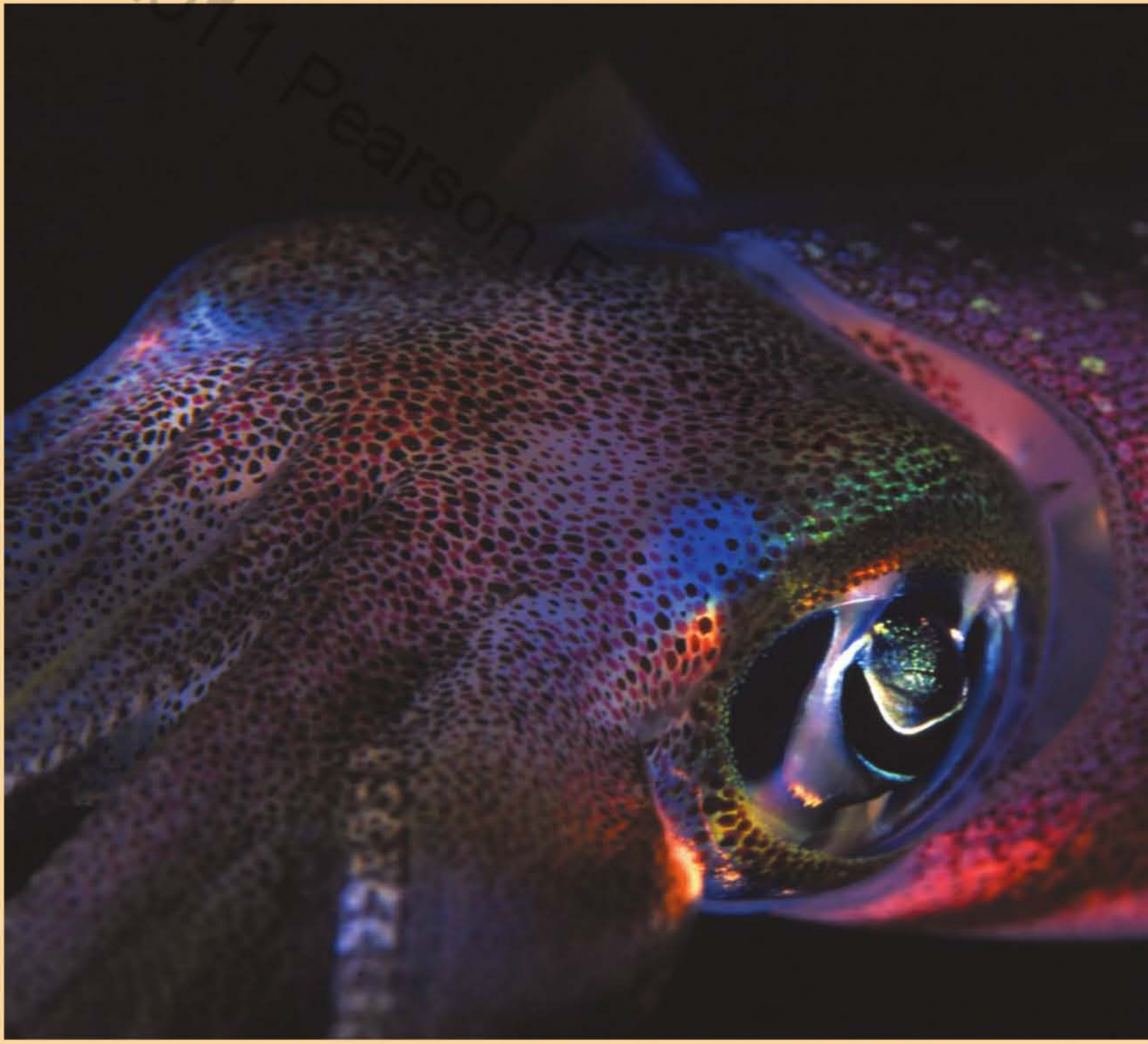
PART VI

Electricity and Magnetism



Much of what is known about your nervous system comes from the study of an animal that seems quite different from humans—the squid. Nerve fibers conduct electrical signals along their length, allowing the brain to direct the actions of the body. How is an electrical signal generated and transmitted in the nervous system of a human or a squid?

Charges, Currents, and Fields

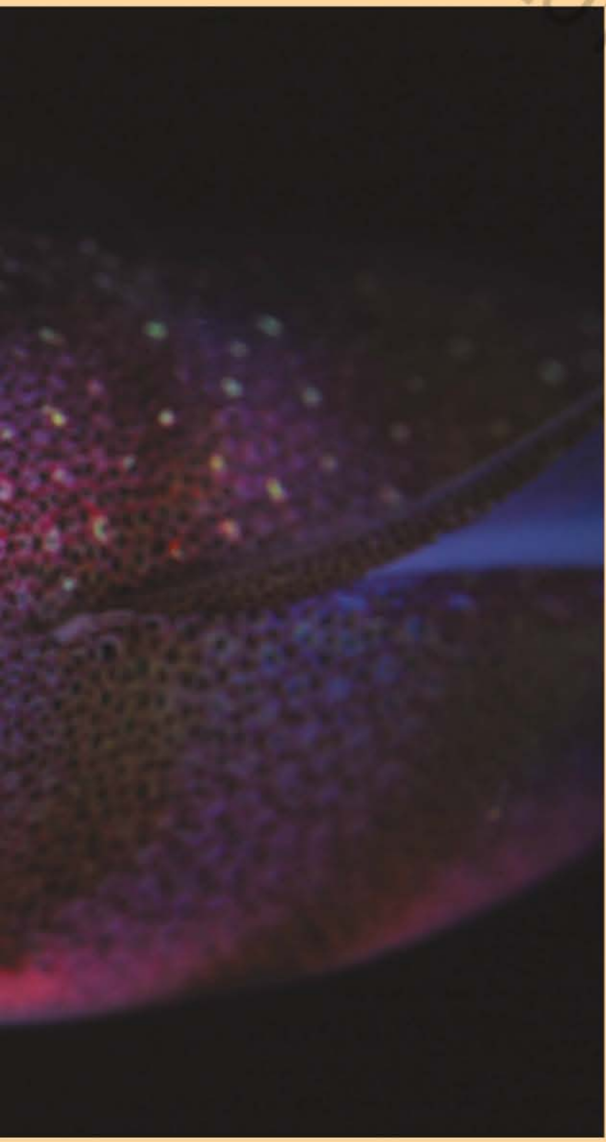
The early Greeks discovered that a piece of amber that has been rubbed briskly can attract feathers or small pieces of straw. They also found that certain stones from the region they called *Magnesia* can pick up pieces of iron. These first experiences with the forces of electricity and magnetism began a chain of investigations that has led to today's high-speed computers, lasers, fiber-optic communications, and magnetic resonance imaging, as well as mundane modern-day miracles such as the lightbulb.

The development of a successful electromagnetic theory, which occupied the leading physicists of Europe for most of the nineteenth century, led to sweeping revolutions in both science and technology. The complete formulation of the theory of the electromagnetic field has been called by no less than Einstein "the most important event in physics since Newton's time."

The basic phenomena of electricity and magnetism are not as familiar to most people as those of mechanics. We will deal with this lack of experience by placing a large emphasis on these basic phenomena. We will begin where the Greeks did, by looking at the forces between objects that have been briskly rubbed, exploring the concept of *electric charge.* It is easy to make systematic observations of how charges behave, and we will be led to consider the forces between charges and how charges behave in different materials. *Electric current,* whether it be for lighting a lightbulb or changing the state of a computer memory element, is simply a controlled motion of charges through conducting materials. One of our goals will be to understand how charges move through electric circuits.

When we turn to magnetic behavior, we will again start where the Greeks did, noting how magnets stick to some metals. Magnets also affect compass needles. And, as we will see, an electric current can affect a compass needle in exactly the same way as a magnet. This observation shows the close connection between electricity and magnetism, which leads us to the phenomenon of *electromagnetic waves.*

Our theory of electricity and magnetism will introduce the entirely new concept of a *field.* Electricity and magnetism are about the long-range interactions of charges, both static charges and moving charges, and the field concept will help us understand how these interactions take place.



Microscopic Models

The field theory provides a macroscopic perspective on the phenomena of electricity and magnetism, but we can also take a microscopic view. At the microscopic level, we want to know what charges are, how they are related to atoms and molecules, and how they move through various kinds of materials. Electromagnetic waves are composed of electric and magnetic fields. The interaction of electromagnetic waves with matter can be analyzed in terms of the interactions of these fields with the charges in matter. When you heat food in a microwave oven, you are using the interactions of electric and magnetic fields with charges in a very fundamental way.

20 Electric Fields and Forces

DNA analysis is often done using gel electrophoresis. A solution of DNA segments is placed in a well at one end of a plate of gel. Different segments migrate through the gel at different rates, leading to the lines in the photo. What force causes the DNA segments to move through the gel?

LOOKING AHEAD ▸▸

The goal of Chapter 20 is to develop a basic understanding of electric phenomena in terms of charges, forces, and fields.

Charges and Forces

We'll find that basic electric phenomena can be understood in terms of a **charge model** of electricity:

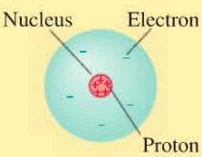
- There are two kinds of charge, called "positive" and "negative" charge.
- There is an attractive force between charges of opposite kind, a repulsive force between charges of the same kind.

When you brush your hair, why do the strands fly away from each other?

Why will a pencil rubbed through your hair pick up small pieces of paper?

Charges, Atoms, and Molecules

To understand charging processes, we'll need to review our contemporary understanding of the atomic nature of matter.



You'll learn that electrons and protons are the basic charges of ordinary matter.

The process of charging an object by rubbing can be understood as a *transfer* of electrons from one material to another.

Coulomb's Law

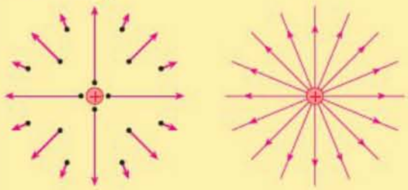
The attractive and repulsive forces between two charged particles can be calculated from **Coulomb's law**.

Coulomb's law tells us how the force between charges depends on their charge and the distance between them.

Looking Back ◂◂
3.1–3.3 Vectors and components
6.6 Newton's law of gravity

The Electric Field

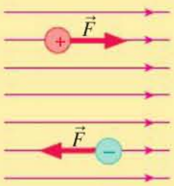
Every charge alters the space around it, creating an **electric field** at every point. This electric field then exerts a force on other charges.



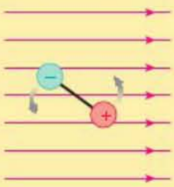
You'll learn how to represent the electric field using **field diagrams** and **field lines.**

Forces and Torques in Electric Fields

Charges in an electric field experience forces and torques due to the field.

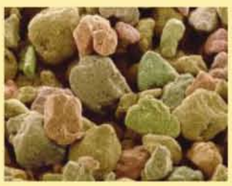


The force on a positive charge is in the same direction as the field; the force on a negative charge is opposite the field.



Two equal but opposite charges form an **electric dipole.** A dipole in an electric field experiences a *torque*.

Strong electric fields are used to remove charged particulates from this power plant's emissions.



In a laser printer, toner particles like these (shown magnified 500×) stick to the paper by electric forces.

Looking Back ◂◂
7.2 Torque

20.1 Charges and Forces

You can receive a mildly unpleasant shock and produce a little spark if you touch a metal doorknob after scuffing your shoes across a carpet. A plastic comb that you've run through your hair will pick up bits of paper and other small objects. In both of these cases, two objects are *rubbed* together. Why should rubbing an object cause forces and sparks? What kind of forces are these? These are the questions with which we begin our study of electricity.

Our first goal is to develop a model for understanding electric phenomena in terms of *charges* and *forces*. We will later use our contemporary knowledge of atoms to understand electricity on a microscopic level, but the basic concepts of electricity make *no* reference to atoms or electrons. The theory of electricity was well established long before the electron was discovered.

The ancient Greeks first noted the electrical nature of matter by observing amber, a form of fossilized tree resin. When rubbed with fur, amber buttons would attract bits of feather, hair, or straw. The Greek word for amber, "elektron," is the source of our words "electric," "electricity," and—of course—"electron."

Experimenting with Charges

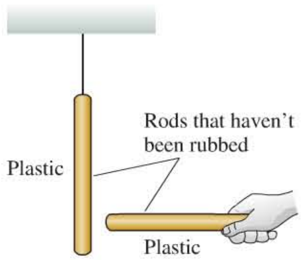
Let us enter a laboratory where we can make observations of electric phenomena. This is a modest laboratory, much like one you would have found in the year 1800. The major tools in the lab are:

- A variety of plastic, glass, and wood rods, each several inches long. These can be held in your hand or suspended by threads from a support.
- A few metal rods with wood handles.
- Pieces of wool and silk.
- Small metal spheres, an inch or two in diameter, on wood stands.

We will manipulate and use these tools with the goal of developing a theory to explain the phenomena we see. The experiments and observations described below are very much like those of early investigators of electric phenomena.

Discovering electricity I

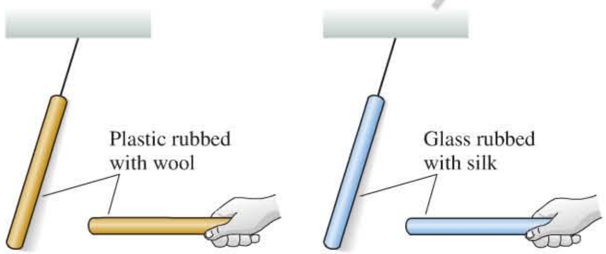
Experiment 1



Take a plastic rod that has been undisturbed for a long period of time and hang it by a thread. Pick up another undisturbed plastic rod and bring it close to the hanging rod. Nothing happens to either rod.

Interpretation: There are no special electrical properties to these undisturbed rods. We say that they are **neutral**.

Experiment 2



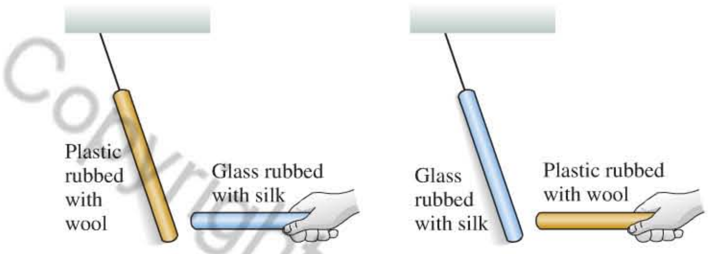
Vigorously rub both the hanging plastic rod and the handheld plastic rod with wool. Now the hanging rod *moves away* from the handheld rod when you bring the two close together. Rubbing two glass rods with silk produces the same result: The two rods repel each other.

Interpretation: Rubbing a rod somehow changes its properties so that forces now act between two such rods. We call this process of rubbing **charging** and say that the rubbed rod is *charged*, or that it has *acquired a* ***charge.***

Experiment 2 shows that there is a *long-range repulsive force* (i.e., a force requiring no contact) between two identical objects that have been charged in the *same* way, such as two plastic rods both rubbed with wool or two glass rods rubbed with silk. The force between charged objects is called the **electric force.** We have seen a long-range force before, gravity, but the gravitational force is always attractive. This is the first time we've observed a repulsive long-range force. However, the electric force is not always repulsive, as the next experiment shows.

Discovering electricity II

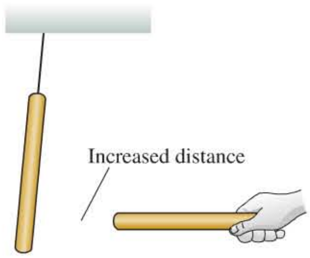
Experiment 3



Bring a glass rod that has been rubbed with silk close to a hanging plastic rod that has been rubbed with wool. These two rods *attract* each other.

Interpretation: We can explain this experiment as well as Experiment 2 by assuming that there are two *different* kinds of charge that a material can acquire. We *define* the kind of charge acquired by a glass rod as *positive* charge, and that acquired by a plastic rod as *negative* charge. Then these two experiments can be summarized as **like charges** (positive/positive or negative/negative) exert repulsive forces on each other, while **opposite charges** (positive/negative) exert attractive forces on each other.

Experiment 4



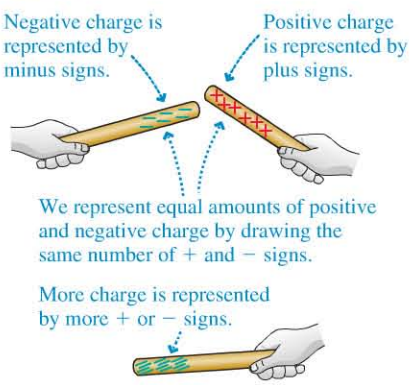
- If the two rods are held farther from each other, the force between them decreases.
- The strength of the force is greater for rods that have been rubbed more vigorously.

Interpretation: Like the gravitational force, the electric force decreases with the distance between the charged objects. And, the greater the charge on the two objects, the greater the force between them.

Although we showed experimental results only for plastic rods rubbed with wool and glass rods rubbed with silk, further experiments show that there are *only* two kinds of charge, positive and negative. For instance, when you rub a balloon on your hair the balloon becomes negatively charged, while nylon rubbed with a polyester cloth becomes positively charged.

Visualizing Charge

FIGURE 20.1 Visualizing charge.



Diagrams are going to be an important tool for understanding and explaining charges and the forces between charged objects. FIGURE 20.1 shows how to draw a *charge diagram,* which gives a schematic picture of the distribution of charge on an object. It's important to realize that the + and − signs drawn in Figure 20.1 do not represent "individual" charges. At this point, we are thinking of charge only as something that can be acquired by an object by rubbing, so in charge diagrams the + and − signs represent where the charge is only in a general way. In Section 20.2 we'll look at an atomic view of charging and learn about the single microscopic charges of protons and electrons.

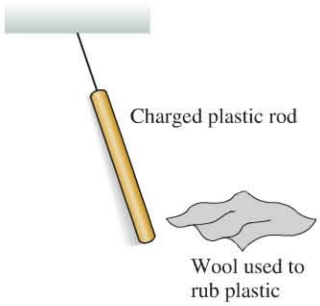
We can gain an important insight into the nature of charge by investigating what happens when we bring together a plastic rod and the wool used to charge it, as the following experiment shows.

Discovering electricity III

Experiment 5

Start with a neutral, uncharged hanging plastic rod and a piece of wool. Rub the plastic rod with the wool, then hold the wool close to the rod. The rod is *attracted* to the wool.

Interpretation: From Experiment 3 we know that the plastic rod has a negative charge. Because the wool attracts the rod, the wool must have a *positive* charge.



Experiment 5 shows that when a plastic rod is rubbed by wool, not only does the plastic rod acquire a negative charge, but also the wool used to rub it acquires a positive charge. This observation can be explained if we postulate that a neutral object is not one that has no charge at all; rather, **a neutral object contains *equal amounts* of positive and negative charge.** Just as in ordinary addition, where $2 + (-2) = 0$, equal amounts of opposite charge "cancel," leaving no overall or *net* charge.

In this model, an object becomes positively charged if the amount of positive charge on it exceeds the amount of negative charge; the mathematical analogy of this is $2 + (-1) = +1$. Similarly, an object is negatively charged when the amount of negative charge on it is greater than the amount of positive charge, analogous to $2 + (-3) = -1$.

As FIGURE 20.2 shows, the rubbing process works by *transferring* charge from one object to the other. When the two are rubbed together, negative charge is transferred from the wool to the rod. This clearly leaves the rod with an excess of negative charge. But the wool, having lost some of its negative charge to the rod, now has an *excess* of positive charge, leaving it positively charged. (We'll see in Section 20.2 why it is usually negative charge that moves.)

FIGURE 20.2 How a plastic rod and wool acquire charge during the rubbing process.

1. The rod and wool are initially neutral.
2. "Neutral" actually means that they each have equal amounts of positive and negative charge.
3. Now we rub the plastic and wool together. As we do so, negative charge moves from the wool to the rod.
4. This leaves the rod with extra negative charge. The wool is left with more positive charge than negative.
5. In a charge diagram, we draw only the *excess* charge. This shows how the rod and wool acquire their charge.

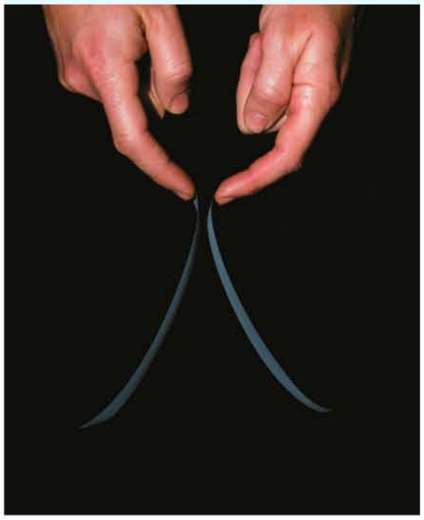
There is another crucial fact about charge implicit in Figure 20.2: Nowhere in the rubbing process was charge either created or destroyed. Charge was merely transferred from one place to another. It turns out that this fact is a fundamental law of nature, the **law of conservation of charge.** If a certain amount of positive charge appears somewhere, an equal amount of negative charge must appear elsewhere so that the net charge doesn't change.

The results of our experiments, and our interpretation of them in terms of positive and negative charge, can be summarized in the following **charge model.**

Charge model, part I The basic postulates of our model are:

1. Frictional forces, such as rubbing, add something called *charge* to an object or remove it from the object. The process itself is called *charging*. More vigorous rubbing produces a larger quantity of charge.
2. There are two kinds of charge, positive and negative.
3. Two objects with *like charge* (positive/positive or negative/negative) exert repulsive forces on each other. Two objects with *opposite charge* (positive/negative) exert attractive forces on each other. We call these *electric forces*.
4. The force between two charged objects is a long-range force. The magnitude of the force increases as the quantity of charge increases and decreases as the distance between the charges increases.
5. *Neutral* objects have an *equal mixture* of positive and negative charge.
6. The rubbing process charges the objects by *transferring* charge (usually negative) from one to the other. The objects acquire equal but opposite charges.
7. Charge is conserved: It cannot be created or destroyed.

TRY IT YOURSELF



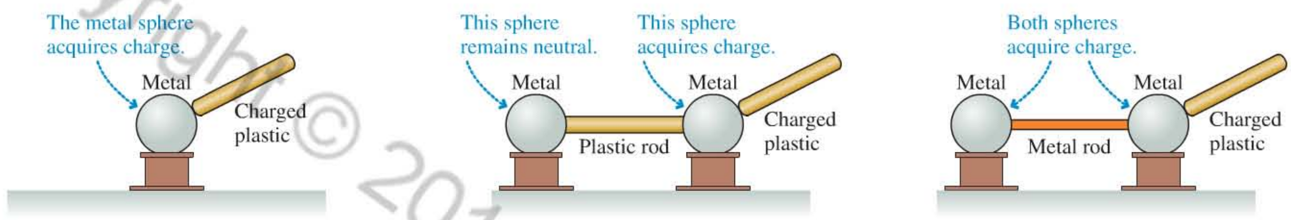
Charges on tape Pull a piece of transparent tape about 6″ long off a roll. Now, pull a second piece of tape off the roll, and hold the two pieces near each other. They show a strong repulsive force. What does this tell you about the charges on the two pieces of tape? How could you prepare the two strips of tape so that they attract?

Insulators and Conductors

Experiments 2, 3, and 5 involved a transfer of charge from one object to another. Let's do some more experiments with charge to look at how charge *moves* on different materials.

Discovering electricity IV

Experiment 6 | Experiment 7 | Experiment 8



Experiment 6: Charge a plastic rod by rubbing it with wool. Touch a neutral metal sphere with the rubbed area of the rod. The metal sphere then repels a charged, hanging plastic rod. The metal sphere appears to have acquired a charge of the same sign as the plastic rod.

Experiment 7: Place two metal spheres close together with a plastic rod connecting them. Charge a second plastic rod, by rubbing, and touch it to one of the metal spheres. Afterward, the metal sphere that was touched repels a charged, hanging plastic rod. The other metal sphere does not.

Experiment 8: Repeat Experiment 7 with a metal rod connecting the two metal spheres. Touch one metal sphere with a charged plastic rod. Afterward, *both* metal spheres repel a charged, hanging plastic rod.

Our final set of experiments has shown that charge can be transferred from one object to another only when the objects *touch*. Contact is required. Removing charge from an object, which you can do by touching it, is called **discharging**.

In Experiments 7 and 8, charge is transferred from the charged rod to the metal sphere as the two are touched together. In Experiment 7, the other sphere remains neutral, indicating that no charge moved along the plastic rod connecting the two spheres. In Experiment 8, by contrast, the other sphere is found to be charged; evidently charge has moved along the metal rod connecting the spheres, transferring some charge from the first sphere to the second. We define **conductors** as those materials through or along which charge easily moves and **insulators** as those materials on or in which charges remain immobile. Glass and plastic are insulators; metal is a conductor.

This new information allows us to add more postulates to our charge model:

Charge model, part II

8. There are two types of materials. Conductors are materials through or along which charge easily moves. Insulators are materials on or in which charges remain fixed in place.
9. Charge can be transferred from one object to another by contact.

NOTE ► Both insulators and conductors can be charged. They differ in the ability of charge to *move*. ◄

◄ A dry day, a plastic slide, and a child with clothes of the right fabric lead to a startling demonstration of electric charges and forces. The rubbing of the child's clothes on the slide has made her build up charge. The body is a good conductor, so the charges spread across her body and her hair. The resulting repulsion produces a dramatic result!

CONCEPTUAL EXAMPLE 20.1 Transferring charge

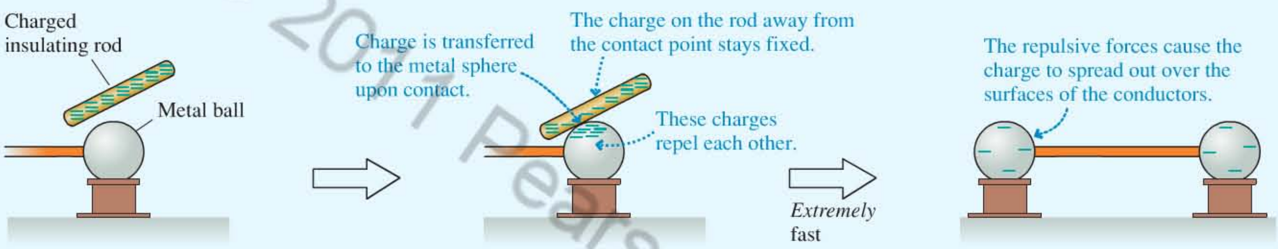
In Experiment 8, touching a metal sphere with a charged plastic rod caused a second metal sphere, connected by a metal rod to the first, to become charged with the same type of charge as the rod. Use the postulates of the charge model to construct a charge diagram for the process.

REASON We need the following ideas from the charge model:

1. **Charge is transferred upon contact.** The plastic rod was charged by rubbing with wool, giving it a negative charge. The charge doesn't move around on the rod, an insulator, but some of the charge is transferred to the metal upon contact.
2. **Metal is a conductor.** Once in the metal, which is a conductor, the charges are free to move around.
3. **Like charges repel.** Because like charges repel, these negative charges quickly move as far apart as they possibly can. Some move through the connecting metal rod to the second sphere. Consequently, the second sphere acquires a net negative charge. The repulsive forces drive the negative charges as far apart as they can possibly get, causing them to end up on the *surfaces* of the conductors.

The charge diagram in FIGURE 20.3 illustrates these three steps.

FIGURE 20.3 A charge diagram for Experiment 8.



In Conceptual Example 20.1, once the charge is placed on the conductor it rapidly distributes itself over the conductor's surface. This movement of charge is *extremely* fast. Other than this very brief interval during which the charges are adjusting, the charges on an isolated conductor are in static equilibrium with the charges at rest. This condition is called **electrostatic equilibrium**.

CONCEPTUAL EXAMPLE 20.2 Drawing a charge diagram for an electroscope

Many electricity demonstrations are carried out with the help of an *electroscope* like the one shown in FIGURE 20.4. Touching the sphere at the top of an electroscope with a charged plastic rod causes the leaves to fly apart and remain hanging at an angle. Use charge diagrams to explain why.

REASON We will use the charge model and our understanding of insulators and conductors to make a series of charge diagrams in FIGURE 20.5 that shows the charging of the electroscope.

ASSESS The charges move around, but, because charge is conserved, the total number of negative charges doesn't change from picture to picture.

FIGURE 20.4 A charged electroscope.

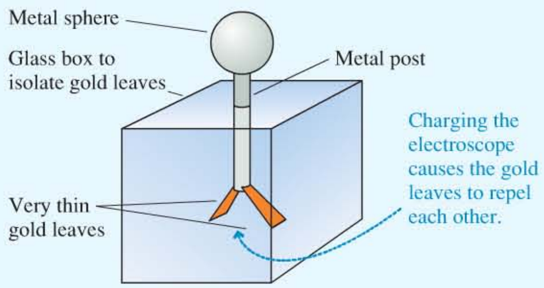
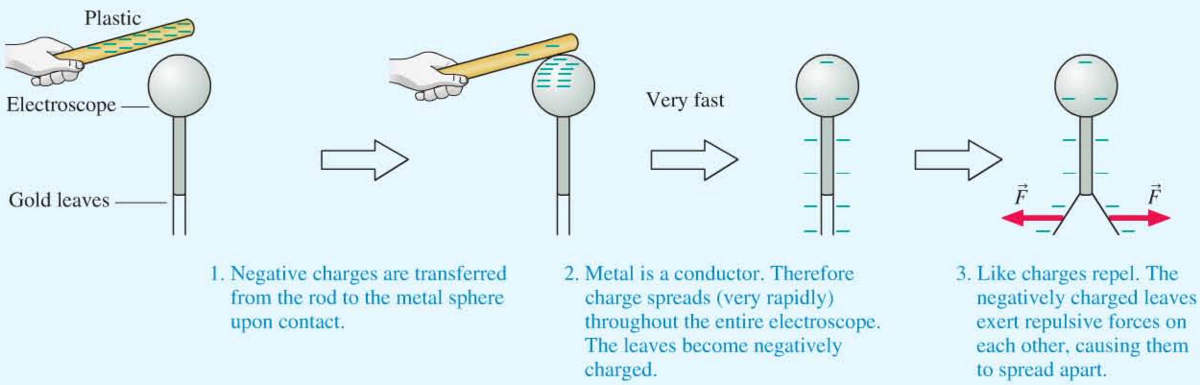
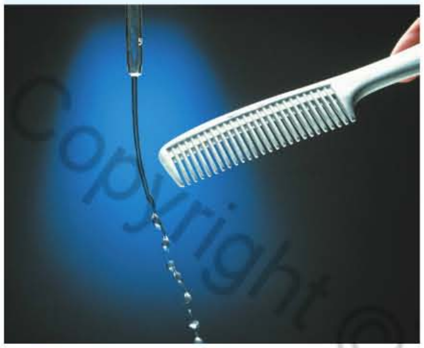


FIGURE 20.5 Charging an electroscope.



TRY IT YOURSELF



Pulling water Turn on your tap so that a thin stream of water flows. Next, run a comb briskly through your hair, and bring the comb close to—but not touching—the stream of water. The deflection of the stream can be quite dramatic! Water from the tap is a reasonably good conductor. The presence of the charged comb separates charges in the water stream, leading to an attractive polarization force.

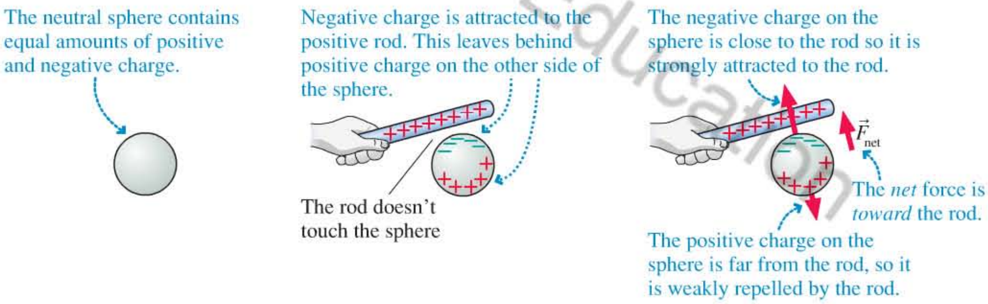
Polarization

At the beginning of this chapter we showed a picture of a small feather being picked up by a piece of amber that had been rubbed with fur. The amber was charged by rubbing, but the feather had not been rubbed—it was *neutral.* How can our charge model explain the attraction of a neutral object toward a charged one?

Although a feather is an insulator, it's easiest to understand this phenomenon by first considering how a neutral *conductor* is attracted to a charged object. **FIGURE 20.6** shows how this works. Because the charged rod doesn't touch the sphere, no charge is added to or removed from the sphere. Instead, the rod attracts some of the sphere's negative charge to the side of the sphere near the rod. This leaves a deficit of negative charge on the opposite side of the sphere, so that side is now positively charged. This slight *separation* of the positive and negative charge in a neutral object when a charged object is brought near is called **charge polarization.**

Figure 20.6 also shows that, because the negative charges at the top of the sphere are more strongly attracted to the rod than the more distant positive charges on the sphere are repelled, there is a net *attractive* force between the rod and the sphere. This **polarization force** arises because the charges in the metal are slightly separated, *not* because the rod and metal are oppositely charged. Had the rod been *negatively* charged, positive charge would move to the upper side of the sphere and negative charge to the bottom. This would again lead to an *attractive* force between the rod and the sphere. **The polarization force between a charged object and a neutral one is always attractive.**

FIGURE 20.6 Why a neutral metal object is attracted to a charged object.



Picking up pollen BIO Rubbing a rod with a cloth gives the rod an electric charge. In a similar fashion, the rapid motion of a bee's wings through the air gives the bee a small positive electric charge. As small pieces of paper are attracted to a charged rod, so are tiny grains of pollen attracted to the charged bee, helping it collect and hold the pollen.

Polarization explains why forces arise between a charged object and a metal object along which charge can freely move. But the feathers attracted to amber are insulators, and charge can't move through an insulator. Nevertheless, the attractive force between a charged object and an insulator is also a polarization force. As we'll learn in the next section, the charge in each *atom* that makes up an insulator can be slightly polarized. Although the charge separation in one atom is exceedingly small, the net effect over all the countless atoms in an insulator is to shift a perceptible amount of charge from one side of the insulator to the other. This is just what's needed to allow a polarization force to arise.

STOP TO THINK 20.1 An electroscope is charged by touching it with a positive glass rod. The electroscope leaves spread apart and the glass rod is removed. Then a negatively charged plastic rod is brought close to the top of the electroscope, but it doesn't touch. What happens to the leaves?

A. The leaves get closer together.
B. The leaves spread farther apart.
C. The leaves do not change their position.

20.2 Charges, Atoms, and Molecules

We have been speaking about giving objects positive or negative charge without explaining what is happening at an atomic level. You already know that the basic constituents of atoms—the nucleus and the electrons surrounding it—are charged. In this section we will connect our observations of the previous section with our understanding of the atomic nature of matter.

Our current model of the atom is that it is made up of a very small and dense positively charged *nucleus,* containing positively charged *protons* as well as neutral particles called *neutrons,* surrounded by much-less-massive orbiting negatively charged *electrons* that form an **electron cloud** surrounding the nucleus, as illustrated in FIGURE 20.7. The atom is held together by the attractive electric force between the positive nucleus and the negative electrons.

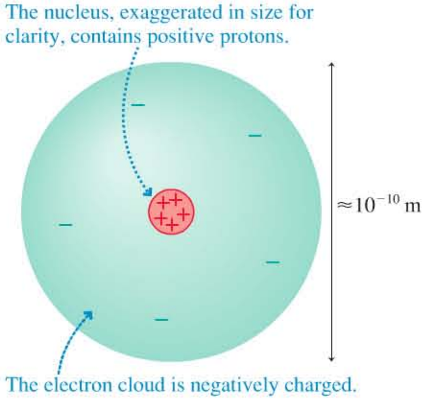


FIGURE 20.7 Our modern view of the atom.

Experiments show that **charge, like mass, is an inherent property of electrons and protons.** It's no more possible to have an electron without charge than it is to have an electron without mass.

An Atomic View of Charging

Electrons and protons are the basic charges in ordinary matter. **There are no other sources of charge.** Consequently, the various observations we made in Section 20.1 need to be explained in terms of electrons and protons.

Experimentally, it's found that electrons and protons have charges of opposite sign but *exactly* equal magnitude. Thus, because charge is due to electrons and protons, **an object is charged if it has an unequal number of electrons and protons.** An object with a negative charge has more electrons than protons; an object with a positive charge has more protons than electrons. Most macroscopic objects have an *equal number* of protons and electrons. Such an object has no *net* charge; we say it is *electrically neutral.*

In practice, objects acquire a positive charge not by gaining protons but by losing electrons. Protons are *extremely* tightly bound within the nucleus and cannot be added to or removed from atoms. Electrons, on the other hand, are bound much more loosely than the protons and can be removed with little effort.

The process of removing an electron from the electron cloud of an atom is called **ionization**. An atom that is missing an electron is called a *positive ion.* Some atoms can accommodate an *extra* electron and thus become a *negative ion.* FIGURE 20.8 shows positive and negative ions.

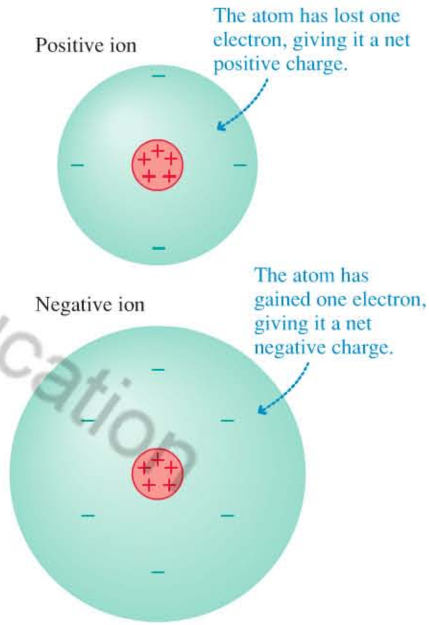
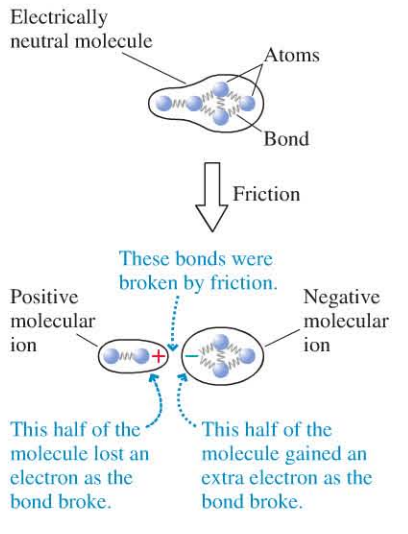


FIGURE 20.8 Positive and negative ions.

The charging processes we observed in Section 20.1 involved rubbing and friction. The forces of friction often cause molecular bonds at the surface to break as two materials slide past each other. Molecules are electrically neutral, but FIGURE 20.9 shows that *molecular ions* can be created when one of the bonds in a large molecule is broken. If the positive molecular ions remain on one material and the negative ions on the other, one of the objects being rubbed ends up with a net positive charge and the other with a net negative charge. This is the way in which a plastic rod is charged by rubbing with wool or a comb is charged by passing through your hair.

FIGURE 20.9 Charging by friction may result from molecular ions produced as bonds are broken.



Charge Conservation

Charge is represented by the symbol q (or sometimes Q). The SI unit of charge is the **coulomb** (C), named for French scientist Charles Coulomb, one of many scientists investigating electricity in the late 18th century.

Protons and electrons, the charged particles in ordinary matter, have the same amount of charge, but of opposite signs. We use the symbol e for the **fundamental charge,** the magnitude of the charge of an electron or a proton. The fundamental charge e has been measured to have the value

$$e = 1.60 \times 10^{-19}\ \mathrm{C}$$

TABLE 20.1 Protons and electrons

Particle	Mass (kg)	Charge (C)
Proton	1.67×10^{-27}	$+e = 1.60 \times 10^{-19}$
Electron	9.11×10^{-31}	$-e = -1.60 \times 10^{-19}$

Table 20.1 lists the masses and charges of protons and electrons.

NOTE ▶ The amount of charge produced by rubbing plastic or glass rods is typically in the range 1 nC (10^{-9} C) to 100 nC (10^{-7} C). This corresponds to an excess or deficit of 10^{10} to 10^{12} electrons. But, because of the enormous number of atoms in a macroscopic object, this represents an excess or deficit of only perhaps 1 electron in 10^{13}. ◀

That charge is associated with electrons and protons explains why charge is conserved. Because electrons and protons are neither created nor destroyed in ordinary processes, their associated charge is conserved as well.

Insulators and Conductors

FIGURE 20.10 A microscopic look at insulators and conductors.

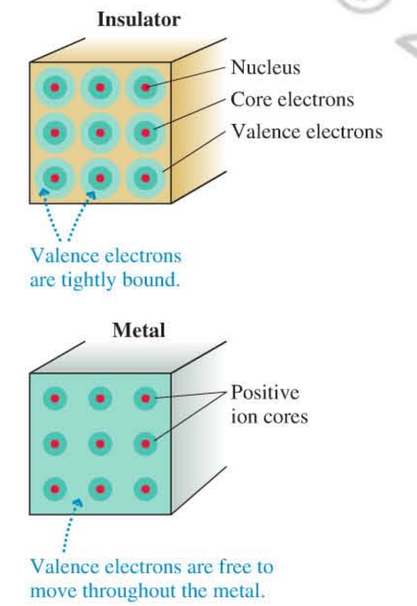
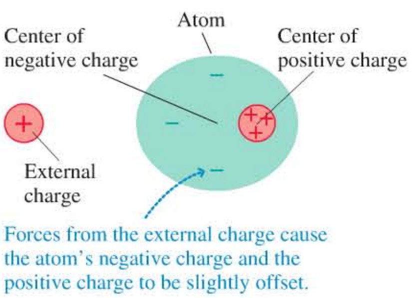


FIGURE 20.10 looks inside an insulator and a metallic conductor. The electrons in the insulator are all tightly bound to the positive nuclei and not free to move around. Charging an insulator by friction leaves patches of molecular ions on the surface, but these patches are immobile.

In metals, the outer atomic electrons (called the *valence electrons* in chemistry) are only weakly bound to the nuclei. As the atoms come together to form a solid, these outer electrons become detached from their parent nuclei and are free to wander about through the entire solid. The solid *as a whole* remains electrically neutral, because we have not added or removed any electrons, but the electrons are now rather like a negatively charged gas or liquid—what physicists like to call a **sea of electrons**—permeating an array of positively charged **ion cores.** However, although the electrons are highly mobile *within* the metal, they are still weakly bound to the ion cores and will not leave the metal.

Electric Dipoles

FIGURE 20.11 An induced electric dipole.



In the last section we noted that an insulator, such as paper, becomes polarized when brought near a charged object. We can use an atomic description of matter to see why.

Consider what happens if we bring a positive charge near a neutral atom. As FIGURE 20.11 shows, the charge polarizes the atom by attracting the electron cloud while repelling the nucleus. The polarization of just one atom is a very small effect, but there are an enormous number of atoms in an insulator. Added together, their net polarization—and the resulting polarization force—can be quite significant. This is how the rubbed amber picks up a feather, exerting an upward polarization force on it larger than the downward force of gravity.

Two equal but opposite charges with a separation between them are called an **electric dipole.** In this case, where the polarization is caused by the external charge, the atom has become an *induced electric dipole.* Because the negative end of the dipole is slightly closer to the positive charge, the attractive force on the negative end slightly exceeds the repulsive force on the positive end, and there is a net force toward the external charge. If a charged rod causes all the atoms in a piece of paper to become induced electric dipoles, the net force is enough to lift the paper to the rod.

Hydrogen Bonding

Some molecules have an asymmetry in their charge distribution that makes them *permanent electric dipoles.* An important example is the water molecule. Bonding between the hydrogen and oxygen atoms results in an unequal sharing of charge that, as shown in FIGURE 20.12, leaves the hydrogen atoms with a small positive charge and the oxygen atom with a small negative charge.

When two water molecules are close, the attractive electric force between the positive hydrogen atom of one molecule and the negative oxygen atom of the second molecule can form a weak bond, called a **hydrogen bond,** as illustrated in FIGURE 20.13. These weak bonds result in a certain "stickiness" between water molecules that is

FIGURE 20.12 A water molecule is a permanent electric dipole.

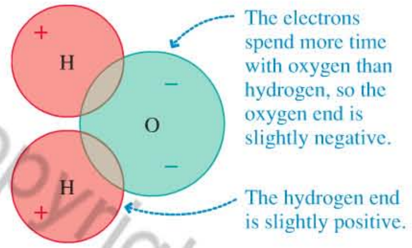
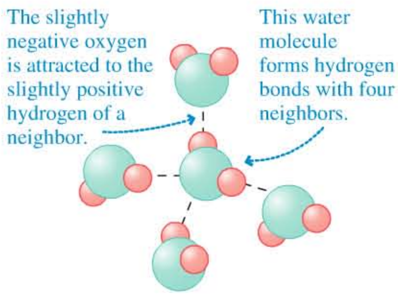


FIGURE 20.13 Hydrogen bonds between water molecules.



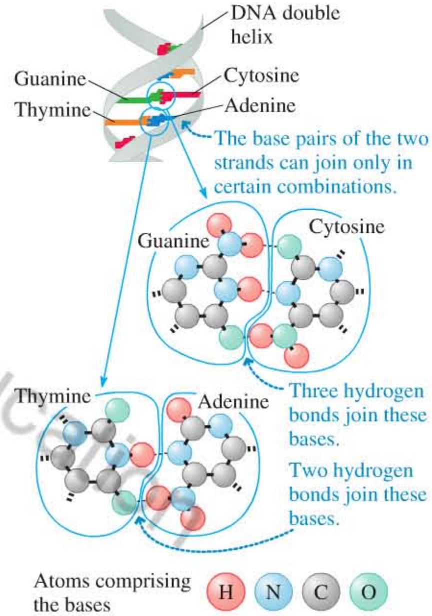
responsible for many of water's special properties, including its expansion on freezing, the wide range of temperatures over which it is liquid, and its high heat of vaporization.

Hydrogen bonds are extremely important in biological systems. As you know, the DNA molecule has the structure of a double helix. Information in DNA is coded in the *nucleotides,* the four molecules guanine, thymine, adenine, and cytosine. The nucleotides on one strand of the DNA helix form hydrogen bonds with the nucleotides on the opposite strand.

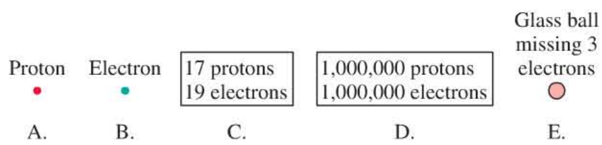
The nucleotides bond only in certain pairs: Cytosine always forms a bond with guanine, adenine with thymine. This preferential bonding is crucial to DNA replication. When the two strands of DNA are taken apart, each separate strand of the DNA forms a template on which another complementary strand can form, creating two identical copies of the original DNA molecule.

The preferential bonding of nucleotide base pairs in DNA is explained by hydrogen bonding. In each of the nucleotides, the hydrogen atoms have a small positive charge, oxygen and nitrogen a small negative charge. The positive hydrogen atoms on one nucleotide attract the negative oxygen or nitrogen atoms on another. As the detail in **FIGURE 20.14** shows, the geometry of the nucleotides allows cytosine to form a hydrogen bond only with guanine, adenine only with thymine.

FIGURE 20.14 Hydrogen bonds in DNA base pairs.



STOP TO THINK 20.2 Rank in order, from most positive to most negative, the charges q_A to q_E of these five systems.



20.3 Coulomb's Law

The last two sections established a *model* of charges and electric forces. This model is very good at explaining electric phenomena and providing a general understanding of electricity. Now we need to become quantitative. Experiment 4 in Section 20.1 found that the electric force increases for objects with more charge and decreases as charged objects are moved farther apart. The force law that describes this behavior is known as *Coulomb's law.*

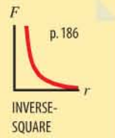
ActivPhysics ONLINE 11.1, 11.2, 11.3

In the mathematical formulation of Coulomb's law, we will use the magnitude of the charge only, not the sign. We show this by using the absolute value notation we used earlier in the book. $|q|$ therefore represents the magnitude of the charge. It is always a positive number, whether the charge is positive or negative.

Coulomb's law

Magnitude: If two charged particles having charges q_1 and q_2 are a distance r apart, the particles exert forces on each other of magnitude

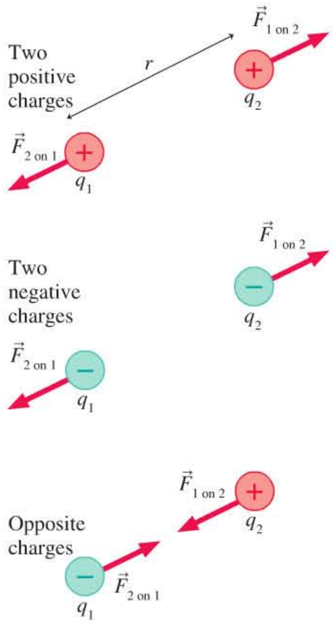
$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2} \tag{20.1}$$



where the charges are in coulombs (C), and $K = 8.99 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$ is called the **electrostatic constant.** These forces are an action/reaction pair, equal in magnitude and opposite in direction. It is customary to round K to $9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$ for all but extremely precise calculations, and we will do so.

Direction: The forces are directed along the line joining the two particles. The forces are *repulsive* for two like charges and *attractive* for two opposite charges.

FIGURE 20.15 Attractive and repulsive forces between charges.



We sometimes speak of the "force between charge q_1 and charge q_2," but keep in mind that we are really dealing with charged *objects* that also have a mass, a size, and other properties. Charge is not some disembodied entity that exists apart from matter. Coulomb's law describes the force between charged *particles.*

NOTE ▶ Coulomb's law applies only to *point charges.* A point charge is an idealized material object with charge and mass but with no size or extension. For practical purposes, two charged objects can be modeled as point charges if they are much smaller than the separation between them. ◀

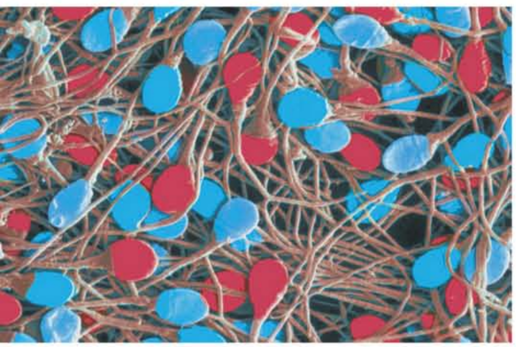
Coulomb's law looks much like Newton's law of gravity, but there is a key difference: The charge q can be either positive or negative, so the forces can be attractive or repulsive. Consequently, the absolute value signs in Equation 20.1 are especially important. The first part of Coulomb's law gives only the *magnitude* of the force, which is always positive. The direction must be determined from the second part of the law. **FIGURE 20.15** shows the forces between different combinations of positive and negative charges.

Using Coulomb's Law

Coulomb's law is a force law, and forces are vectors. **Electric forces, like other forces, can be superimposed.** If multiple charges 1, 2, 3, . . . are present, the *net* electric force on charge j due to all other charges is therefore the sum of all the individual forces due to each charge; that is,

$$\vec{F}_{\text{net}} = \vec{F}_{1\text{ on }j} + \vec{F}_{2\text{ on }j} + \vec{F}_{3\text{ on }j} + \cdots \tag{20.2}$$

where each of the forces $\vec{F}_{i\text{ on }j}$ is given by Equation 20.1. These conditions are the basis of a strategy for using Coulomb's law to solve electric force problems.



◀ **Separating the girls from the boys** BIO Sperm cells can be sorted according to whether they contain an X or a Y chromosome. The cells are put into solution, and the solution is forced through a nozzle, which breaks the solution into droplets. Suppose a droplet contains a sperm cell. An optical test measures which type of chromosome, X or Y, the cell has. The droplet is then given a positive charge if it has an X sperm cell, negative if it contains a Y. The droplets fall between two oppositely charged plates where they are pushed left or right depending on their charge—separating the X from the Y.

PROBLEM-SOLVING STRATEGY 20.1 **Electric forces and Coulomb's law**

PREPARE Identify point charges or objects that can be modeled as point charges. Create a visual overview in which you establish a coordinate system, show the positions of the charges, show the force vectors on the charges, define distances and angles, and identify what the problem is trying to find.

SOLVE The magnitude of the force between point charges is given by Coulomb's law:

$$F_{1\,\mathrm{on}\,2} = F_{2\,\mathrm{on}\,1} = \frac{K|q_1||q_2|}{r^2}$$

Use your visual overview as a guide to the use of this law:

- Show the directions of the forces—repulsive for like charges, attractive for opposite charges—on the visual overview.
- When possible, do graphical vector addition on the visual overview. While not exact, it tells you the type of answer you should expect.
- Write each force vector in terms of its x- and y-components, then add the components to find the net force. Use the visual overview to determine which components are positive and which are negative.

ASSESS Check that your result has the correct units, is reasonable, and answers the question.

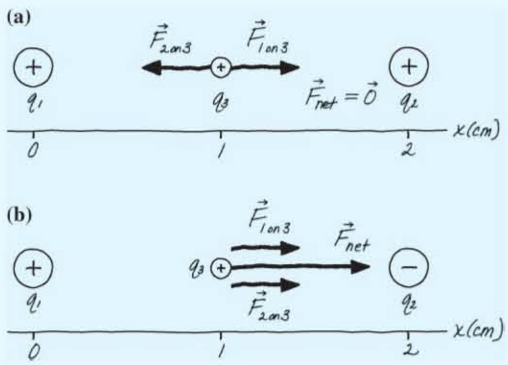
Exercise 21

EXAMPLE 20.3 **Adding electric forces in one dimension**

Two +10 nC charged particles are 2.0 cm apart on the x-axis. What is the net force on a +1.0 nC charge midway between them? What is the net force if the charged particle on the right is replaced by a −10 nC charge?

PREPARE We proceed using the steps of Problem-Solving Strategy 20.1. We model the charged particles as point charges. The visual overview of **FIGURE 20.16** establishes a coordinate system and shows the forces $\vec{F}_{1\,\mathrm{on}\,3}$ and $\vec{F}_{2\,\mathrm{on}\,3}$. Figure 20.16a shows a +10 nC charge on the right; Figure 20.16b shows a −10 nC charge.

FIGURE 20.16 A visual overview of the forces for the two cases.



SOLVE Electric forces are vectors, and the net force on q_3 is the *vector* sum $\vec{F}_{\mathrm{net}} = \vec{F}_{1\,\mathrm{on}\,3} + \vec{F}_{2\,\mathrm{on}\,3}$. Charges q_1 and q_2 each exert a repulsive force on q_3, but these forces are equal in magnitude and opposite in direction. Consequently, $\vec{F}_{\mathrm{net}} = \vec{0}$. The situation changes if q_2 is negative, as in Figure 20.16b. In this case, the two forces are equal in magnitude but in the *same* direction, so $\vec{F}_{\mathrm{net}} = 2\vec{F}_{1\,\mathrm{on}\,3}$. The magnitude of the force is given by Coulomb's law. The force due to q_1 is

$$F_{1\,\mathrm{on}\,3} = \frac{K|q_1||q_3|}{r_{13}^2}$$

$$= \frac{(9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2})(10 \times 10^{-9}\ \mathrm{C})(1.0 \times 10^{-9}\ \mathrm{C})}{(0.010\ \mathrm{m})^2}$$

$$= 9.0 \times 10^{-4}\ \mathrm{N}$$

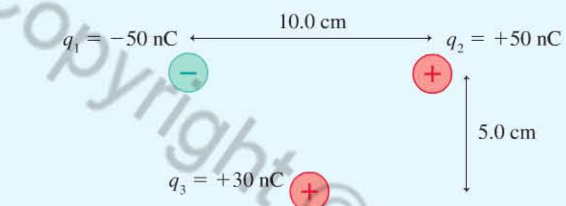
There is an equal force due to q_2, so the net force on the 1.0 nC charge is $\vec{F}_{\mathrm{net}} = (1.8 \times 10^{-3}\ \mathrm{N}$, to the right).

ASSESS This example illustrates the important idea that electric forces are *vectors*. An important part of assessing our answer is to see if it is "reasonable." In the second case, the net force on the charge is approximately 1 mN. Generally, charges of a few nC separated by a few cm experience forces in the range from a fraction of a mN to several mN. With this guideline, the answer appears to be reasonable.

EXAMPLE 20.4 Adding electric forces in two dimensions

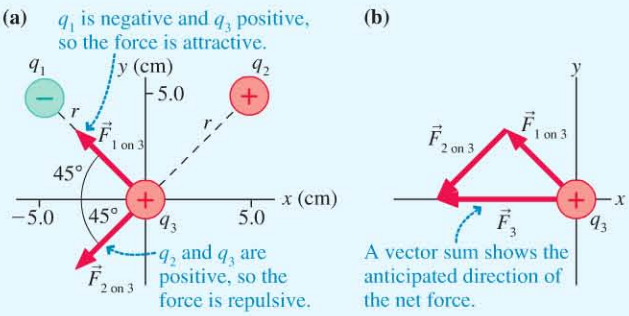
Three charged particles with $q_1 = -50$ nC, $q_2 = +50$ nC, and $q_3 = +30$ nC are placed as shown in FIGURE 20.17. What is the net force on charge q_3 due to the other two charges?

FIGURE 20.17 The arrangement of the charges.



PREPARE We solve for the net force using the steps of Problem-Solving Strategy 20.1, beginning with the visual overview shown in FIGURE 20.18a. We have defined a coordinate system, with charge q_3 at the origin. We have drawn the forces on charge q_3, with directions determined by the signs of the charges. We can see from the geometry that the forces $\vec{F}_{1\,\text{on}\,3}$ and $\vec{F}_{2\,\text{on}\,3}$ are at the angles noted in the figure. The vector addition in FIGURE 20.18b shows the anticipated direction of the net force; this will be a good check on our final result. The distance between charges q_1 and q_3 is the same as that between charges q_2 and q_3; this distance r is $= \sqrt{(5.0\text{ cm})^2 + (5.0\text{ cm})^2} = 7.07$ cm.

FIGURE 20.18 A visual overview of the charges and forces.



SOLVE We are interested in the net force on charge q_3. Let's start by using Coulomb's law to compute the magnitudes of the two forces on charge q_3:

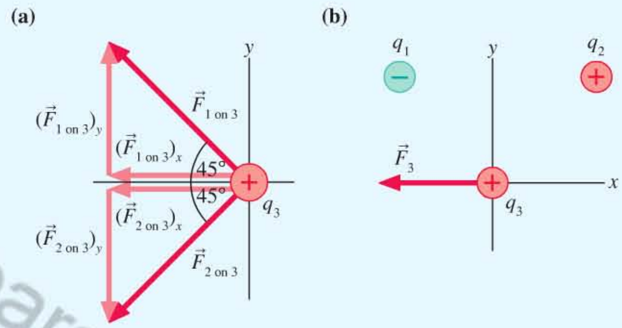
$$F_{1\,\text{on}\,3} = \frac{K|q_1||q_3|}{r^2}$$
$$= \frac{(9.0 \times 10^9\text{ N}\cdot\text{m}^2/\text{C}^2)(50 \times 10^{-9}\text{ C})(30 \times 10^{-9}\text{ C})}{(0.0707\text{ m})^2}$$
$$= 2.7 \times 10^{-3}\text{ N}$$

The magnitudes of the charges and the distance are the same for $F_{2\,\text{on}\,3}$, so

$$F_{2\,\text{on}\,3} = \frac{K|q_2||q_3|}{r^2} = 2.7 \times 10^{-3}\text{ N}$$

The components of these forces are illustrated in FIGURE 20.19a.

FIGURE 20.19 The net force on q_3 is to the left.



Computing values for the components, we find

$$(F_{1\,\text{on}\,3})_x = -(2.7 \times 10^{-3}\text{ N})\cos 45° = -1.9 \times 10^{-3}\text{ N}$$
$$(F_{1\,\text{on}\,3})_y = (2.7 \times 10^{-3}\text{ N})\sin 45° = 1.9 \times 10^{-3}\text{ N}$$
$$(F_{2\,\text{on}\,3})_x = -(2.7 \times 10^{-3}\text{ N})\cos 45° = -1.9 \times 10^{-3}\text{ N}$$
$$(F_{2\,\text{on}\,3})_y = -(2.7 \times 10^{-3}\text{ N})\sin 45° = -1.9 \times 10^{-3}\text{ N}$$

Next, we add components of the net force:

$$F_{3x} = (F_{1\,\text{on}\,3})_x + (F_{2\,\text{on}\,3})_x = -1.9 \times 10^{-3}\text{ N} - 1.9 \times 10^{-3}\text{ N}$$
$$= -3.8 \times 10^{-3}\text{ N}$$
$$F_{3y} = (F_{1\,\text{on}\,3})_y + (F_{2\,\text{on}\,3})_y$$
$$= +1.9 \times 10^{-3}\text{ N} - 1.9 \times 10^{-3}\text{ N} = 0$$

Thus the net force, as shown in FIGURE 20.19b, is

$$\vec{F}_3 = (3.8 \times 10^{-3}\text{ N}, -x\text{-direction})$$

ASSESS The net force is directed to the left, as we anticipated. The magnitude of the net force, a few mN, seems reasonable as well.

EXAMPLE 20.5 Comparing electric and gravitational forces

A small plastic sphere is charged to -10 nC. It is held 1.0 cm above a small glass bead at rest on a table. The bead has a mass of 15 mg and a charge of $+10$ nC. Will the glass bead "leap up" to the plastic sphere?

PREPARE We model the plastic sphere and glass bead as point charges. FIGURE 20.20 establishes a y-axis, identifies the plastic sphere as q_1 and the glass bead as q_2, and shows a free-body diagram. We don't yet know the relative magnitudes of the gravitational and electric forces. In our diagram, we assume that $F_{1\,\text{on}\,2} < w$, so there is an additional upward normal force. This choice allows us to complete the diagram, but it does not affect our calculations or final answer.

SOLVE If $F_{1\,\text{on}\,2}$ is less than the bead's weight $w = m_2 g$, then the bead will remain at rest on the table with $\vec{F}_{1\,\text{on}\,2} + \vec{w} + \vec{n} = \vec{0}$. But

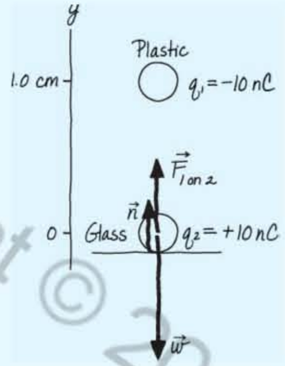


FIGURE 20.20 A visual overview showing the charges and forces.

if $F_{1\,on\,2}$ is greater than the bead's weight, the glass bead will accelerate upward from the table. Using the values provided, we have

$$F_{1\,on\,2} = \frac{K|q_1||q_2|}{r^2} = 9.0 \times 10^{-3}\ \text{N}$$
$$w = m_2 g = 1.5 \times 10^{-4}\ \text{N}$$

$F_{1\,on\,2}$ exceeds the bead's weight by a factor of 60, so the glass bead will leap upward.

ASSESS The answer is different from what we assumed in the diagram, but this assumption did not affect the final result. The values used in this example are realistic for spheres $\approx$2 mm in diameter. In general, as in this example, electric forces are *significantly* larger than weight forces. Consequently, we can neglect weight forces when working electric-force problems unless the particles are fairly massive.

STOP TO THINK 20.3 Charges 1 and 2 exert repulsive forces on each other. $q_1 = 4q_2$. Which statement is true?

A. $F_{1\,on\,2} > F_{2\,on\,1}$ B. $F_{1\,on\,2} = F_{2\,on\,1}$ C. $F_{1\,on\,2} < F_{2\,on\,1}$

20.4 The Concept of the Electric Field

Coulomb's law is the basic law of electrostatics. We can use Coulomb's law to calculate the force a positive charge exerts on a nearby negative charge. But there is an unanswered question: How does the negative charge "know" that the positive charge is there? Coulomb's law tells us how to calculate the magnitude and direction of the force, but it doesn't tell us how the force is transmitted through empty space from one charge to the other. To answer this question, we will introduce the *field model,* first suggested in the early 19th century by Michael Faraday, a British investigator of electricity and magnetism.

FIGURE 20.21 shows a photograph of the surface of a shallow pan of oil with tiny grass seeds floating on it. When charged spheres, one positive and one negative, touch the surface of the oil, the grass seeds line up to form a regular pattern. The pattern suggests that some kind of electric influence from the charges *fills the space* around the charges. Perhaps the grass seeds are reacting to this influence, creating the pattern that we see. This alteration of the space around the charges could be the *mechanism* by which the long-range Coulomb's law force is exerted.

This is the essence of the field model. Consider the attractive force between a positive charge A and a negative charge B. **FIGURE 20.22** shows the difference between the force model, which we have been using, and the field model. **In the field model, it is the alteration of space around charge A that is the *agent* that exerts a force on charge B.** This alteration of space is what we call a **field.** The charge makes an alteration *everywhere* in space. Other charges then respond to the alteration at their position.

The field model applies to many branches of physics. The space around a charge is altered to create the **electric field.** The alteration of the space around a mass is called the **gravitational field.** The alteration of the space around a magnet is called the **magnetic field,** which we will consider in Chapter 24.

The Field Model

The field model might seem arbitrary and abstract. We can already calculate forces between charges; why introduce another way of looking at things? We will find that the field model is a very useful tool for visualizing and calculating forces for complex

FIGURE 20.21 Visualizing the electric field.

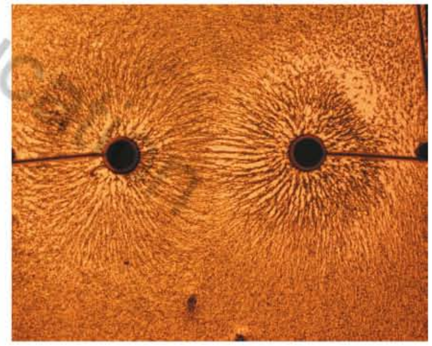
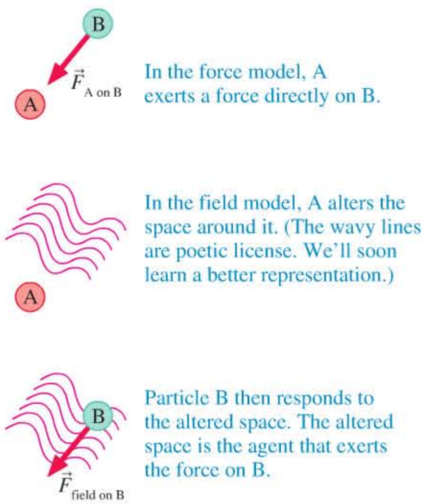


FIGURE 20.22 The force and field models for the interaction between two charges.



arrangements of charges. However, there's a more fundamental reason for introducing the electric field. When we begin to study fields that change with time, we'll find phenomena that can be understood *only* in terms of fields.

We begin our investigation of electric fields by postulating a **field model** that describes how charges interact:

1. A group of charges, which we will call the **source charges,** alter the space around them by creating an *electric field* $\vec{E}$.
2. If another charge is then placed in this electric field, it experiences a force $\vec{F}$ exerted *by the field.*

Suppose charge q experiences an electric force $\vec{F}_{\text{on}\,q}$ due to other charges. The strength and direction of this force vary as q is moved from point to point in space. This suggests that "something" is present at each point in space to cause the force that charge q experiences. We define the electric field $\vec{E}$ at the point (x, y, z) as

$$\vec{E} \text{ at } (x, y, z) = \frac{\vec{F}_{\text{on}\,q} \text{ at } (x, y, z)}{q} \tag{20.3}$$

Electric field at a point defined by the force on charge q

We're *defining* the electric field as a force-to-charge ratio; hence the units of the electric field are newtons per coulomb, or N/C. The magnitude E of the electric field is called the **electric field strength**. Typical electric field strengths are given in Table 20.2.

You can think of using charge q as a *probe* to determine if an electric field is present at a point in space. If charge q experiences an electric force at a point in space, as FIGURE 20.23a shows, then there is an electric field at that point causing the force. Further, we *define* the electric field at that point to be the vector given by Equation 20.3. FIGURE 20.23b shows the electric field at two points, but you can imagine "mapping out" the electric field by moving the charge q all through space.

FIGURE 20.23 Charge q is a probe of the electric field.

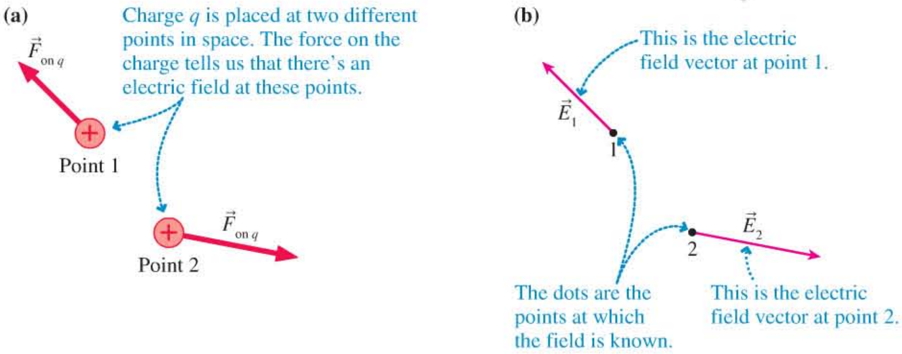


TABLE 20.2 Typical electric field strengths

Field	Field strength (N/C)
Inside a current-carrying wire	10^{-2}
Earth's field, near the earth's surface	10^{2}
Near objects charged by rubbing	10^{3} to 10^{6}
Needed to cause a spark in air	10^{6}
Inside a cell membrane	10^{7}
Inside an atom	10^{11}

The basic idea of the field model is that **the field is the agent that exerts an electric force on charge q**. Notice three important things about the field:

1. The electric field, a vector, exists at every point in space. Electric field diagrams will show a sample of the vectors, but there is an electric field vector at every point whether one is shown or not.
2. If the probe charge q is positive, the electric field vector points in the same direction as the force on the charge; if negative, the electric field vector points opposite the force.
3. Because q appears in Equation 20.3, it may seem that the electric field depends on the magnitude of the charge used to probe the field. It doesn't. We know from Coulomb's law that the force $\vec{F}_{\text{on}\,q}$ is proportional to q. Thus the electric field defined in Equation 20.3 is *independent* of the charge q that probes the field. The electric field depends only on the source charges that create the field.

The Electric Field of a Point Charge

FIGURE 20.24a shows a point source charge q that creates an electric field at all points in space. We can use a second charge, shown as q' in FIGURE 20.24b, to serve as a probe of the electric field created by charge q.

For the moment, assume both charges are positive. The force on q', which is repulsive and points directly away from q, is given by Coulomb's law:

$$\vec{F}_{\text{on}\,q'} = \left(\frac{Kqq'}{r^2}, \text{ away from } q\right) \tag{20.4}$$

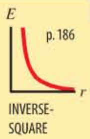
Equation 20.3 defines the electric field in terms of the force on the probe charge as $\vec{E} = \vec{F}_{\text{on}\,q'}/q'$, so for a positive charge q,

$$\vec{E} = \left(\frac{Kq}{r^2}, \text{ away from } q\right) \tag{20.5}$$

The electric field is shown in FIGURE 20.24c.

If q is negative, the magnitude of the force on the probe charge is the same as in Equation 20.5, but the direction is toward q, so the general expression for the field is

$$\vec{E} = \left(\frac{K|q|}{r^2}, \begin{bmatrix} \text{away from } q \text{ if } q > 0 \\ \text{toward } q \text{ if } q < 0 \end{bmatrix}\right) \tag{20.6}$$



Electric field of point charge q at a distance r from the charge

NOTE ► The expression for the electric field is similar to Coulomb's law. To distinguish the two, remember that Coulomb's law has the product of two charges in the numerator. It describes the force between *two* charges. The electric field has a single charge in the numerator. It is the field of a *single* charge. ◄

EXAMPLE 20.6 Finding the electric field of a proton

The electron in a hydrogen atom orbits the proton at a radius of 0.053 nm. What is the electric field due to the proton at the position of the electron?

SOLVE The proton's charge is $q = e$. At the distance of the electron, the magnitude of the field is

$$E = \frac{Ke}{r^2} = \frac{(9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2)(1.60 \times 10^{-19}\ \text{C})}{(5.3 \times 10^{-11}\ \text{m})^2}$$
$$= 5.1 \times 10^{11}\ \text{N/C}$$

Because the proton is positive, the electric field is directed away from the proton:

$$\vec{E} = (5.1 \times 10^{11}\ \text{N/C, outward from the proton})$$

ASSESS This is a large field, but Table 20.2 shows that this is the correct magnitude for the field within an atom.

By drawing electric field vectors at a number of points around a positive point charge, we can construct an **electric field diagram** such as the one shown in FIGURE 20.25a. Notice that the field vectors all point straight away from charge q. We can draw a field diagram for a negative point charge in a similar fashion, as in FIGURE 20.25b. In this case, the field vectors point toward the charge, as this would be the direction of the force on a positive probe charge.

In the coming sections, as we use electric field diagrams, keep these points in mind:

1. The diagram is just a representative sample of electric field vectors. The field exists at all the other points. A well-drawn diagram gives a good indication of what the field would be like at a neighboring point.

FIGURE 20.24 Charge q' is used to probe the electric field of point charge q.

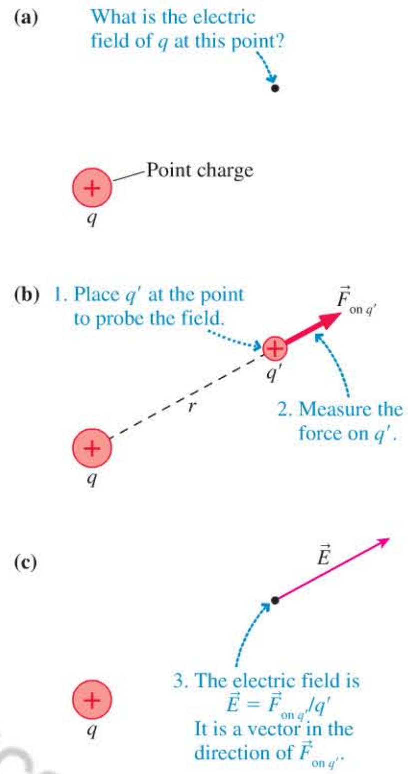
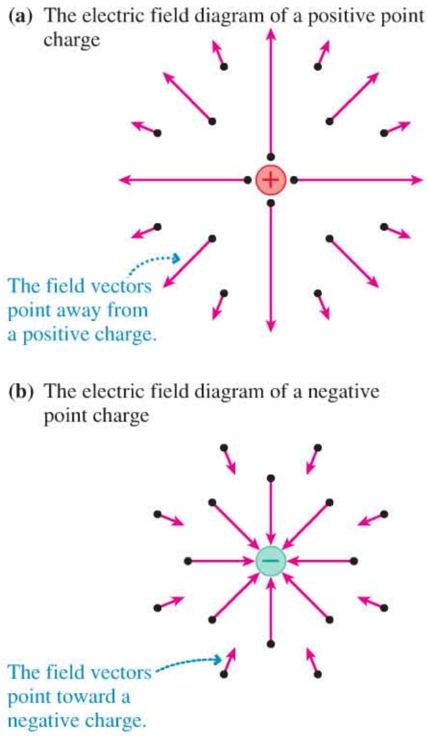
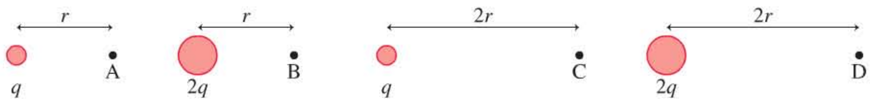


FIGURE 20.25 The electric field near a point charge.



2. The arrow indicates the direction and the strength of the electric field *at the point to which it is attached*—at the point where the *tail* of the vector is placed. The length of any vector is significant only relative to the lengths of other vectors.
3. Although we have to draw a vector across the page, from one point to another, an electric field vector does not "stretch" from one point to another. Each vector represents the electric field at *one point* in space.

STOP TO THINK 20.4 Rank in order, from largest to smallest, the electric field strengths E_A to E_D at points A to D.



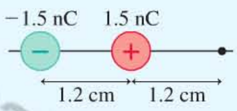
20.5 Applications of the Electric Field

Suppose we want to find the electric field due to more than one source charge. No matter what the number of source charges, the electric field at a point in space can be found by looking at the force on a probe charge. Because the net force on the probe charge is the vector sum of the forces due to all of the individual charges, **the electric field due to multiple charges is the vector sum of the electric field due to each of the charges.**

EXAMPLE 20.7 Finding the field near a dipole

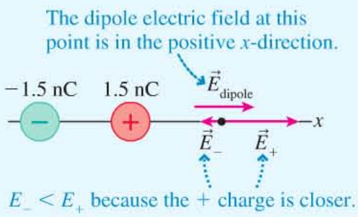
A dipole consists of a positive and negative charge separated by 1.2 cm, as shown in FIGURE 20.26. What is the electric field strength along the line connecting the charges at a point 1.2 cm to the right of the positive charge?

FIGURE 20.26 Charges and distances for a dipole.



PREPARE We define the x-axis to be along the line connecting the two charges, as in FIGURE 20.27. The dipole has no net charge, but it does have a net electric field. The point at which we calculate the field is 1.2 cm from the positive charge and 2.4 cm from the negative charge. Thus the electric field of the positive charge will be larger, as shown in Figure 20.27. The net electric field of the dipole is the vector sum of these two fields, so the electric field of the dipole at this point is in the positive x-direction.

FIGURE 20.27 Visual overview for finding the electric field.



SOLVE The magnitudes of the fields of the two charges are given by Equation 20.6, so the magnitude of the dipole field is

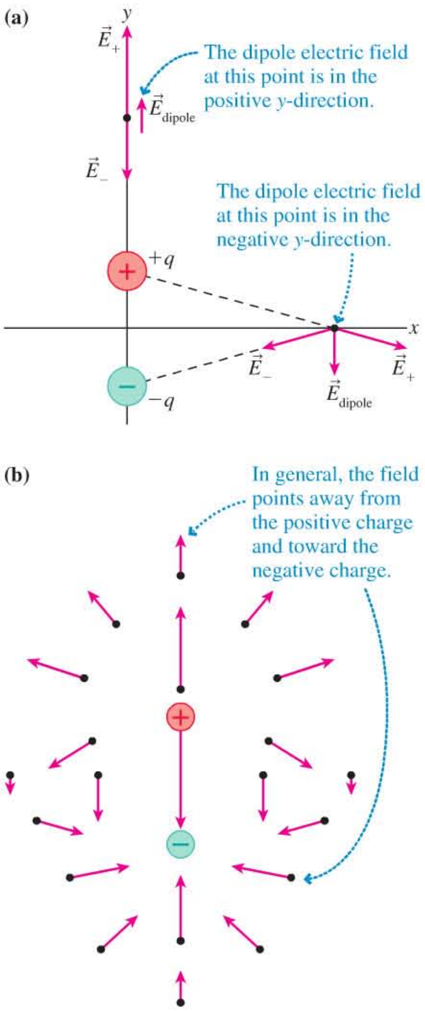
$$E_{dipole} = E_+ - E_-$$

$$= \frac{\left(9.0\times10^9\,\frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}\right)(1.5\times10^{-9}\,\mathrm{C})}{(0.012\,\mathrm{m})^2} - \frac{\left(9.0\times10^9\,\frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}\right)(1.5\times10^{-9}\,\mathrm{C})}{(0.024\,\mathrm{m})^2}$$

$$= 7.0\times10^4\ \mathrm{N/C}$$

ASSESS Table 20.2 lists the fields due to objects charged by rubbing as typically 10^3 to 10^6 N/C, and we've already seen that charges caused by rubbing are in the range of 1–10 nC. Our answer is in this range and thus is reasonable.

FIGURE 20.28 The electric field of a dipole.



The electric dipole is an important charge distribution that we will see many times, so it's worth exploring the full field diagram. FIGURE 20.28 shows a dipole oriented along the y-axis. We can determine the field at any point by a vector addition of the fields of the two charges, as shown in Figure 20.28a. If we repeat this process at many points, we end up with the field diagram of Figure 20.28b. This is more complex than the field of a single charge, but it accurately shows how two charges alter the space around them.

Uniform Electric Fields

FIGURE 20.29a shows another important practical situation, one we'll meet many times. Two conducting plates, called **electrodes,** are face-to-face with a narrow gap between them. One electrode has total charge $+Q$ and the other has total charge $-Q$. This arrangement of two electrodes, closely spaced and charged equally but oppositely, is called a **parallel-plate capacitor.** What is the electric field between the two plates? To keep things simple, we will focus on the field in the central region, far from the edges. FIGURE 20.29b shows a blown-up cross-section view of a region near the center of the plates.

At any point, the electric field is the vector sum of the fields from all of the positive charges and all of the negative charges on the plates. However, the field of a point charge decreases inversely with the square of its distance, so in practice only the nearby charges contribute to the field. As FIGURE 20.30a shows, the horizontal components of the individual fields cancel, while the vertical components add to give an electric field vector pointing from the positive plate toward the negative plate. The exact position of the point we've chosen is not crucial; moving either right or left would produce a similar result.

By mapping the electric field at many points, we find that the field inside a parallel-plate capacitor is the same—in both strength and direction—at every point. This is called a **uniform electric field.** FIGURE 20.30b shows that a uniform electric field is represented with parallel electric field vectors of equal length. A more detailed analysis finds that the electric field inside a parallel-plate capacitor is

FIGURE 20.29 A parallel-plate capacitor.

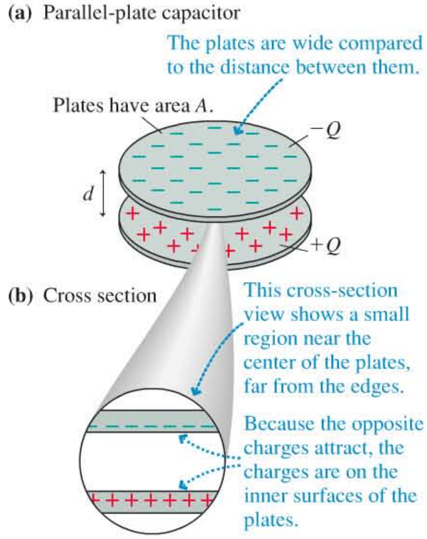
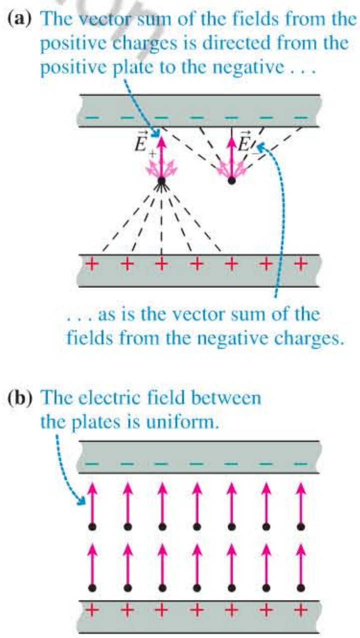
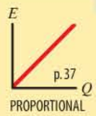


FIGURE 20.30 The electric field inside a parallel-plate capacitor.



$$\vec{E}_{\text{capacitor}} = \left(\frac{Q}{\epsilon_0 A}, \text{ from positive to negative}\right) \tag{20.7}$$

Electric field in a parallel-plate capacitor with plate area A and charge Q



Equation 20.7 introduces a new constant ϵ_0, pronounced "epsilon zero" or "epsilon naught," called the **permittivity constant.** Its value is related to the electrostatic constant as

$$\epsilon_0 = \frac{1}{4\pi K} = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2$$

There are a few things to note about the field in a parallel-plate capacitor:

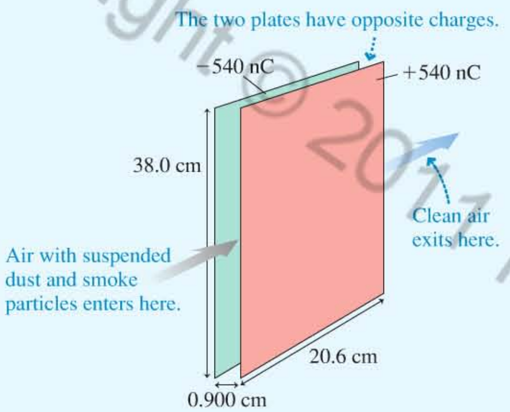
- The field depends on the charge-to-area ratio Q/A, which is often called the *charge density.* If the charges are packed more closely, the field will be larger.
- Our analysis requires that the separation of the plates be small compared to their size. If this is true, the spacing between the plates does not affect the electric field, *and this spacing does not appear in Equation 20.7.*
- Although Figure 20.29 shows circular electrodes, the shape of the electrodes—circular or square or any other shape—is not relevant as long as the electrodes are very close together.

NOTE ► The charges on the plates are equal and opposite, $+Q$ and $-Q$, so the net charge is zero. The symbol Q in Equation 20.7 is the *magnitude* of the charge on each plate. ◄

EXAMPLE 20.8 **Finding the field in an air cleaner**

Long highway tunnels must have air cleaners to remove dust and soot coming from passing cars and trucks. In one type, known as an *electrostatic precipitator,* air passes between two oppositely charged metal plates, as in **FIGURE 20.31**. The large electric field between the plates ionizes dust and soot particles, which then feel a force due to the field. This force causes the charged particles to move toward and stick to one or the other plate, removing them from the air. A typical unit has dimensions and charges as shown in Figure 20.31. What is the electric field between the plates?

FIGURE 20.31 An electrostatic precipitator.



PREPARE Because the spacing between the plates is much smaller than their size, this is a parallel-plate capacitor with a uniform electric field between the plates.

SOLVE We find the field using Equation 20.7. The direction is from the positive to the negative plate, which is to the left. The area of the plates is $A = (0.206\text{ m})(0.380\text{ m}) = 0.0783\text{ m}^2$, so the field strength between the plates is

$$E = \frac{Q}{\epsilon_0 A} = \frac{540 \times 10^{-9}\text{ C}}{(8.85 \times 10^{-12}\text{ C}^2/\text{N}\cdot\text{m}^2)(0.0783\text{ m}^2)}$$
$$= 7.79 \times 10^5\text{ N/C}$$

The question asked for the electric field, a vector, not just for the field strength. The electric field between the plates is

$$\vec{E} = (7.79 \times 10^5\text{ N/C, to the left})$$

ASSESS Table 20.2 shows that a field of 10^6 N/C will create a spark in air. The field we calculated between the plates is just a bit less than this, which makes sense. The field should be large, but not large enough to make a spark jump between the plates!

Electric Field Lines

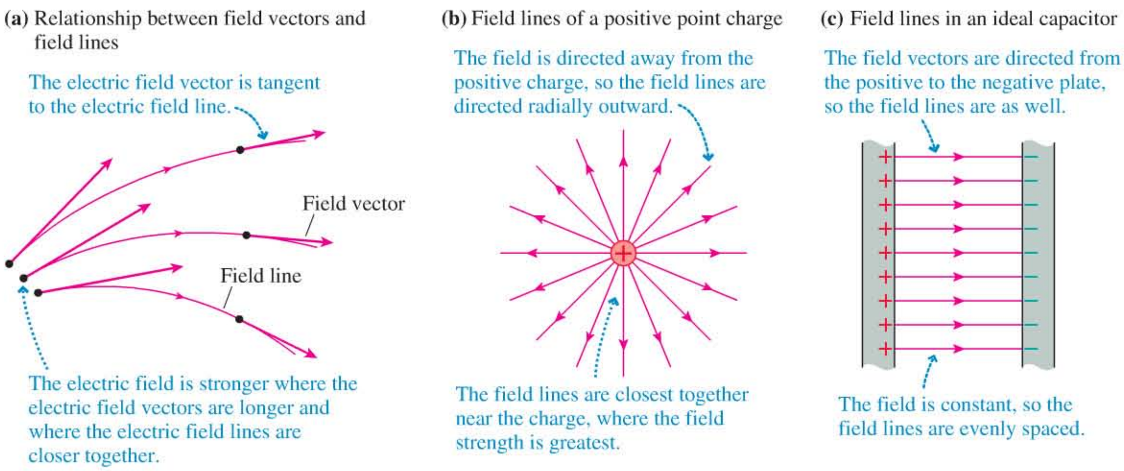
11.4, 11.5, 11.6 ActivPhysics ONLINE

We can't see the electric field, so we use pictorial tools like electric field diagrams to help us visualize the electric field in a region of space. Another way to picture the field is to draw **electric field lines.** These are imaginary lines drawn through a region of space so that

- The tangent to a field line at any point is in the direction of the electric field $\vec{E}$ at that point, and
- The field lines are closer together where the electric field strength is greater.

FIGURE 20.32a shows the relationship between electric field lines and electric field vectors in one region of space. If we know what the field vectors look like, we can extrapolate to the field lines, as in **FIGURES 20.32b** and **20.32c** for the electric field lines near a positive charge and between the plates of a capacitor.

FIGURE 20.32 Field vectors and field lines.



If we have an arrangement of charges, we can draw field lines as a guide to what the field looks like. As you generate a field line picture, there are two rules to keep in mind:

- Field lines cannot cross. The tangent to the field line is the electric field vector, which indicates the direction of the force on a positive charge. The force must be in a unique, well-defined direction, so two field lines cannot cross.
- The electric field is created by charges. Field lines start on a positive charge and end on a negative charge.

You can use the above information as the basis of a technique for sketching a field-line picture for an arrangement of charges. Draw field lines starting on positive charges and moving toward negative charges. Draw the lines tangent to the field vector at each point. Make the lines close together where the field is strong, far apart where the field is weak. For example, **FIGURE 20.33** pictures the electric field of a dipole using electric field lines. You should compare this to Figure 20.28b, which illustrated the field with field vectors.

FIGURE 20.33 Electric field lines for a dipole.

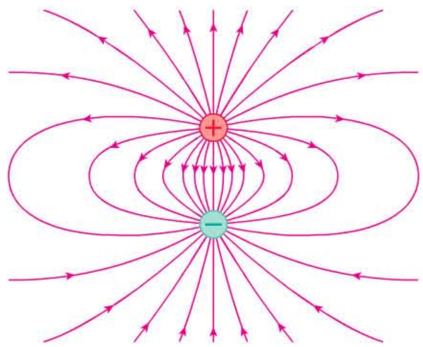
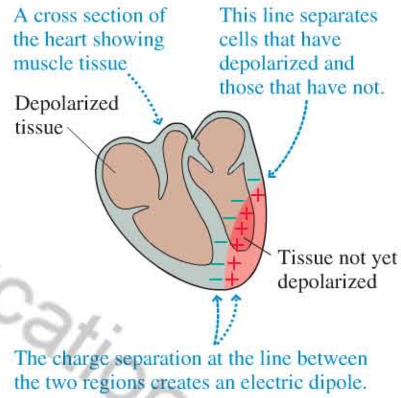
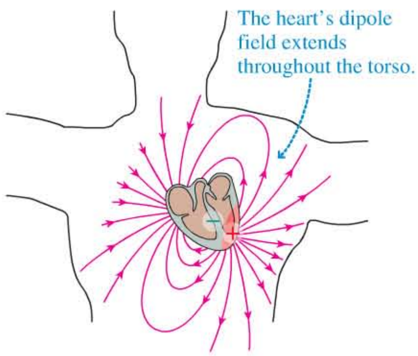


FIGURE 20.34 The beating heart generates a dipole electric field.

(a) The electric dipole of the heart



(b) The field of the heart in the body



The Electric Field of the Heart

Nerve and muscle cells have a prominent electrical nature. As we will see in detail in Chapter 23, a cell membrane is an insulator that encloses a conducting fluid and is surrounded by conducting fluid. While resting, the membrane is *polarized* with positive charges on the outside of the cell, negative charges on the inside. When a nerve or a muscle cell is stimulated, the polarity of the membrane switches; we say that the cell *depolarizes*. Later, when the charge balance is restored, we say that the cell *repolarizes*.

All nerve and muscle cells generate an electrical signal when depolarization occurs, but the largest electrical signal in the body comes from the heart. The rhythmic beating of the heart is produced by a highly coordinated wave of depolarization that sweeps across the tissue of the heart. As **FIGURE 20.34a** shows, the surface of the heart is positive on one side of the boundary between tissue that is depolarized and tissue that is not yet depolarized, negative on the other. In other words, the heart is a large electric dipole. The orientation and strength of the dipole change during each beat of the heart as the depolarization wave sweeps across it.

The electric dipole of the heart generates a dipole electric field that extends throughout the torso, as shown in **FIGURE 20.34b**. As we will see in Chapter 21, an *electrocardiogram* measures the changing electric field of the heart as it beats. Measurement of the heart's electric field can be used to diagnose the operation of the heart.

STOP TO THINK 20.5 Which of the following is the correct representation of the electric field created by two positive charges?

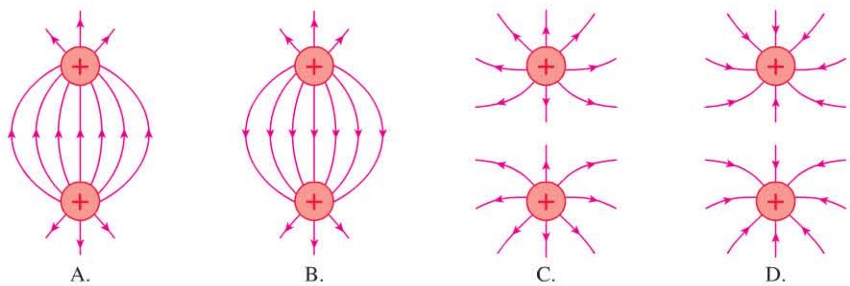
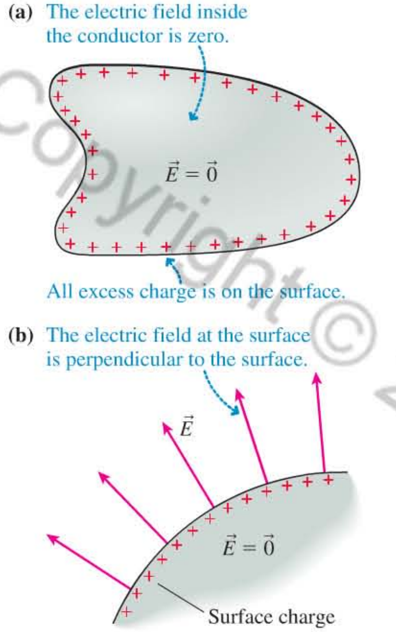


FIGURE 20.35 The electric field inside and outside a charged conductor.



20.6 Conductors and Electric Fields

Consider a conductor in electrostatic equilibrium (recall that this means that none of the charges are moving). Suppose there were an electric field inside the conductor. Electric fields exert forces on charges, so an internal electric field would exert forces on the charges in the conductor. Because charges in a conductor are free to move, these forces would cause the charges to move. But that would violate the assumption that all the charges are at rest. Thus we're forced to conclude that **the electric field is zero at all points inside a conductor in electrostatic equilibrium.**

Because the electric field inside a conductor in electrostatic equilibrium is zero, any *excess* charge on the conductor must lie at its surface, as shown in FIGURE 20.35a. Any charge in the interior of the conductor would create an electric field there, in violation of our conclusion that the field inside is zero. Physically, excess charge ends up on the surface because the repulsive forces between like charges cause them to move as far apart as possible without leaving the conductor.

FIGURE 20.35b shows that **the electric field right at the surface of a charged conductor is perpendicular to the surface.** To see that this is so, suppose $\vec{E}$ had a component tangent to the surface. This component of $\vec{E}$ would exert a force on charges at the surface and cause them to move along the surface, thus violating the assumption that all charges are at rest. The only exterior electric field consistent with electrostatic equilibrium is one that is perpendicular to the surface.

CONCEPTUAL EXAMPLE 20.9 Drawing electric field lines for a charged sphere and a plate

FIGURE 20.36 shows a positively charged metal sphere above a conducting plate with a negative charge. Sketch the electric field lines.

REASON Field lines start on positive charges and end on negative charges. Thus we draw the field lines from the positive sphere to the negative plate, perpendicular to both surfaces, as shown in FIGURE 20.37. The single field line that goes upward tells us that there is a field above the sphere, but that it is weak.

FIGURE 20.36 The charged sphere and plate.

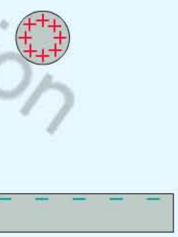


FIGURE 20.37 Drawing field lines from sphere to plate.

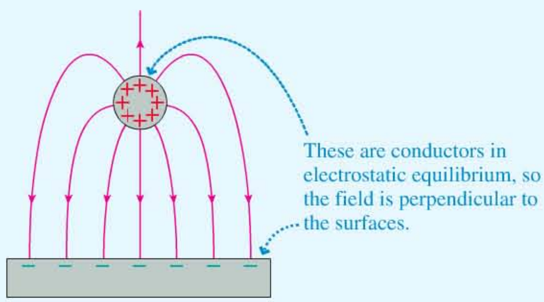
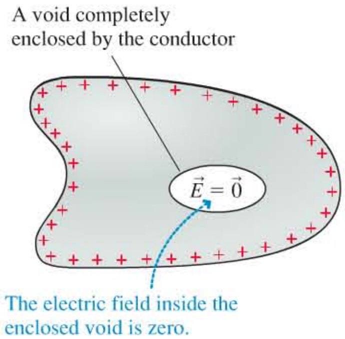


FIGURE 20.38 shows a practical use of these ideas. Here we see a charged conductor with a completely enclosed void. The excess charge on the conductor is at the surface and the electric field within the conductor is zero, so there's nothing that could create an electric field within the enclosure. We can conclude that **the electric field within a conducting enclosure is zero.**

A conducting box can be used to exclude electric fields from a region of space; this is called **screening.** Solid metal walls are ideal, but in practice wire screen or wire mesh provides sufficient screening for all but the most sensitive applications.

FIGURE 20.38 A region of space enclosed by conducting walls is screened from electric fields.



CONCEPTUAL EXAMPLE 20.10 **Analyzing static protection**

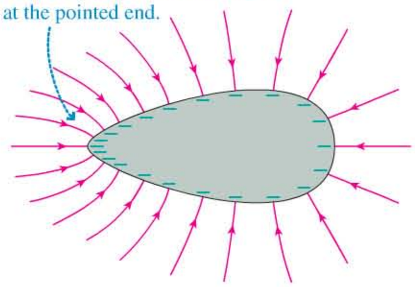
Computer chips and other electronic components are very sensitive to electric charges and fields. Even a small static charge or field may damage them. Such components are shipped and stored in conducting bags. How do these bags protect the components stored inside?

REASON Such a bag, when sealed, forms a conducting shell around its interior. All excess charge is on the surface of the bag, and the electric field inside is zero. A chip or component inside the bag is protected from damaging charges and fields.

Although any excess charge on a conductor will be found on the surface, it may not be uniformly distributed. **FIGURE 20.39** shows a charged conductor that is more pointed at one end than the other. It turns out that the density of charge is highest—and thus the electric field is strongest—at the pointed end.

The sharper the point, the stronger the field. The electric field near very sharp points may be strong enough to ionize the air around it. Lightning rods on buildings have such a point at the top. If charge begins to accumulate on the building, meaning a lightning strike might be imminent, a large field develops at the tip of the rod. Once the field ionizes the air, excess charge from the building can dissipate into the air, reducing the electric field and thus reducing the probability of a lightning strike. A lightning rod is intended to *prevent* a lightning strike.

FIGURE 20.39 The electric field is strongest at the pointed end.



▶ **Electrolocation** BIO Many fish have stacks of specially adapted cells called *electrocytes* that develop electric charges across them. The electrocytes in the tail of this fish (called an elephant nose) form an electric dipole that produces an electric field in the water around it. The elephant nose has sensors along its body that can detect very small changes in this electric field. A nearby conductor—such as another fish—will alter this field. The elephant nose uses these changes in the field to "see" around it. These fish live in very murky water where vision is of little use, so you can see the advantage of having such an alternative form of perception.

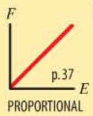
20.7 Forces and Torques in Electric Fields

ActivPhysics Online 11.9, 11.10

The electric field was defined in terms of the force on a charge. In practice, we often want to turn the definition around to find the force exerted on a charge in a known electric field. If a charge q is placed at a point in space where the electric field is $\vec{E}$, then according to Equation 20.3 the charge experiences an electric force

$$\vec{F}_{\text{on } q} = q\vec{E} \qquad (20.8)$$

Force on a charge due to an electric field



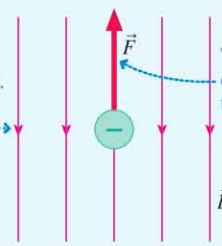
If q is positive, the force on charge q is in the direction of $\vec{E}$. The force on a negative charge is *opposite* the direction of $\vec{E}$.

EXAMPLE 20.11 **Finding the force on an electron in the atmosphere**

Under normal circumstances, the earth's electric field outdoors near ground level is uniform, about 100 N/C, directed down. What is the electric force on a free electron in the atmosphere? What acceleration does this force cause?

PREPARE The electric field is uniform, as shown in the field diagram of **FIGURE 20.40**. Whatever the position of the electron, it experiences the same field. Because the electron is negative, the force on it is opposite the field—upward.

FIGURE 20.40 An electron in the earth's electric field.



Continued

SOLVE The magnitude of the force is given by Equation 20.8:

$$F = eE = (1.6 \times 10^{-19}\ \text{C})(100\ \text{N/C}) = 1.6 \times 10^{-17}\ \text{N}$$

Thus the force on the electron is

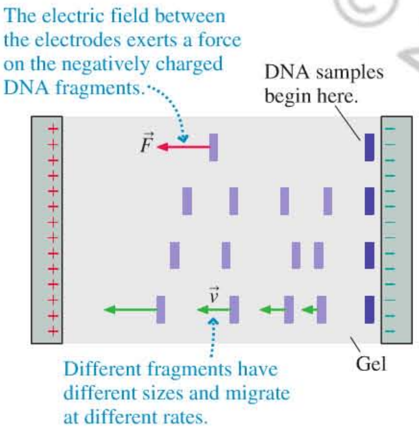
$$\vec{F} = (1.6 \times 10^{-17}\ \text{N, upward})$$

The electron will accelerate upward, in the direction of the force. The magnitude of the acceleration is

$$a = \frac{F}{m} = \frac{1.6 \times 10^{-17}\ \text{N}}{9.1 \times 10^{-31}\ \text{kg}} = 1.8 \times 10^{13}\ \text{m/s}^2$$

ASSESS This everyday field produces an extremely large acceleration on a free electron. Forces and accelerations at the atomic scale are quite different from what we are used to for macroscopic objects.

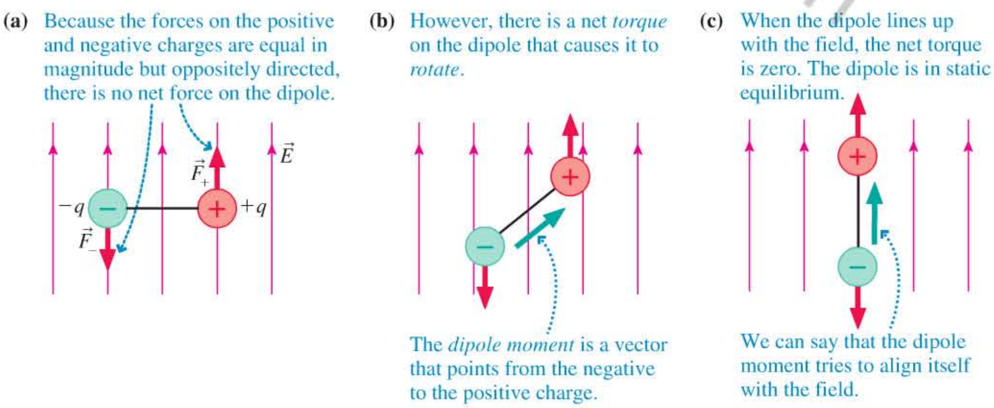
FIGURE 20.41 Electrophoresis of DNA samples.



The photo at the start of the chapter showed the colored lines produced by gel electrophoresis of a sample of DNA. The first step of the analysis is to put the sample of DNA into solution. The DNA is then cut into fragments by enzymes. In solution, these fragments have a negative charge. Drops of solution containing the charged DNA fragments are placed in wells at one end of a container of gel. Electrodes at opposite ends of the gel create an electric field that exerts an electric force on the DNA fragments in the solution, as illustrated in FIGURE 20.41. The electric force makes the fragments move through the gel, but drag forces cause fragments of different sizes to migrate at different rates, with smaller fragments migrating faster than larger ones. After some time, the fragments sort themselves into distinct lines, creating a "genetic fingerprint." Two identical samples of DNA will produce the same set of fragments and thus the same pattern in the gel, but the odds are extremely small that two unrelated DNA samples would produce the same pattern.

If an electric dipole is placed in a uniform electric field, as shown in FIGURE 20.42a, the electric force on its negative charge is equal in magnitude but opposite in direction to the force on its positive charge. Thus an electric dipole in a uniform electric field experiences *no net force*. However, as you can see from FIGURE 20.42b, there is a net *torque* on the dipole that causes it to *rotate*.

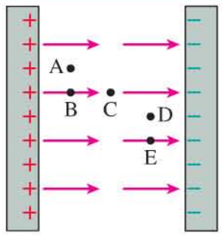
FIGURE 20.42 Forces and torques on an electric dipole.



It is useful to define the **electric dipole moment,** a vector pointing from the negative to the positive charge of a dipole. As Figures 20.42b and 20.42c show, an electric dipole in a uniform electric field experiences a torque that causes it to rotate. **The equilibrium position of a dipole in an electric field is with the electric dipole moment aligned with the field.**

Earlier, we saw a photo of grass seeds lined up with the electric field from two charged electrodes. Now we can understand why the seeds line up as they do. First, the electric field polarizes the seeds, inducing opposite charges on their ends. The seeds are induced electric dipoles, with dipole moments along the axis of each seed. Second, torques on the dipole moments cause them to line up with the electric field, revealing its structure.

STOP TO THINK 20.6 Rank in order, from largest to smallest, the forces F_A to F_E a proton would experience if placed at points A to E in this parallel-plate capacitor.



INTEGRATED EXAMPLE 20.12 A cathode-ray tube

Some televisions, older computer monitors, and other electronic equipment use a *cathode-ray tube*, or CRT, to create an image on a screen. In a CRT, electrons are accelerated by an electric field inside an electron "gun," creating a beam of electrons all moving along in a straight line at the same high speed. A second electric field then steers these electrons to a particular point on a phosphor-coated glass screen, causing the phosphor to glow brightly at that point. By rapidly varying the steering electric field and the intensity of the electron beam, the spot of electrons can be swept over the entire screen, resulting in the familiar glowing picture of a television.

FIGURE 20.43 shows a simplified model of the internal structure of a CRT. Electrons—emitted from a hot filament—start with zero speed at the negative plate of a parallel-plate capacitor. The electric field inside this capacitor accelerates the electrons toward the positive plate, where they exit the capacitor with speed v_1 through a small hole. They then coast along at this speed until they enter the steering electric field of the deflector. This field causes them to follow a curved trajectory, exiting at an angle θ with respect to their original direction.

a. The CRT designer has specified that the electrons must leave the 4.0-cm-wide electron gun with a speed of 6.0×10^7 m/s. What electric field strength is needed inside the electron-gun capacitor?

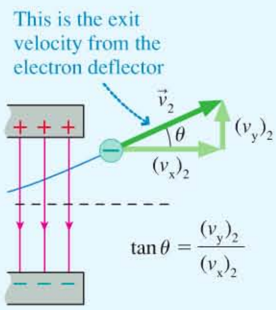
b. The steering electric field has a constant strength of 1.5×10^5 N/C over the 5.0 cm length of the deflector. By what angle θ are the electrons deflected?

PREPARE We'll use a coordinate system in which the x-axis is horizontal and the y-axis vertical.

a. We can use constant-acceleration kinematics to find the electron's acceleration inside the electron gun. Newton's second law then gives the force on the electron, which we can relate to the electric field using Equation 20.3: $\vec{E} = \vec{F}_{\text{on } q}/q$.

b. Because the electric field is vertically down, the force on a negative electron is vertically up. An electron will accelerate vertically, but not horizontally, so the x-component of its velocity remains unchanged and equal to v_1 as it passes through the deflector. This is exactly analogous to the motion of a projectile, and the electrons follow a projectile-like parabolic trajectory. Just as with projectile motion, we'll use the horizontal motion to find the time interval, then use the time interval to find the final velocity in the y-direction. As **FIGURE 20.44** shows, the ratio of the electron's y- and x-components of velocity can be used to find θ.

FIGURE 20.44 The exit velocity of the electron.



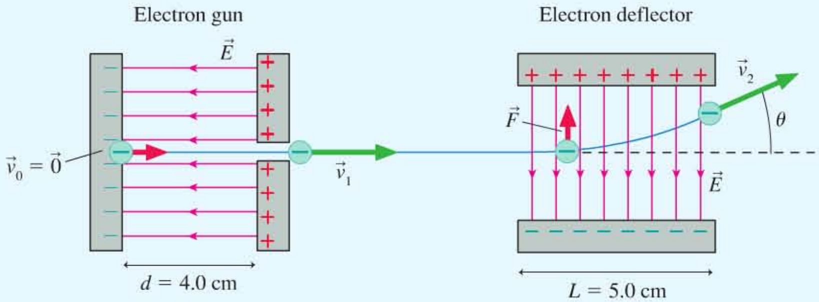
SOLVE a. One of the constant-acceleration kinematic equations from Chapter 2 was $(v_x)_1^2 = (v_x)_0^2 + 2a_x\Delta x$. Using $(v_x)_0 = 0$ and $\Delta x = d = 4.0$ cm, we find that an electron's acceleration inside the electron gun is

$$a_x = \frac{(v_x)_1^2}{2d} = \frac{(6.0 \times 10^7 \text{ m/s})^2}{2(0.040 \text{ m})} = 4.5 \times 10^{16} \text{ m/s}^2$$

Newton's second law tells us that the force causing this acceleration is

$$F_x = ma_x = (9.1 \times 10^{-31} \text{ kg})(4.5 \times 10^{16} \text{ m/s}^2)$$
$$= 4.1 \times 10^{-14} \text{ N}$$

FIGURE 20.43 The electron gun and electron deflector of a CRT.



Continued

Then, by Equation 20.3, the electric field is

$$E_x = \frac{F_x}{q} = \frac{4.1 \times 10^{-14}\ \text{N}}{-1.6 \times 10^{-19}\ \text{C}} = -2.6 \times 10^5\ \text{N/C}$$

This is a field in the negative x-direction, as we can see in Figure 20.43, with strength 2.6×10^5 N/C.

b. The y-component of the electron's acceleration in the deflector is

$$a_y = \frac{F_y}{m} = \frac{eE_y}{m} = \frac{(-1.6 \times 10^{-19}\ \text{C})(-1.5 \times 10^5\ \text{N/C})}{9.1 \times 10^{-31}\ \text{kg}}$$
$$= 2.6 \times 10^{16}\ \text{m/s}^2$$

The negative electrons have an upward (positive) acceleration. This acceleration causes an electron to leave the deflector with a y-component of velocity

$$(v_y)_2 = a_y \Delta t$$

where Δt is the time the electron spends in the deflector. Because the x-component of the velocity is constant, this time is simply

$$\Delta t = \frac{L}{(v_x)_1} = \frac{0.050\ \text{m}}{6.0 \times 10^7\ \text{m/s}} = 8.3 \times 10^{-10}\ \text{s}$$

Thus

$$(v_y)_2 = a_y \Delta t = (2.6 \times 10^{16}\ \text{m/s}^2)(8.3 \times 10^{-10}\ \text{s})$$
$$= 2.2 \times 10^7\ \text{m/s}$$

Referring to Figure 20.44, and using $(v_x)_2 = (v_x)_1$ because there's no horizontal acceleration, we see that

$$\tan\theta = \frac{(v_y)_2}{(v_x)_2} = \frac{2.2 \times 10^7\ \text{m/s}}{6.0 \times 10^7\ \text{m/s}} = 0.37$$

so that

$$\theta = \tan^{-1}(0.37) = 20°$$

ASSESS A strong field accelerates the electrons in the x-direction, while a weaker one accelerates them in the y-direction. Thus it is reasonable that the ratio of the y- to the x-component of velocity is significantly less than 1.

The CRT shown in Figure 20.43 deflects electrons only vertically. A real CRT has a second electron deflector, rotated 90°, to provide a horizontal deflection. The two deflectors working together can scan the electron beam over all points on the television screen.

SUMMARY

The goal of Chapter 20 has been to develop a basic understanding of electric phenomena in terms of charges, forces, and fields.

GENERAL PRINCIPLES

Charge

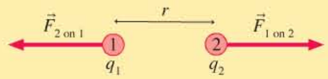
There are two kinds of charges, called **positive** and **negative.**

- Atoms consist of a nucleus containing positively charged protons surrounded by a cloud of negatively charged electrons.
- The **fundamental charge** e is the magnitude of the charge on an electron or proton: $e = 1.60 \times 10^{-19}$ C.
- Matter with equal amounts of positive and negative charge is **neutral**.
- Charge is conserved; it can't be created or destroyed.

Coulomb's Law

The forces between two charged particles q_1 and q_2 separated by distance r are

$$F_{1\,\text{on}\,2} = F_{2\,\text{on}\,1} = \frac{K|q_1||q_2|}{r^2}$$



where $K = 8.99 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$ is the **electrostatic constant.** These forces are an action/reaction pair directed along the line joining the particles.

- The forces are repulsive for two like charges, attractive for two opposite charges.
- The net force on a charge is the vector sum of the forces from all other charges.
- The unit of charge is the coulomb (C).

IMPORTANT CONCEPTS

The Electric Field

Charges interact with each other via the electric field $\vec{E}$.

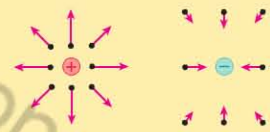
- Charge A alters the space around it by creating an electric field.

- The field is the agent that exerts a force on charge B. $\qquad \vec{F}_{\text{on B}} = q_B \vec{E}$
- An electric field is identified and measured in terms of the force on a probe charge q. The unit of the electric field is N/C. $\qquad \vec{E} = \dfrac{\vec{F}_{\text{on}\,q}}{q}$
- The electric field is a vector. The electric field from multiple charges is the vector sum of the fields from the individual charges. $\qquad \vec{E}_{\text{total}} = \vec{E}_1 + \vec{E}_2 + \cdots$

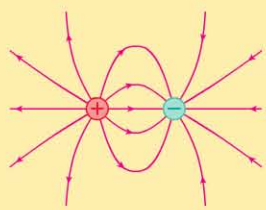
Visualizing the electric field

The electric field exists at all points in space.

- An electric field vector shows the field only at one point, the point at the tail of the vector.
- A **field diagram** shows field vectors at several points.



- **Electric field lines:**
  - are always parallel to the field vectors.
  - are close where the field is strong, far apart where the field is weak.
  - go from positive to negative charges.



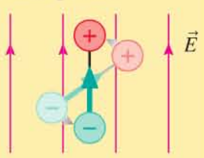
APPLICATIONS

There are two types of material, **insulators** and **conductors.**

- Charge remains fixed on an insulator.
- Charge moves easily through conductors.
- Charge is transferred by contact between objects.

A **dipole** has no net charge, but has a field because the two charges are separated.

A dipole will rotate to align with an electric field.



Electric fields: important cases

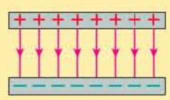
The electric field of a **point charge** is

$$\vec{E} = \left(\frac{K|q|}{r^2}, \begin{bmatrix} \text{away from } q \text{ if } q > 0 \\ \text{toward } q \text{ if } q < 0 \end{bmatrix}\right)$$

The electric field inside a **parallel-plate capacitor** is uniform:

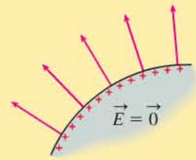
$$\vec{E} = \left(\frac{Q}{\epsilon_0 A}, \text{from positive to negative}\right)$$

where $\epsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\text{N} \cdot \text{m}^2$ is the **permittivity constant.**

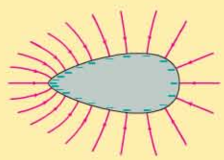


Conductors in electric fields

- The electric field inside a conductor in **electrostatic equilibrium** is zero.
- Any excess charge is on the surface.



- The electric field is perpendicular to the surface.
- The density of charge and the electric field are highest near a pointed end.



Problems labeled INT integrate significant material from earlier chapters; BIO are of biological or medical interest.

Problem difficulty is labeled as | (straightforward) to ||||| (challenging).

QUESTIONS

Conceptual Questions

1. What is alike about charges when we say "two like charges"? Do they look, smell, or taste the same?
2. Four lightweight balls A, B, C, and D are suspended by threads. Ball A has been touched by a plastic rod that was rubbed with wool. When the balls are brought close together, without touching, the following observations are made:
   - Balls B, C, and D are attracted to ball A.
   - Balls B and D have no effect on each other.
   - Ball B is attracted to ball C.

   What are the charge states (positive, negative, or neutral) of balls A, B, C, and D? Explain.
3. Plastic and glass rods that have been charged by rubbing with wool and silk, respectively, hang by threads.
   a. An object repels the plastic rod. Can you predict what it will do to the glass rod? If so, what? If not, why not? Explain.
   b. A different object attracts the plastic rod. Can you predict what it will do to the glass rod? If so, what? If not, why not? Explain.
4. a. Can an insulator be charged? If so, how would you charge an insulator? If not, why not?
   b. Can a conductor be charged? If so, how would you charge a conductor? If not, why not?
5. When you take clothes out of the drier right after it stops, the clothes often stick to your hands and arms. Is your body charged? If so, how did it acquire a charge? If not, why does this happen?
6. A lightweight metal ball hangs by a thread. When a charged rod is held near, the ball moves toward the rod, touches the rod, then quickly "flies away" from the rod. Explain this behavior.
7. As shown in Figure Q20.7, metal sphere A has 4 units of negative charge and metal sphere B has 2 units of positive charge. The two spheres are brought into contact. What is the final charge state of each sphere? Explain.

FIGURE Q20.7

8. Figure Q20.8 shows a positively charged rod held near, but not touching, a neutral metal sphere.
   a. Add plusses and minuses to the figure to show the charge distribution on the sphere.
   b. Does the sphere experience a net force? If so, in which direction? Explain.

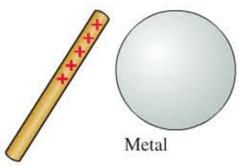
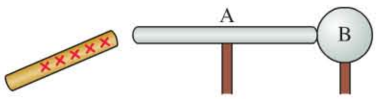


FIGURE Q20.8

9. A plastic balloon that has been rubbed with wool will stick to a wall.
   a. Can you conclude that the wall is charged? If not, why not? If so, where does the charge come from?
   b. Draw a charge diagram showing how the balloon is held to the wall.
10. You are given two metal spheres on portable insulating stands, a glass rod, and a piece of silk. Explain how to give the spheres *exactly* equal but opposite charges.
11. BIO A honeybee acquires a positive electric charge as it flies through the air. This charge causes pollen grains to be attracted to the bee. Explain, using words and diagrams, how a neutral, conducting pollen grain will be attracted to a positively charged bee.
12. A metal rod A and a metal sphere B, on insulating stands, touch each other as shown in Figure Q20.12. They are originally neutral. A positively charged rod is brought near (but not touching) the far end of A. While the charged rod is still close, A and B are separated. The charged rod is then withdrawn. Is the sphere then positively charged, negatively charged, or neutral? Explain.

FIGURE Q20.12



13. Each part of Figure Q20.13 shows two points near two charges. Compare the electric field strengths E_1 and E_2 at these two points. Is $E_1 > E_2$, $E_1 = E_2$, or $E_1 < E_2$?

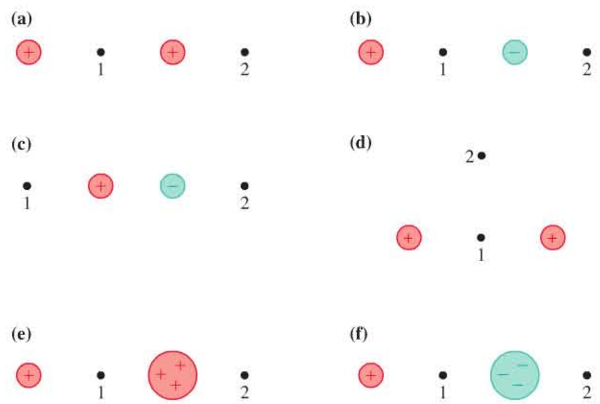


FIGURE Q20.13

14. Iontophoresis is a noninvasive process that transports drugs through the skin without needles. In the photo, the red electrode is positive and the black electrode is negative. The electric field between the electrodes will drive the negatively charged molecules of an anesthetic through the skin. Should the drug be placed at the red or the black electrode? Explain.
BIO

15. Rank in order, from largest to smallest, noting any ties, the electric field strengths E_1 to E_4 at points 1 to 4 in Figure Q20.15.

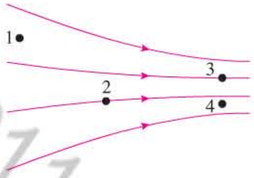


FIGURE Q20.15

16. A 10 nC charge sits at a point in space where the magnitude of the electric field is 1200 N/C. What will the magnitude of the field be if the 10 nC charge is replaced by a 20 nC charge?
17. When DNA breaks into fragments in a cell, electrostatic forces may actually inhibit repair. Explain why this happens.
BIO
18. A hollow soda straw is uniformly charged, as shown in Figure Q20.18. What is the electric field at the center (inside) of the straw? Explain.

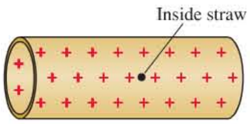


FIGURE Q20.18

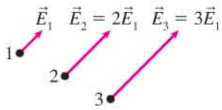


FIGURE Q20.19

19. A small positive charge q experiences a force of magnitude F_1 when placed at point 1 in Figure Q20.19. In terms of F_1:
    a. What is the magnitude of the force on charge q at point 3?
    b. What is the magnitude of the force on a charge $3q$ at point 1?
    c. What is the magnitude of the force on a charge $2q$ at point 2?
    d. What is the magnitude of the force on a charge $-2q$ at point 2?
20. A typical commercial airplane is struck by lightning about once per year. When this happens, the external metal skin of the airplane might be burned, but the people and equipment inside the aircraft experience no ill effects. Explain why this is so.
21. Microbes such as bacteria have small positive charges when in solution. Public health agencies are exploring a new way to measure the presence of small numbers of microbes in drinking water by using electric forces to concentrate the microbes. Water is sent between the two oppositely charged electrodes of a parallel-plate capacitor. Any microbes in the water will collect on one of the electrodes.
BIO
    a. On which electrode will the microbes collect?
    b. How could the microbes be easily removed from the electrodes for analysis?
22. a. Is there a point between a 10 nC charge and a 20 nC charge at which the electric field is zero? If so, which charge is this point closer to? If not, why not?
    b. Repeat part a for the case of a 10 nC charge and a −20 nC charge.

Multiple-Choice Questions

23. | Two lightweight, electrically neutral conducting balls hang from threads. Choose the diagram in Figure Q20.23 that shows how the balls hang after:
    a. Both are touched by a negatively charged rod.
    b. Ball 1 is touched by a negatively charged rod and ball 2 is touched by a positively charged rod.
    c. Both are touched by a negatively charged rod but ball 2 picks up more charge than ball 1.
    d. Only ball 1 is touched by a negatively charged rod.

    Note that parts a through d are independent; these are not actions taken in sequence.

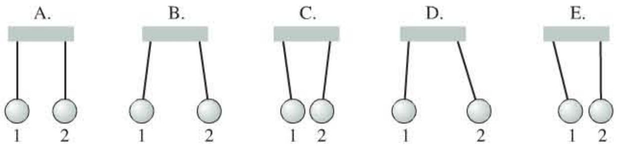


FIGURE Q20.23

24. | All the charges in Figure Q20.24 have the same magnitude. In which case does the electric field at the dot have the largest magnitude?

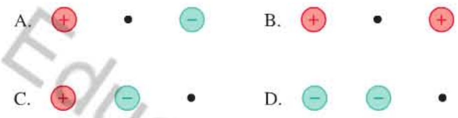


FIGURE Q20.24

25. | All the charges in Figure Q20.25 have the same magnitude. In which case does the electric field at the dot have the largest magnitude?

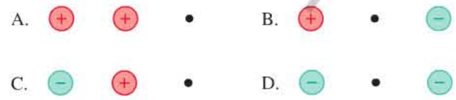


FIGURE Q20.25

26. | All the charges in Figure Q20.26 have the same magnitude. In which case does the electric field at the dot have the largest magnitude?

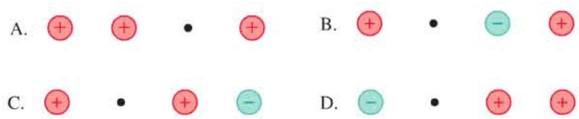


FIGURE Q20.26

27. | A glass bead charged to +3.5 nC exerts an 8.0×10^{-4} N repulsive electric force on a plastic bead 2.9 cm away. What is the charge on the plastic bead?
    A. +2.1 nC B. +7.4 nC
    C. +21 nC D. +740 nC
28. | A +7.5 nC point charge and a −2.0 nC point charge are 3.0 cm apart. What is the electric field strength at the midpoint between the two charges?
    A. 3.3×10^3 N/C B. 5.7×10^3 N/C
    C. 2.2×10^5 N/C D. 3.8×10^5 N/C

29. || Three point charges are arranged as shown in Figure Q20.29. Which arrow best represents the direction of the electric field vector at the position of the dot?

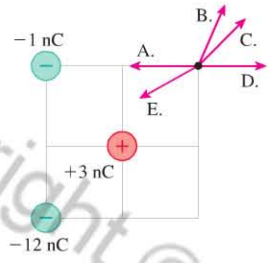


FIGURE Q20.29

30. || A rod has positive charge $+q$ at one end and negative charge $-q$ at the other, forming a dipole. The dipole is placed in a nonuniform electric field represented by the field lines in Figure Q20.30. Which arrow best indicates the direction of the net electric force on the dipole?

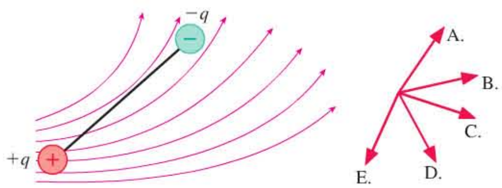


FIGURE Q20.30

PROBLEMS

Section 20.1 Charges and Forces

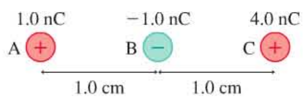
Section 20.2 Charges, Atoms, and Molecules

1. ||| A glass rod is charged to +5.0 nC by rubbing.
   a. Have electrons been removed from the rod or protons added? Explain.
   b. How many electrons have been removed or protons added?
2. ||| A plastic rod is charged to −20 nC by rubbing.
   a. Have electrons been added to the rod or protons removed? Explain.
   b. How many electrons have been added or protons removed?
3. ||| Suppose you have 1.0 mol of O_2 gas. How many coulombs of positive charge are contained in the atomic nuclei of this gas?
   INT
4. || A plastic rod that has been charged to −15.0 nC touches a metal sphere. Afterward, the rod's charge is −10.0 nC.
   a. What kind of charged particle was transferred between the rod and the sphere, and in which direction? That is, did it move from the rod to the sphere or from the sphere to the rod?
   b. How many charged particles were transferred?
5. || A glass rod that has been charged to +12.0 nC touches a metal sphere. Afterward, the rod's charge is +8.0 nC.
   a. What kind of charged particle was transferred between the rod and the sphere, and in which direction? That is, did it move from the rod to the sphere or from the sphere to the rod?
   b. How many charged particles were transferred?
6. ||| Two identical metal spheres A and B are connected by a metal rod. Both are initially neutral. 1.0×10^{12} electrons are added to sphere A, then the connecting rod is removed. Afterward, what are the charge of A and the charge of B?
7. || Two identical metal spheres A and B are connected by a plastic rod. Both are initially neutral. 1.0×10^{12} electrons are added to sphere A, then the connecting rod is removed. Afterward, what are the charge of A and the charge of B?
8. || If two identical conducting spheres are in contact, any excess charge will be evenly distributed between the two. Three identical metal spheres are labeled A, B, and C. Initially, A has charge q, B has charge $-q/2$, and C is uncharged.
   a. What is the final charge on each sphere if C is touched to B, removed, and then touched to A?
   b. Starting again from the initial conditions, what is the charge on each sphere if C is touched to A, removed, and then touched to B?

Section 20.3 Coulomb's Law

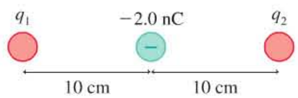
9. || Two 1.0 kg masses are 1.0 m apart on a frictionless table. Each has +1.0 μC of charge.
   INT
   a. What is the magnitude of the electric force on one of the masses?
   b. What is the initial acceleration of each mass if they are released and allowed to move?
10. ||| Two small plastic spheres each have a mass of 2.0 g and a charge of −50.0 nC. They are placed 2.0 cm apart.
   a. What is the magnitude of the electric force between the spheres?
   b. By what factor is the electric force on a sphere larger than its weight?
11. ||| A small plastic sphere with a charge of −5.0 nC is near another small plastic sphere with a charge of −12 nC. If the spheres repel one another with a force of magnitude 8.2×10^{-4} N, what is the distance between the spheres?
12. ||| A small metal bead, labeled A, has a charge of 25 nC. It is touched to metal bead B, initially neutral, so that the two beads share the 25 nC charge, but not necessarily equally. When the two beads are then placed 5.0 cm apart, the force between them is 5.4×10^{-4} N. What are the charges q_A and q_B on the beads?
13. |||| A small glass bead has been charged to +20 nC. A tiny ball bearing 1.0 cm above the bead feels a 0.018 N downward electric force. What is the charge on the ball bearing?
14. | What are the magnitude and direction of the electric force on charge A in Figure P20.14?

FIGURE P20.14



15. ||| In Figure P20.15, charge q_2 experiences no net electric force. What is q_1?

FIGURE P20.15



16. | Object A, which has been charged to +10 nC, is at the origin. Object B, which has been charged to −20 nC, is at $(x, y) = (0.0\text{ cm}, 2.0\text{ cm})$. What are the magnitude and direction of the electric force on each object?

17. | INT A small glass bead has been charged to +20 nC. What are the magnitude and direction of the acceleration of (a) a proton and (b) an electron that is 1.0 cm from the center of the bead?

Section 20.4 The Concept of the Electric Field

18. || What magnitude charge creates a 1.0 N/C electric field at a point 1.0 m away?

19. || What are the strength and direction of the electric field 2.0 cm from a small glass bead that has been charged to +6.0 nC?

20. || A 30 nC charged particle and a 50 nC charged particle are near each other. There are no other charges nearby. The electric force on the 30 nC particle is 0.035 N. The 50 nC particle is then moved very far away. Afterward, what is the magnitude of the electric field at its original position?

21. | What are the strength and direction of the electric field 1.0 mm from (a) a proton and (b) an electron?

22. | A +10 nC charge is located at the origin.
   a. What are the strengths of the electric fields at the positions $(x, y) = (5.0\text{ cm}, 0.0\text{ cm})$, $(-5.0\text{ cm}, 5.0\text{ cm})$, and $(-5.0\text{ cm}, -5.0\text{ cm})$?
   b. Draw a field diagram showing the electric field vectors at these points.

23. | A −10 nC charge is located at the origin.
   a. What are the strengths of the electric fields at the positions $(x, y) = (0.0\text{ cm}, 5.0\text{ cm})$, $(-5.0\text{ cm}, -5.0\text{ cm})$, and $(-5.0\text{ cm}, 5.0\text{ cm})$?
   b. Draw a field diagram showing the electric field vectors at these points.

24. ||| What are the strength and direction of the electric field at the position indicated by the dot in Figure P20.24? Specify the direction as an angle above or below horizontal.

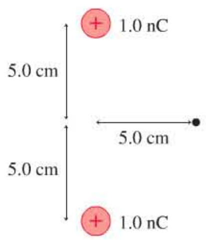


FIGURE P20.24

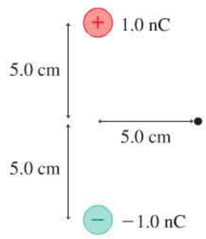


FIGURE P20.25

25. || What are the strength and direction of the electric field at the position indicated by the dot in Figure P20.25? Specify the direction as an angle above or below horizontal.

Section 20.5 Applications of the Electric Field

26. || INT What are the strength and direction of an electric field that will balance the weight of a 1.0 g plastic sphere that has been charged to −3.0 nC?

27. | INT What are the strength and direction of an electric field that will balance the weight of (a) a proton and (b) an electron?

28. || INT A 0.10 g plastic bead is charged by the addition of 1.0×10^{10} excess electrons. What electric field $\vec{E}$ (strength and direction) will cause the bead to hang suspended in the air?

29. || A parallel-plate capacitor is constructed of two square plates, size $L \times L$, separated by distance d. The plates are given charge $\pm Q$. What is the ratio E_f/E_i of the final electric field strength E_f to the initial electric field strength E_i if:
   a. Q is doubled?
   b. L is doubled?
   c. d is doubled?

30. || A parallel-plate capacitor is formed from two 4.0 cm × 4.0 cm electrodes spaced 2.0 mm apart. The electric field strength inside the capacitor is 1.0×10^6 N/C. What is the charge (in nC) on each electrode?

31. | Two identical closely spaced circular disks form a parallel-plate capacitor. Transferring 1.5×10^9 electrons from one disk to the other causes the electric field strength between them to be 1.0×10^5 N/C. What are the diameters of the disks?

Section 20.6 Conductors and Electric Fields

32. ||| Storm clouds may build up large negative charges near their bottom edges. The earth is a good conductor, so the charge on the cloud attracts an equal and opposite charge on the earth under the cloud. The electric field strength near the earth depends on the shape of the earth's surface, as we can explain with a simple model. The top metal plate in Figure 20.32 has uniformly distributed negative charge. The bottom metal plate, which has a high point, has an equal and opposite charge that is free to move.
   a. Sketch the two plates and the region between them, showing the distribution of positive charge on the bottom plate.
   b. Complete your diagram by sketching electric field lines between the two plates. Be sure to note the direction of the field. Where is the field strongest?
   c. Explain why it is more dangerous to be on top of a hill or mountain during a lightning storm than on level ground.

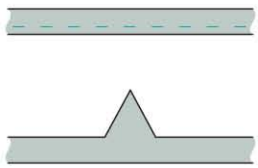


FIGURE P20.32

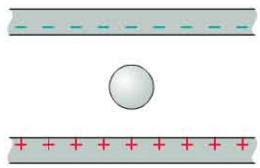


FIGURE P20.33

33. || A neutral conducting sphere is between two parallel charged plates, as shown in Figure P20.33. Sketch the electric field lines in the region between the plates. Be sure to include the effect of the conducting sphere.

Section 20.7 Forces and Torques in Electric Fields

34. ||| INT Two small plastic spheres, one charged to 17 nC and the other to −17 nC, are connected by a 25-mm-long insulating rod. Suppose this dipole is placed in a uniform electric field with strength 7.4×10^5 N/C. What is the maximum possible torque on the dipole?

35. || BIO A protein molecule in an electrophoresis gel has a negative charge. The exact charge depends on the pH of the solution, but 30 excess electrons is typical. What is the magnitude of the electric force on a protein with this charge in a 1500 N/C electric field?

36. BIO Large electric fields in cell membranes cause ions to move through the cell wall, as we will explore in Chapter 23. The field strength in a typical membrane is 1.0×10^7 N/C. What is the magnitude of the force on a calcium ion with charge $+e$?

37. INT Molecules of carbon monoxide are permanent electric dipoles due to unequal sharing of electrons between the carbon and oxygen atoms. Figure P20.37 shows the distance and charges. Suppose a carbon monoxide molecule with a horizontal axis is in a vertical electric field of strength 15,000 N/C.

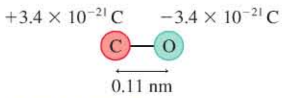


FIGURE P20.37

a. What is the magnitude of the net force on the molecule?
b. What is the magnitude of the torque on the molecule?

General Problems

38. INT A 2.0-mm-diameter copper ball is charged to +50 nC. What fraction of its electrons have been removed? The density of copper is 8900 kg/m^3.

39. INT Pennies today are copper-covered zinc, but older pennies are 3.1 g of solid copper. What are the total positive charge and total negative charge in a solid copper penny that is electrically neutral? The density of copper is 8900 kg/m^3.

40. INT Two protons are 2.0 fm apart. (1 fm = 1 femtometer = 1×10^{-15} m.)
a. What is the magnitude of the electric force on one proton due to the other proton?
b. What is the magnitude of the gravitational force on one proton due to the other proton?
c. What is the ratio of the electric force to the gravitational force?

41. INT The nucleus of a ^{125}Xe atom (an isotope of the element xenon with mass 125 u) is 6.0 fm in diameter. It has 54 protons and charge $q = +54e$. (1 fm = 1 femtometer = 1×10^{-15} m.)
a. What is the electric force on a proton 2.0 fm from the surface of the nucleus?
b. What is the proton's acceleration?
Hint: Treat the spherical nucleus as a point charge.

42. INT Two equally charged, 1.00 g spheres are placed with 2.00 cm between their centers. When released, each begins to accelerate at 225 m/s^2. What is the magnitude of the charge on each sphere?

43. Objects A and B are both positively charged. Both have a mass of 100 g, but A has twice the charge of B. When A and B are placed with 10 cm between their centers, B experiences an electric force of 0.45 N.
a. How large is the force on A?
b. What are the charges q_A and q_B?

44. An electric dipole is formed from ± 1.0 nC point charges spaced 2.0 mm apart. The dipole is centered at the origin, oriented along the y-axis. What is the electric field strength at the points (a) $(x, y) = (10 \text{ mm}, 0 \text{ mm})$ and (b) $(x, y) = (0 \text{ mm}, 10 \text{ mm})$?

45. What are the strength and direction of the electric field at the position indicated by the dot in Figure P20.45? Specify the direction as an angle above or below horizontal.

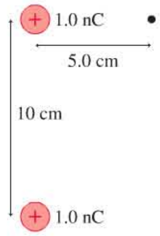


FIGURE P20.45

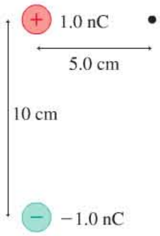


FIGURE P20.46

46. What are the strength and direction of the electric field at the position indicated by the dot in Figure P20.46? Specify the direction as an angle above or below horizontal.

47. What is the force on the 1.0 nC charge in Figure P20.47? Give your answer as a magnitude and a direction.

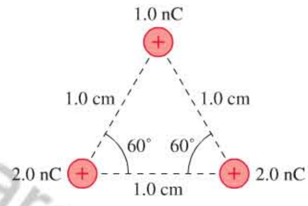


FIGURE P20.47

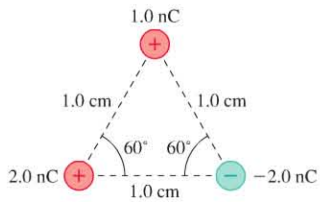


FIGURE P20.48

48. What is the force on the 1.0 nC charge in Figure P20.48? Give your answer as a magnitude and a direction.

49. What is the magnitude of the force on the 1.0 nC charge in the middle of Figure P20.49 due to the four other charges?

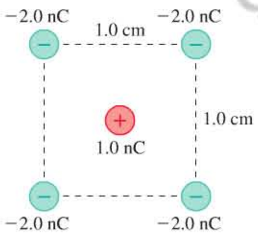


FIGURE P20.49

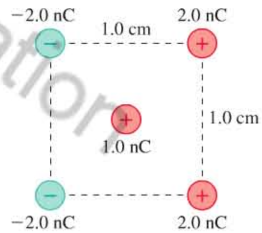


FIGURE P20.50

50. What are the magnitude and direction of the force on the 1.0 nC charge in the middle of Figure P20.50 due to the four other charges?

51. What are the magnitude and direction of the force on the 1.0 nC charge at the bottom of Figure P20.51?

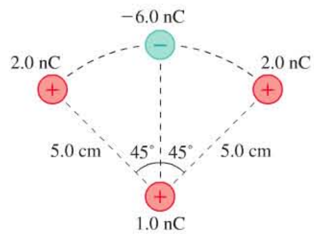


FIGURE P20.51

52. A 5.0 nC point charge sits at $x = 0$. At the same time, a 4500 N/C uniform electric field (created by distant source charges) points in the positive x-direction. At what point along the x-axis, if any, would (a) a proton and (b) an electron experience no net force?

53. || The net force on the 1.0 nC charge in Figure P20.53 is zero. What is q?

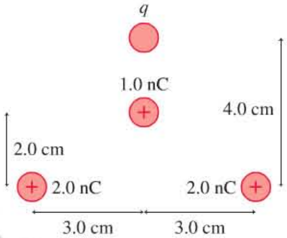


FIGURE P20.53

54. || Two particles have positive charges q and Q. A third charged particle is placed halfway between them. What must this particle's charge be so that the net force on charge Q is zero?

55. ||||| Figure P20.55 shows four charges at the corners of a square of side L. Assume q and Q are positive.
   a. Draw a diagram showing the three forces on charge q due to the other charges. Give your vectors the correct relative lengths.
   b. Find an expression for the magnitude of the net force on q.

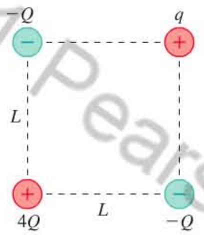


FIGURE P20.55

56. | INT Suppose the magnitude of the proton charge differs from that of the electron charge by a mere 1 part in 10^9.
   a. What would be the force between two 2.0-mm-diameter copper spheres 1.0 cm apart? Assume that each copper atom has an equal number of electrons and protons. The density of copper is 8900 kg/m^3.
   b. Would this amount of force be detectable? What can you conclude from the fact that no such forces are observed?

57. ||| INT In a simple model of the hydrogen atom, the electron moves in a circular orbit of radius 0.053 nm around a stationary proton. How many revolutions per second does the electron make?
Hint: What must be true for a force that causes circular motion?

58. ||| BIO A 0.10 g honeybee acquires a charge of +23 pC while flying.
   a. The electric field near the surface of the earth is typically 100 N/C, directed downward. What is the ratio of the electric force on the bee to the bee's weight?
   b. What electric field strength and direction would allow the bee to hang suspended in the air?

59. ||||| A +10 nC charge is located at $(x, y) = (0\text{ cm}, 10\text{ cm})$ and a −5.0 nC charge is located $(x, y) = (5.0\text{ cm}, 0\text{ cm})$. Where would a −10 nC charge need to be located in order that the electric field at the origin be zero?

60. ||| INT Two 2.0-cm-diameter disks face each other, 1.0 mm apart. They are charged to ±10 nC.
   a. What is the electric field strength between the disks?
   b. A proton is shot from the negative disk toward the positive disk. What launch speed must the proton have to just barely reach the positive disk?

61. |||| INT The electron gun in a television tube uses a uniform electric field to accelerate electrons from rest to 5.0×10^7 m/s in a distance of 1.2 cm. What is the electric field strength?

62. |||| INT A 0.020 g plastic bead hangs from a lightweight thread. Another bead is fixed in position beneath the point where the thread is tied. If both beads have charge q, the moveable bead swings out to the position shown in Figure P20.62. What is q?

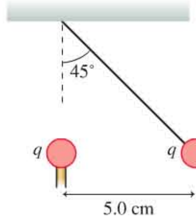


FIGURE P20.62

63. ||| INT You have a lightweight spring whose unstretched length is 4.0 cm. You're curious to see if you can use this spring to measure charge. First, you attach one end of the spring to the ceiling and hang a 1.0 g mass from it. This stretches the spring to a length of 5.0 cm. You then attach two small plastic beads to the opposite ends of the spring, lay the spring on a frictionless table, and give each plastic bead the same charge. This stretches the spring to a length of 4.5 cm. What is the magnitude of the charge (in nC) on each bead?

64. ||||| INT Two 3.0 g spheres on 1.0-m-long threads repel each other after being equally charged, as shown in Figure P20.64. What is the charge q?

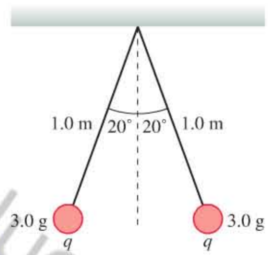


FIGURE P20.64

65. ||||| INT An electric field $\vec{E}$ = (100,000 N/C, right) causes the 5.0 g ball in Figure P20.65 to hang at a 20° angle. What is the charge on the ball?

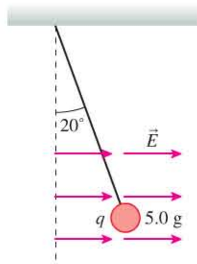


FIGURE P20.65

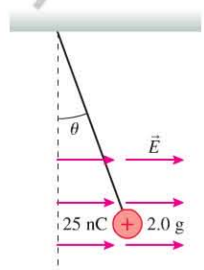


FIGURE P20.66

66. |||| INT An electric field $\vec{E}$ = (200,000 N/C, right) causes the 2.0 g ball in Figure P20.66 to hang at an angle. What is θ?

67. || INT A small charged bead has a mass of 1.0 g. It is held in a uniform electric field $\vec{E}$ = (200,000 N/C, up). When the bead is released, it accelerates upward with an acceleration of 20 m/s^2. What is the charge on the bead?

68. || INT A bead with a mass of 0.050 g and a charge of 15 nC is free to slide on a vertical rod. At the base of the rod is a fixed 10 nC charge. In equilibrium, at what height above the fixed charge does the bead rest?

69. || INT A small bead with a positive charge q is free to slide on a horizontal wire of length 4.0 cm. At the left end of the wire is a fixed charge q, and at the right end is a fixed charge $4q$. How far from the left end of the wire does the bead come to rest?

In Problems 70 and 71 you are given the equation used to solve a problem. For each of these,

a. Write a realistic problem for which this is the correct equation.
b. Finish the solution of the problem.

70. | $$\frac{(9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \times N \times (1.60 \times 10^{-19}\ \mathrm{C})}{(1.0 \times 10^{-6}\ \mathrm{m})^2} = 1.5 \times 10^6\ \mathrm{N/C}$$

71. | $$\frac{(9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2})q^2}{(0.015\ \mathrm{m})^2} = 0.020\ \mathrm{N}$$

Passage Problems

Flow Cytometry BIO

Flow cytometry, illustrated in Figure P20.72, is a technique used to sort cells by type. The cells are placed in a conducting saline solution which is then forced from a nozzle. The stream breaks up into small droplets, each containing one cell. A metal collar surrounds the stream right at the point where the droplets separate from the stream. Charging the collar polarizes the conducting liquid, causing the droplets to become charged as they break off from the stream. A laser beam probes the solution just upstream from the charging collar, looking for the presence of certain types of cells. All droplets containing one particular type of cell are given the same charge by the charging collar. Droplets with other desired types of cells receive a different charge, and droplets with no desired cell receive no charge. The charged droplets then pass between two parallel charged electrodes where they receive a horizontal force that directs them into different collection tubes, depending on their charge.

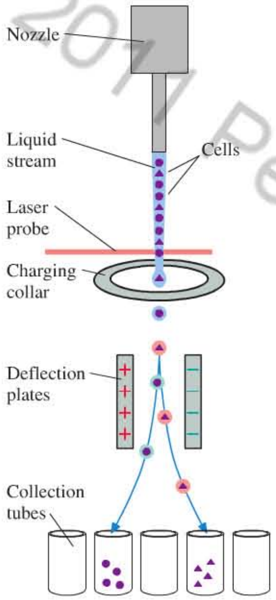


FIGURE P20.72

72. | If the charging collar has a positive charge, the net charge on a droplet separating from the stream will be
A. Positive. B. Negative. C. Neutral.
D. The charge will depend on the type of cell.

73. | Which of the following describes the charges on the droplets that end up in the five tubes, moving from left to right?
A. $+2q, +q, 0, -q, -2q$
B. $+q, +2q, 0, -2q, -q$
C. $-q, -2q, 0, +2q, +q$
D. $-2q, -q, 0, +q, +2q$

74. | Because the droplets are conductors, a droplet's positive and negative charges will separate while the droplet is in the region between the deflection plates. Suppose a neutral droplet passes between the plates. The droplet's dipole moment will point
A. Up. B. Down. C. Left. D. Right.

75. | Another way to sort the droplets would be to give each droplet the same charge, then vary the electric field between the deflection plates. For the apparatus as sketched, this technique will not work because
A. Several droplets are between the plates at one time, and they would all feel the same force.
B. The cells in the solution have net charges that would affect the droplet charge.
C. A droplet with a net charge would always experience a net force between the plates.
D. The droplets would all repel each other, and this force would dominate the deflecting force.

STOP TO THINK ANSWERS

Stop to Think 20.1: A. The electroscope is originally given a positive charge. The charge spreads out, and the leaves repel each other. When a rod with a negative charge is brought near, some of the positive charge is attracted to the top of the electroscope, away from the leaves. There is less charge on the leaves, and so they move closer together.

Stop to Think 20.2: $q_E(+3e) > q_A(+1e) > q_D(0) > q_B(-1e) > q_C(-2e)$.

Stop to Think 20.3: B. The two forces are an action/reaction pair, opposite in direction but *equal* in magnitude.

Stop to Think 20.4: $E_B > E_A > E_D > E_C$. The field is proportional to the charge, and inversely proportional to the square of the distance.

Stop to Think 20.5: C. Electric field lines *start* on positive charges. Very near to each of the positive charges, the field lines should look like the field lines of a single positive charge.

Stop to Think 20.6: $F_A = F_B = F_C = F_D = F_E$. The field inside a capacitor is the same at all points. Because the field is uniform, the force on the proton will be the same at all points. The electric field exists at all points whether or not a vector is shown at that point.