drop through the filament divided by the current that arises as a result. Making the filament thicker or shorter will lower its resistance, as will changing its composition to make collisions less frequent.

Our voltage–altitude analogy with bicyclists on a hill is again helpful. Anything that increases the number of bicyclists across the hill's width or allows those bicyclists to maintain a higher average speed for a given hill height will decrease the hill's "bicycle resistance" and increase the current of bicyclists rolling down it. In fact, "bicycle resistance" is defined as the hill height divided by the current of bicyclists it produces. Making the hill wider or shorter will lower its bicycle resistance, as will changing its rockiness to make collisions less frequent.

Combining these observations, we see that the current flowing through the filament is proportional to the voltage drop through it and inversely proportional to the filament's electrical resistance, which can be written:

$$\text{current} = \frac{\text{voltage drop}}{\text{electrical resistance}}. \tag{10.3.3}$$

This relationship is called **Ohm's law**, after its discoverer Georg Simon Ohm ■. Structuring it this way separates the causes (voltage drop and electrical resistance) from their effect (current flow). However, this equation is often rearranged to eliminate the division. The relationship then takes its customary form, which can be written as a word equation:

$$\text{voltage drop} = \text{current} \cdot \text{electrical resistance}, \tag{10.3.4}$$

in symbols:

$$V = I \cdot R,$$

and in everyday language:

Long, skinny jumper cables have large resistances. When you connect them to a battery in order to jumpstart your car, they'll carry a relatively small current and your car probably won't start.

The SI unit of electrical resistance, the volt-per-ampere, is called the **ohm** (abbreviated Ω, the Greek letter omega). Despite its simplicity, Ohm's law is extremely useful in physics and electrical engineering. It applies to so many systems that nearly everything is **ohmic**—that is, can be characterized by an electrical resistance. Once an object's electrical resistance is known, the current flowing through it can be calculated from its voltage drop or its voltage drop can be calculated from the current flowing through it. Those few objects that don't obey Ohm's law, such as the diodes we'll examine in Chapter 12, are said to be non-ohmic.

■ German physicist Georg Simon Ohm (1787–1854) served as a professor of mathematics, first at the Jesuits' college of Cologne and then at the polytechnic school of Nuremberg. His numerous publications were undistinguished, with the exception of one pamphlet on the relationship between current and voltage. This extraordinary document, written in 1827, was initially dismissed by other physicists, even though it was based on good experimental evidence and explained many previous observations by others. In despair, Ohm resigned his position at Cologne, and it was not until the 1840s that his work was accepted. He was finally appointed professor of physics at Munich only two years before his death.

Ohm's Law

The voltage drop through a wire is equal to the current flowing through that wire times the wire's electrical resistance.

Finally, an object's electrical resistance is typically temperature-dependent. Rising temperature increases the number of mobile charges in an object but also makes them collide more frequently with the jiggling atoms. If the increasing collision frequency dominates, as it does in metals, an object's resistance increases with temperature. For example, a filament carries less and less current as it approaches operating temperature, a behavior that helps it avoid overheating. However, if the increase in mobile charges dominates, as it does in semiconductors, an object's resistance decreases with temperature. This explains why semiconductor-based computer chips carry more and more current as they get hotter and will self-destruct at excessive temperatures.

Check Your Understanding #6: Skin Protection

Your skin has a much larger electrical resistance than your tissues. If you touch the two terminals of a battery with your fingers, where is the larger voltage drop—in your skin or in your tissues?

Answer: The larger voltage drop is in your skin.

Why: The fluids in your body resemble salt water when exposed to voltages; they conduct current relatively well. If it weren't for your skin's large electrical resistance, even battery voltages would be capable of pushing large currents through you and might disrupt your heart and other functions. However, your skin's high resistance protects you from battery voltages. As long as your skin is dry and intact, it usually takes higher voltages to push enough current through you to cause injury.

Check Your Figures #3: Light Resistance

Two 3-W flashlight bulbs have different resistances: 3 Ω and 12 Ω. Which bulb is meant to operate from two 1.5-V alkaline batteries?

Answer: It's the 3-Ω bulb.

Why: Equation 10.3.3 indicates that, with the voltage drop of 3 V supplied by the two alkaline batteries, the 3-Ω bulb will carry:

$$\text{current} = \frac{\text{voltage drop}}{\text{electrical resistance}} = \frac{3\ \text{V}}{3\ \Omega} = 1\ \text{A}.$$

Equation 10.3.1 then shows that this bulb consumes the specified 3 W:

$$\text{power consumed} = \text{voltage drop} \cdot \text{current} = 3\text{V} \cdot 1\text{A} = 3\text{W}.$$

With a voltage drop of 3 V, the 12-Ω bulb will carry a current of 0.25 A and consume just 0.75 W of power. It needs a voltage drop of 6 V to consume 3 W.

Epilogue for Chapter 10

This chapter dealt with three venues in which charge and electricity play important roles. In *static electricity*, we introduced the concept of electric charge and discussed the attractive and repulsive forces that charged particles exert on one another. We studied the electrostatic potential energies stored in those charge forces and the relationship between this energy and the voltages of various locations. We learned how different objects acquire net charges through contact and how high voltages can be produced by separating large quantities of opposite charge.

In *xerographic copiers*, we studied electric fields and saw how those fields can be used to move charges from one place to another. We examined the corona discharges that form in the strong electric fields around sharp points or thin wires at high voltages. We also saw how placing a charge on one object can induce an opposite charge on a grounded object nearby.

In *flashlights*, we examined circuits to see how a current of electric charges can transfer power from batteries to a lightbulb. We found that both voltage and current contribute to this power transfer, and we learned how the bulb's electrical resistance governs the power it consumes.

Explanation: Moving Water without Touching It

This experiment uses contact between dissimilar materials to give the comb a net electric charge. Electrons shift from your hair to the comb, leaving your hair positively charged and the comb negatively charged. Because the comb is an electrical insulator, its negative charge remains trapped on its surface for a long time.

As you hold the negatively charged comb near the water stream, the comb attracts positive charges present in the water and repels negative charges. Because the water conducts electricity somewhat, positive charges can travel down the water stream from the faucet while negative charges travel the other way. The water thus acquires a net positive charge in the presence of the negatively charged comb, an example of charging by induction. Since the oppositely charged water and comb attract one another, the water accelerates toward the comb and arcs sideways as it falls.

Chapter Summary

How Static Electricity Works: When clothes tumble about in the dryer, contact between dissimilar materials transfers negatively charged electrons from one item to the other. As a result of this contact-charging effect, the various garments acquire net charges, some positive and others negative. When the clothes are subsequently separated, the work done in pulling them apart becomes electrostatic potential energy and the clothes develop high voltages. High voltages can also develop when you walk across a carpet or drive your car along the road. Since high voltage tends to push charges into the air as leaks and sparks, static charging can be a nuisance. You can control it with the help of conducting materials: allowing charge to move spontaneously from high voltage to low voltage prevents large quantities of separated charge from accumulating so that high voltages can't develop.

How Xerographic Copiers Work: The photoconductor in a xerographic copier allows light to control the distribution of electric charge on its surface. This photoconductor is uniformly precoated with charge by passing it near a corona discharge. An optical image of the original document is then projected onto this charged photoconductor. Wherever light hits the photoconductor, the surface charge escapes. The result is a charge image on the photoconductor. Tiny black toner particles, oppositely charged from the unilluminated portions of the photoconductor, are brought near the charge image. These toner particles stick to the charged portions of the photoconductor, forming a visible image of the document. The toner particles are then transferred to and fused onto a sheet of paper to create a finished copy.

How Flashlights Work: A flashlight produces light when a current flows through its electric circuit. This circuit consists of a chain of batteries, a lightbulb, a switch, and several metal strips, all connected in a continuous loop. The current obtains power as it passes through the battery, and it releases this power as it passes through the filament of the lightbulb, heating that filament white-hot.

The switch provides a way to control the flow of current in the circuit. When the switch is off, it breaks the circuit and prevents current from flowing completely around the circuit. Without a steady current to carry power from the batteries to the bulb, the bulb is dark. When the switch is on, it completes the circuit so that power can reach the bulb and the bulb lights up.

Important Laws and Equations

1. Coulomb's Law: The magnitudes of the electrostatic forces between two objects are equal to the Coulomb constant times the product of their two electric charges divided by the square of the distance separating them, or

$$\text{force} = \frac{\text{Coulomb constant} \cdot \text{charge}_1 \cdot \text{charge}_2}{(\text{distance between charges})^2}. \quad (10.1.1)$$

If the charges are like, then the forces are repulsive. If the charges are opposite, then the forces are attractive.

2. The Force Exerted on a Charge by an Electric Field: A charge experiences a force equal to the product of its charge times the electric field, or

$$\text{force} = \text{charge} \cdot \text{electric field}, \quad (10.2.1)$$

where the force points in the direction of the electric field.

3. The Electric Field Due to a Voltage Drop: A voltage drop produces an electric field equal to that voltage drop divided by the distance over which the drop occurs, or

$$\text{electric field} = \text{voltage gradient} = \frac{\text{voltage drop}}{\text{distance}}, \quad (10.2.2)$$

where the field points in the direction of the most rapid voltage decrease.

4. Power Consumption: The electric power consumed by a device is the voltage drop across it times the current flowing through it, or

$$\text{power consumed} = \text{voltage drop} \cdot \text{current}. \quad (10.3.1)$$

5. Power Production: The electric power provided by a device is the voltage rise across it times the current flowing through it, or

$$\text{power provided} = \text{voltage rise} \cdot \text{current}. \quad (10.3.2)$$

6. Ohm's Law: The voltage drop through an ohmic object is equal to the current flowing through it times its electrical resistance, or

$$\text{voltage drop} = \text{current} \cdot \text{electrical resistance}. \quad (10.3.4)$$

This equation does not apply to non-ohmic devices.

Exercises

1. If two objects repel one another, you know they have like charges on them. How would you determine whether these charges are both positive or negative?

2. You have an electrically neutral toy that you divide into two pieces. You notice that at least one of those pieces has an electric charge. Do the two pieces attract or repel one another, or neither?

3. Suppose that you had an electrically charged stick. If you divided the stick in half, each half would have half the original charge. If you split each of these halves, each piece would have a quarter of the original charge. Can you keep on dividing the charge in this manner forever? If not, why not?

4. A Ping-Pong ball contains an enormous number of electrically charged particles. Why don't two Ping-Pong balls normally exert electrostatic forces on each other?

5. In industrial settings, neutral metal objects are often coated by spraying them with electrically charged paint or powder particles. How does placing charge on the particles help them to stick to an object's surface?

6. The paint or powder particles discussed in Exercise 5 are all given the same electric charge. Why does this type of charging ensure that the coating will be highly uniform?

7. If the forces between electric charges didn't diminish with distance, an electrically charged balloon wouldn't cling to an electrically neutral wall. Why not?

8. An ion generator clears smoke from room air by electrically charging the smoke particles. Why will those charged smoke particles stick to the walls and furniture?

9. After you extract two pieces of adhesive tape from a tape dispenser, those pieces will repel one another. Explain their repulsion.

10. After you peel a sticker from its paper backing, the two attract one another. Explain their attraction.

11. You're holding two balloons, one covered with positive charge and one with negative charge. Compare their voltages.

12. You begin to separate the two balloons in Exercise 11. You do work on the balloons, so your energy decreases. Where does your energy go?

13. When you separate the balloons in Exercise 12, do their voltages change? If so, how do those voltages change?

14. A car battery is labeled as providing 12 V. Compare the electrostatic potential energy of positive charge on the battery's negative terminal with that on its positive terminal.

15. When technicians work with static-sensitive electronics, they try to make as much of their environment electrically conducting as possible. Why does this conductivity diminish the threat of static electricity?

16. Antistatic fabric treatments render the fabrics slightly conducting. How does this treatment help diminish static electricity?

17. Holding your hand on a static generator (e.g., a Van de Graff generator) can make your hair stand up, but only if you are standing on a good electrical insulator. Why is that insulator important?

18. In Exercise 17, having used a hair conditioner recently actually helps your hair stand up. Why?

19. The electric field around an electrically charged hairbrush diminishes with distance from that hairbrush. Use Coulomb's law to explain this decrease in the magnitude of the field.

20. Which way does the electric field point around the positive terminal of an alkaline battery?

21. Which has the stronger electric field between its two terminals: a 1.5-V AA battery or a standard 9-V battery? Explain.

22. You have 100 AA batteries. How should you connect those batteries to one another and then shape the resulting chain in order to make the strongest electric field?

23. It may seem dangerous to be in a car during a thunderstorm, but it's actually relatively safe. Since the car is essentially a metal box, the inside of the car is electrically neutral. Why does any charge on the car move to its outside surface?

24. Delicate electromagnetic experiments are sometimes performed inside metal walled or screened rooms. Why does that enclosure minimize stray electric fields?

25. When a positively charged cloud passes overhead during a thunderstorm, which way does the electric field point?

26. The cloud in Exercise 25 attracts a large negative charge to the top of a tree in an open meadow. Why is the magnitude of the electric field larger on top of this tree than elsewhere in the meadow?

27. Corona discharges can occur wherever there is a very strong electric field. Why is there a strong electric field around a sharp point on an electrically charged metal object?

28. To minimize corona discharges, electric power pylons sometimes shroud connectors and other sharp features with smoothly curving metal rings or shells. How do those broad, smooth structures prevent corona discharges?

29. If you're ever standing on a mountaintop when a dark cloud passes overhead and your hair stands up, get off the mountain fast. How would your hair have acquired the charge to make it stand up?

30. The power source for an electric fence pumps charge from the earth to the fence wire, which is insulated from the earth. The earth can conduct electricity. When an animal walks into the wire, it receives a shock. Identify the circuit through which the current flows.

31. A bird can perch on a high-voltage power line without getting a shock. Why doesn't current flow through the bird?

32. The two prongs of a power cord are meant to carry current to and from a lamp. If you were to plug only one of the prongs into an outlet, the lamp wouldn't light at all. Why wouldn't it at least glow at half its normal brightness?

33. The rear defroster of your car is a pattern of thin metal strips across the window. When you turn the defroster on, current flows through those metal strips. Why are there wires attached to both ends of the metal strips?

34. If you touch only one of the metal contacts on a headphone plug to the headphone jack of a portable audio player, what volume will the headphones produce?

35. If you transfer some (positive) charge to a battery's negative terminal, some of that charge will quickly move to the battery's positive terminal. Will the battery's store of chemical potential energy have changed and, if so, will it have increased or decreased?

36. If you transfer some positive charge to a battery's positive terminal, some of that charge will quickly move to the battery's negative terminal. Will the battery's store of chemical potential energy have changed and, if so, will it have increased or decreased?

37. When you plug a portable appliance into the power socket inside an automobile, current flows to the appliance through the central pin of that socket and returns to the car through the socket's outer ring. Which of the socket's contacts has the higher voltage?

38. When current is flowing through a car's rear defroster (Exercise 33), the voltage at each end of the metal strips is different. Which end of each strip has the higher voltage—the one through which current enters the strip or the one through which current leaves—and what causes the voltage drop?

39. You're given a sealed box with two terminals on it. You use some wires and batteries to send an electric current into the box's left terminal and find that this current emerges from the right terminal. If the voltage of the right terminal is 6 V higher than that of the left terminal, is the box consuming power or providing it? Is it more likely to contain batteries or lightbulbs? How can you tell?

40. One time-honored but slightly unpleasant way in which a hobbyist determines how much energy is left in a 9-V battery is to touch both of its terminals to his tongue briefly. He experiences a pinching feeling that's mild when the battery is almost dead but one that's startlingly sharp when the battery is fresh. (Don't try this technique yourself.) What is the circuit involved in this "taste test"? How is energy being transferred?

41. Spot welding is used to fuse two sheets of metal together at one small spot. Two copper electrodes pinch the sheets together at a point and then run a huge electric current through that point. The two sheets melt and flow together to form a spot weld. Why does this technique work only with relatively poor conductors of electricity such as stainless steel and not with excellent conductors such as copper?

42. Why is it important that the filament of a lightbulb have a much larger electrical resistance than the supporting wires that carry current to and from that filament?

Problems

1. You remove two socks from a hot dryer and find that they repel with forces of 0.001 N when they're 1 cm apart. If they have equal charges, how much charge does each sock have?

2. If you separate the socks in Problem 1 until they're 5 cm apart, what force will each sock exert on the other?

3. If you were to separate all of the electrons and protons in 1 g (0.001 kg) of matter, you'd have about 96,000 C of positive charge and the same amount of negative charge. If you placed these charges 1 m apart, how strong would the attractive forces between them be?

4. If you placed 1 C of positive charge on the earth and 1 C of negative charge 384,500 km away on the moon, how much force would the positive charge on the earth experience?

5. How close would you have to bring 1 C of positive charge and 1 C of negative charge for them to exert forces of 1 N on one another?

6. The upward net force on the space shuttle at launch is 10,000,000 N. What is the least amount of charge you could move from its nose to the launch pad, 60 m below, and thereby prevent it from lifting off?

7. What force will a 0.01-C charge experience in a 5-N/C electric field pointing upward?

8. A sock with a charge of -0.0005 C is in a 1000-N/C electric field pointing toward the right. What force does the sock experience?

9. A piece of plastic wrap with a charge of 0.00005 C experiences a forward force of 0.0010 N. What is the local electric field?

10. A Styrofoam ball with a charge of -1.0×10^{-6} C experiences an upward force of 0.01 N in an electric field. What is that electric field?