This comb has been rubbed by a cloth or paper towel to give it a static electric charge. Because the comb is electrically charged, it induces a separation of charge in all those scraps of paper, and thus attracts them.

CHAPTER 16

ELECTRIC CHARGE AND ELECTRIC FIELD

The word "electricity" may evoke an image of complex technology: computers, lights, motors, electric power. But the tric force would seem to play an even deeper role in our lives cording to atomic theory, the forces that act between atoms and mol to hold them together to form liquids and solids are electrical forces electric forces are also involved in the metabolic processes that within our bodies. Many of the forces we have dealt with so far, elastic forces, the normal force, and other contact forces (push pulls) are now considered to result from electric forces acting at the ic level. This does not include gravity, however, which is a separate

The earliest studies on electricity date back to the ancients, but been only in the past two centuries that electricity was studied in detail will discuss the development of ideas about electricity, including devices, as well as the relation to magnetism, in the next seven chapters

[†] As we discussed in Section 5–10, physicists in this century came to recognize four fundamental forces in nature: (1) gravitational force, (2) electromagnetic force (we later that electric and magnetic forces are intimately related), (3) strong nuclear (4) weak nuclear force. The last two forces operate at the level of the nucleus of The electromagnetic and weak nuclear forces are now thought to have a common known as the electroweak force. We will discuss these forces in later chapters.

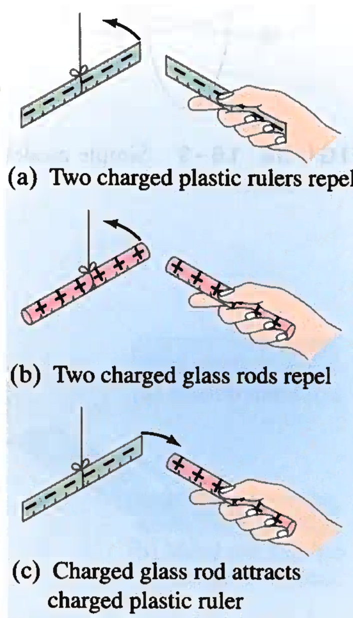

(a) (b)

FIGURE 16–1 Rub a plastic ruler and bring it close to some tiny pieces of paper.

16–1 Static Electricity; Electric Charge and Its Conservation

The word *electricity* comes from the Greek word *elektron*, which means "amber." Amber is petrified tree resin, and the ancients knew that if you rub an amber rod with a piece of cloth, the amber attracts small pieces of leaves or dust. A piece of hard rubber, a glass rod, or a plastic ruler rubbed with a cloth will also display this "amber effect," or **static electricity** as we call it today. You can readily pick up small pieces of paper with a plastic comb or ruler that you've just vigorously rubbed with even a paper towel. See the photo on the previous page and Fig. 16–1. You have probably experienced static electricity when combing your hair or when taking a synthetic blouse or shirt from a clothes dryer. And you may have felt a shock when you touched a metal doorknob after sliding across a car seat or walking across a nylon carpet. In each case, an object becomes "charged" due to a rubbing process and is said to possess a net **electric charge**.

FIGURE 16–2 Unlike charges attract, whereas like charges repel one another.


(a) Two charged plastic rulers repel

(b) Two charged glass rods repel

(c) Charged glass rod attracts charged plastic ruler

Is all electric charge the same, or is it possible that there is more than one type? In fact, there are two types of electric charge, as the following simple experiments show. A plastic ruler is suspended by a thread and rubbed vigorously with a cloth to charge it. When a second ruler, which has also been charged in the same way, is brought close to the first, it is found that the one ruler *repels* the other. This is shown in Fig. 16–2a. Similarly, if a rubbed glass rod is brought close to a second charged glass rod, again a repulsive force is seen to act, Fig. 16–2b. However, if the charged glass rod is brought close to the charged plastic ruler, it is found that they *attract* each other, Fig. 16–2c. The charge on the glass must therefore be different from that on the plastic. Indeed, it is found experimentally that all charged objects fall into one of two categories. Either they are attracted to the plastic and repelled by the glass, just as glass is; or they are repelled by the plastic and attracted to the glass, just as the plastic ruler is. Thus there seem to be two, and only two, types of electric charge. Each type of charge repels the same type but attracts the opposite type. That is: **unlike charges attract; like charges repel**.

Likes repel; unlikes attract

The two types of electric charge were referred to as *positive* and *negative* by the American statesman, philosopher, and scientist Benjamin Franklin (1706–1790). The choice of which name went with which type of charge was of course arbitrary. Franklin's choice sets the charge on the rubbed glass rod to be positive charge, so the charge on a rubbed plastic ruler (or amber) is called negative charge. We still follow this convention today.

Franklin argued that whenever a certain amount of charge is produced on one body in a process, an equal amount of the opposite type of charge is produced on another body. The positive and negative are to be treated *algebraically*, so that during any process, the net change in the amount of charge produced is zero. For example, when a plastic ruler is rubbed with a paper towel, the plastic acquires a negative charge and the towel an equal amount of positive charge. The charges are separated, but the sum of the two is zero. This is an example of a law that is now well established: the **law of conservation of electric charge**, which states that

LAW OF CONSERVATION OF ELECTRIC CHARGE

the net amount of electric charge produced in any process is zero;

If one object or one region of space acquires a positive charge, then an equal amount of negative charge will be found in neighboring areas or objects. No violations have ever been found, and this conservation law is as firmly established as those for energy and momentum.

16–2 Electric Charge in the Atom

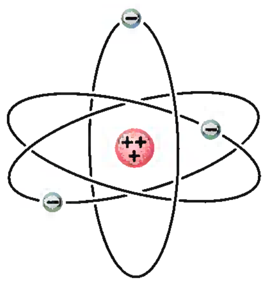


FIGURE 16–3 Simple model of the atom.

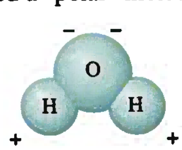
Only within the past century has it become clear that electricity starts inside the atom itself. In later chapters we will discuss atomic structure and the ideas that led to our present view of the atom in more detail. But it will help our understanding of electricity if we discuss it briefly now.

Today's view, somewhat simplified, shows the atom as having a heavy, positively charged nucleus surrounded by one or more negatively charged electrons (Fig. 16–3). The nucleus contains protons, which are positively charged, and neutrons, which have no net electric charge. The magnitude of the charge on protons and electrons is exactly the same, but their signs are opposite. Hence, neutral atoms contain equal numbers of protons and electrons. Sometimes, however, an atom may lose one or more of its electrons, or may gain extra electrons. In this case the atom will have a net positive or negative charge, and is called an **ion**.

In solid materials the nuclei tend to remain close to fixed positions, whereas some of the electrons move quite freely. The charging of a solid object by rubbing is explained mainly by the transfer of electrons from one material to the other. When a plastic ruler becomes negatively charged by rubbing with a paper towel, the transfer of electrons from the towel to the plastic leaves the towel with a positive charge equal in magnitude to the negative charge acquired by the plastic. (In liquids and gases, nuclei or ions can move as well as electrons.)

Normally when objects are charged by rubbing, they hold their charge only for a limited time and eventually return to the neutral state. Where does the charge go? In some cases it is neutralized by charged ions in the air (formed, for example, by collisions with charged particles known as cosmic rays that reach the Earth from space). Often more importantly, the charge can "leak off" onto water molecules in the air. This is because water molecules are **polar**—that is, even though they are neutral, their charge is not distributed uniformly, Fig. 16–4. Thus the extra electrons on, say, a charged plastic ruler can "leak off" into the air because they are attracted to the positive end of water molecules. A positively charged object, on the other hand, can be neutralized by transfer of loosely held electrons from water molecules in the air. On dry days, static electricity is much more noticeable since the air contains fewer water molecules to allow leakage. On humid or rainy days, it is difficult to make any object hold its charge for long.

FIGURE 16–4 Diagram of a water molecule. Because it has opposite charges on different ends, it is called a "polar" molecule.



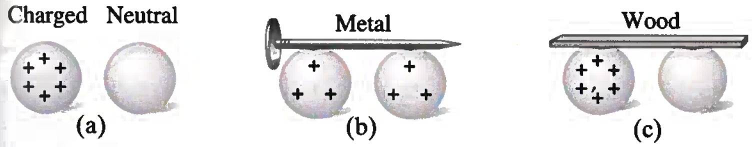


FIGURE 16–5 (a) A charged metal sphere and a neutral metal sphere. (b) The two spheres connected by a metal nail, which conducts charge from one to the other. (c) The two spheres connected by an insulator (wood): almost no charge is conducted.

16–3 Insulators and Conductors

Suppose we have two metal spheres, one highly charged and the other electrically neutral (Fig. 16–5a). If we now place an iron nail so that it touches both the spheres (Fig. 16–5b), it is found that the previously uncharged sphere quickly becomes charged. If, instead, we connect the two spheres together by a wooden rod or a piece of rubber (Fig. 16–5c), the uncharged ball does not become noticeably charged. Materials like the iron nail are said to be **conductors** of electricity, whereas wood and rubber are **nonconductors** or **insulators**.

Metals are good conductors

Metals are generally good conductors whereas most other materials are insulators (although even insulators conduct electricity very slightly). It is interesting that nearly all natural materials fall into one or the other of these two quite distinct categories. There are a few materials, however (notably silicon, germanium, and carbon), that fall into an intermediate (but distinct) category known as **semiconductors**.

From the atomic point of view, the electrons in an insulating material are bound very tightly to the nuclei. In a good conductor, on the other hand, some of the electrons are bound very loosely and can move about freely within the material (although they cannot *leave* the metal easily) and are often referred to as *free electrons* or *conduction electrons*. When a positively charged object is brought close to or touches a conductor, the free electrons are attracted by this positive charge and move quickly toward it. On the other hand, the free electrons move swiftly away from a negative charge that is brought close. In a semiconductor, there are very few free electrons, and in an insulator, almost none.

16–4 Induced Charge; the Electroscope

Suppose a positively charged metal object is brought close to an uncharged metal object. If the two touch, the free electrons in the neutral one are attracted to the positively charged object and some will pass over to it, Fig. 16–6. Since the second object is now missing some of its negative electrons, it will have a net positive charge. This process is called "charging by conduction," or "by contact," and the two objects end up with the same sign of charge.

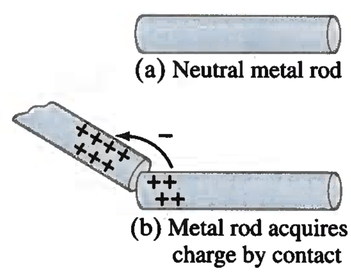
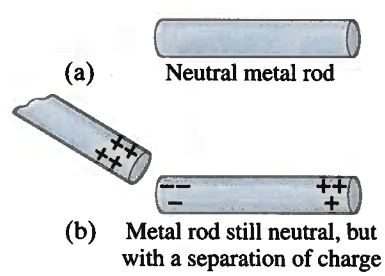


FIGURE 16–6 (a) Neutral metal rod acquires a charge (b) when placed in contact with a charged metal object.

Now suppose a positively charged object is brought close to a neutral metal rod, but does not touch it. Although the electrons of the metal rod do not leave the rod, they still move within the metal toward the charged object, which leaves a positive charge at the opposite end, Fig. 16–7. A charge is said to have been *induced* at the two ends of the metal rod. Of course no net charge has been created in the rod; charges have merely been *separated*. The net charge on the metal rod is still zero. However, if the metal were broken into two pieces, we could have two charged objects, one charged positively and one charged negatively.

FIGURE 16–7 Charging by induction.



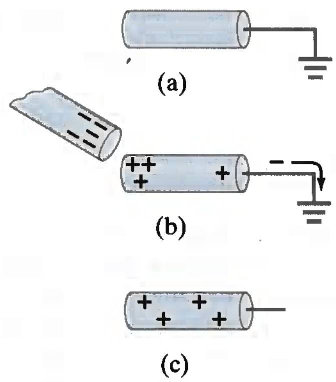


FIGURE 16-8 Inducing a charge on an object connected to ground.

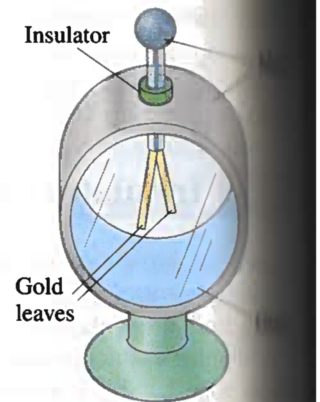


FIGURE 16-9 Elec

Another way to induce a net charge on a metal object is to con with a conducting wire to the ground (or a conducting pipe leadin the ground) as shown in Fig. 16–8a (⏚ means "ground"). The ob then said to be "grounded" or "earthed." Now the Earth, since it large and can conduct, can easily accept or give up electrons; hence like a reservoir for charge. If a charged object—let's say negativ time—is brought up close to the metal, free electrons in the metal pelled and many of them move down the wire into the Earth, Fig. 16 This leaves the metal positively charged. If the wire is now cut, the will have a positive induced charge on it (Fig. 16–8c). If the wire w after the negative object is moved away, the electrons would all moved back into the metal and it would be neutral.

An **electroscope** is a device that can be used for detecting ch As shown in Fig. 16–9, inside of a case are two movable leaves, made of gold. (Sometimes only one leaf is movable.) The leave connected by a conductor to a metal ball on the outside of the cas are insulated from the case itself. If a positively charged object is b close to the knob, a separation of charge is induced, as electrons are ed up into the ball, leaving the leaves positively charged, Fig. 16 The two leaves repel each other as shown. If, instead, the knob is ch by conduction, the whole apparatus acquires a net charge as show Fig. 16–10b. In either case, the greater the amount of charge, the great separation of the leaves.

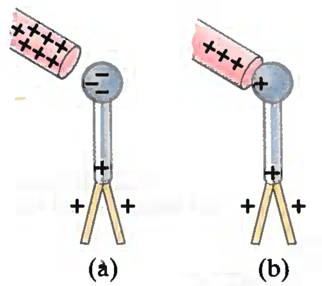
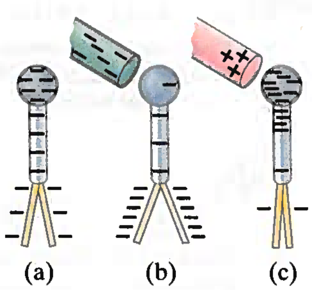


FIGURE 16-10 Electroscope charged (a) by induction, (b) by conduction.

FIGURE 16-11 A previously charged electroscope can be used to determine the sign of a given charge.



Note, however, that you cannot tell the sign of the charge in thi since a negative charge will cause the leaves to separate just as much equal-magnitude positive charge—in either case the two leaves repel other. An electroscope can, however, be used to determine the sign of charge if it is first charged by conduction, say negatively, as in Fig. 16 Now if a negative object is brought close, as in Fig. 16–11b, more elect are induced to move down into the leaves and they separate furthe the other hand, if a positive charge is brought close, the electrons are duced to flow upward, leaving the leaves less negative and their separa is reduced, Fig. 16–11c.

The electroscope was much used in the early studies of electricity same principle, aided by some electronics, is used in much more sen modern **electrometers**.

16–5 Coulomb's Law

We have seen that an electric charge exerts a force on other electric charges. What factors affect the magnitude of this force? To answer this, the French physicist Charles Coulomb (1736–1806) investigated electric forces in the 1780s using a torsion balance (Fig. 16–12) much like that used by Cavendish for his studies of the gravitational force (Section 5–6).

Although precise instruments for the measurement of electric charge were not available in Coulomb's time, he was able to prepare small spheres with different magnitudes of charge in which the *ratio* of the charges was known. He reasoned that if a charged conducting sphere is placed in contact with an identical uncharged sphere, the charge on the first would be shared equally by the two of them because of symmetry. He thus had a way to produce charges equal to $\frac{1}{2}$, $\frac{1}{4}$, and so on, of the original charge. Although he had some difficulty with induced charges, Coulomb was able to argue that the force one tiny charged object exerted on a second tiny charged object is directly proportional to the charge on each of them. That is, if the charge on either one of the objects was doubled, the force was doubled; and if the charge on both of the objects was doubled, the force increased to four times the original value. This was the case when the distance between the two charges remained the same. If the distance between them was allowed to increase, he found that the force decreased with the *square of the distance* between them. That is, if the distance was doubled, the force fell to one-fourth of its original value. Thus, Coulomb concluded, the force one tiny charged object exerts on a second one is proportional to the product of the magnitude of the charge on one, Q_1, times the magnitude of the charge on the other, Q_2, and inversely proportional to the square of the distance r between them (Fig. 16–13). As an equation, we can write **Coulomb's law** as

$$F = k\frac{Q_1 Q_2}{r^2}, \qquad (16\text{–}1)$$

COULOMB'S LAW

where k is a proportionality constant. The validity of Coulomb's law today rests on precision measurements that are much more sophisticated than Coulomb's original experiment.

Since we are dealing here with a new quantity (electric charge), we could choose its unit so that the proportionality constant k in Eq. 16–1 would be one. Indeed, such a system of units was once common.† However, the most widely used unit now is the **coulomb** (C), which is the SI unit. The precise definition of the coulomb today is in terms of electric current and magnetic field, and will be discussed later (Section 20–7). In SI units, k has the value

Unit for charge: the coulomb

$$k = 8.988 \times 10^9\,\mathrm{N{\cdot}m^2/C^2} \approx 9.0 \times 10^9\,\mathrm{N{\cdot}m^2/C^2}.$$

Thus, 1 C is that amount of charge which, if placed on each of two point objects 1.0 m apart, will result in each object exerting a force of $(9.0 \times 10^9\,\mathrm{N{\cdot}m^2/C^2})(1.0\,\mathrm{C})(1.0\,\mathrm{C})/(1.0\,\mathrm{m})^2 = 9.0 \times 10^9\,\mathrm{N}$ on the other. This would be an enormous force, equal to the weight of almost a million tons. We don't normally encounter charges as large as a coulomb.

Charges produced by rubbing ordinary objects (such as a comb or plastic ruler) are typically around a microcoulomb ($1\,\mu\mathrm{C} = 10^{-6}\,\mathrm{C}$) or

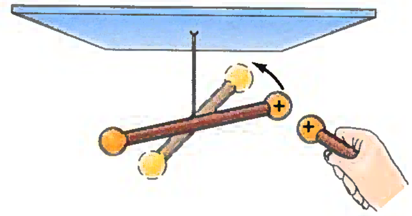
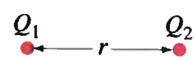


FIGURE 16–12 Schematic diagram of Coulomb's apparatus. It is similar to Cavendish's, which was used for the gravitational force. When a charged sphere is placed close to the one on the suspended bar, the bar rotates slightly. The suspending fiber resists the twisting motion and the angle of twist is proportional to the force applied. By the use of this apparatus, Coulomb investigated how the electric force varies as a function of the magnitude of the charges and of the distance between them.

FIGURE 16–13 Coulomb's law, Eq. 16–1, gives the force between two point charges, Q_1 and Q_2, a distance r apart.



†This is a cgs system of units, and the unit of electric charge is called the *electrostatic unit* (esu) or the statcoulomb. One esu is defined as that charge, on each of two point objects 1 cm apart, that gives rise to a force of 1 dyne.

less. The magnitude of the charge on one electron, on the other han been determined to be about 1.602×10^{-19} C, and its sign is negati is the smallest known charge,† and because of its fundamental natu given the symbol e and is often referred to as the *elementary charg*

Charge on electron (the elementary charge)

$$e = 1.602 \times 10^{-19}\ \text{C}.$$

Note that e is defined as a positive number, so the charge on the ele $-e$. (The charge on a proton, on the other hand, is $+e$). Since an cannot gain or lose a fraction of an electron, the net charge on any must be an integral multiple of this charge. Electric charge is thus sa **quantized** (existing only in discrete amounts: $1e, 2e, 3e$, etc.). Becaus small, however, we normally don't notice this discreteness in macro charges (1 μC requires about 10^{13} electrons), which thus seem conti

Electric charge is quantized

Equation 16–1 gives the *magnitude* of the electric force that eith ject exerts on the other, when the magnitudes of the charges Q_1 and given. The *direction* of the electric force *is always along the line join two objects*. If the two charges have the same sign, the force on eithe is directed away from the other. If the two charges have opposite sig force on one is directed toward the other, Fig. 16–14. Notice that th one charge exerts on the second is equal but opposite to that exerted second on the first, in accord with Newton's third law.

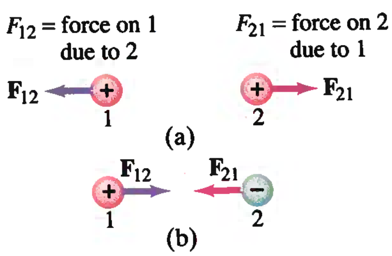


FIGURE 16–14 Direction of the force depends on whether the charges have (a) the same sign, or (b) opposite sign.

[Note the similarity of Coulomb's law to the law of universal gravit Eq. 5–4. Both are inverse square laws ($F \propto 1/r^2$). Both also have a p tionality to a product of a property of each body—mass for gravity, el charge for electricity. A major difference between the two laws is that g ty is always an attractive force, whereas the electric force can be eithe tractive or repulsive.]

The constant k in Eq. 16–1 is often written in terms of another co ϵ_0, called the **permittivity of free space**. It is related to k by $k =$ Coulomb's law can then be written

COULOMB'S LAW (in terms of ϵ_0)

$$F = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r^2},$$

where

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

Equation 16–2 looks more complicated than Eq. 16–1, but other mental equations we haven't seen yet are simpler in terms of ϵ_0 than k. It doesn't matter which form we use, of course, since Eqs. 16 16–2 are equivalent.

It should be recognized that Eqs. 16–1 and 16–2 apply to whose size is much smaller than the distance between them. Ideally precise for **point charges** (spatial size negligible compared to oth tances). For finite-sized objects, it is not always clear what value to r, particularly since the charge may not be distributed uniformly objects. If the two objects are spheres and the charge is known to tributed uniformly on each, then r is the distance between their cen

Coulomb's law describes the force between two charges whe are at rest. Additional forces come into play when charges are in m and these will be discussed in later chapters. In this chapter we only charges at rest, the study of which is called **electrostatics**.

†According to the standard model of elementary particle physics, subnuclear partic quarks have a smaller charge than that on the electron, equal to $\frac{1}{3}e$ or $\frac{2}{3}e$. Quarks h been detected directly, and theory indicates that free quarks may not be detectable

When calculating with Coulomb's law, we usually ignore the signs of the charges and determine direction based on whether the force is attractive or repulsive.

EXAMPLE 16–1 **Electric force on electron by proton.** Determine the magnitude of the electric force on the electron of a hydrogen atom exerted by the single proton ($Q_2 = +e$) that is its nucleus. Assume the electron "orbits" the proton at its average distance of $r = 0.53 \times 10^{-10}$ m, Fig. 16–15.

SOLUTION We use Eq. 16–1 with $r = 0.53 \times 10^{-10}$ m, and $Q_1 = Q_2 = 1.6 \times 10^{-19}$ C (ignoring the signs of the charges):

$$F = \frac{(9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2})(1.6 \times 10^{-19}\ \mathrm{C})(1.6 \times 10^{-19}\ \mathrm{C})}{(0.53 \times 10^{-10}\ \mathrm{m})^2}$$

$$= 8.2 \times 10^{-8}\ \mathrm{N}.$$

The direction of the force on the electron is toward the proton, since the charges have opposite signs and the force is attractive.

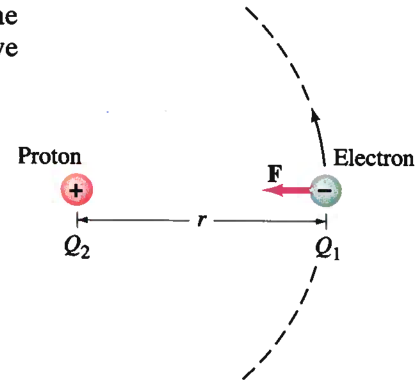


FIGURE 16–15 Example 16–1.

CONCEPTUAL EXAMPLE 16–2 **Which charge exerts the greater force?** Two positive point charges, $Q_1 = 50\,\mu$C and $Q_2 = 1\,\mu$C, are separated by a distance l, Fig. 16–16. Which is larger in magnitude, the force that Q_1 exerts on Q_2, or the force that Q_2 exerts on Q_1?

RESPONSE From Coulomb's law, the force on Q_1 exerted by Q_2 is:

$$F_{12} = k\frac{Q_1 Q_2}{l^2}.$$

The force on Q_2 exerted by Q_1 is the same except that Q_1 and Q_2 are reversed. The equation is symmetric with respect to the two charges, so $F_{21} = F_{12}$. Newton's third law also tells us that these two forces must have equal magnitude.

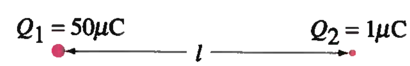


FIGURE 16–16 Example 16–2.

It is very important to keep in mind that Eq. 16–1 (or 16–2) gives the force on a charge due to only *one* other charge. If several (or many) charges are present, the *net force on any one of them will be the vector sum of the forces due to each of the others.*

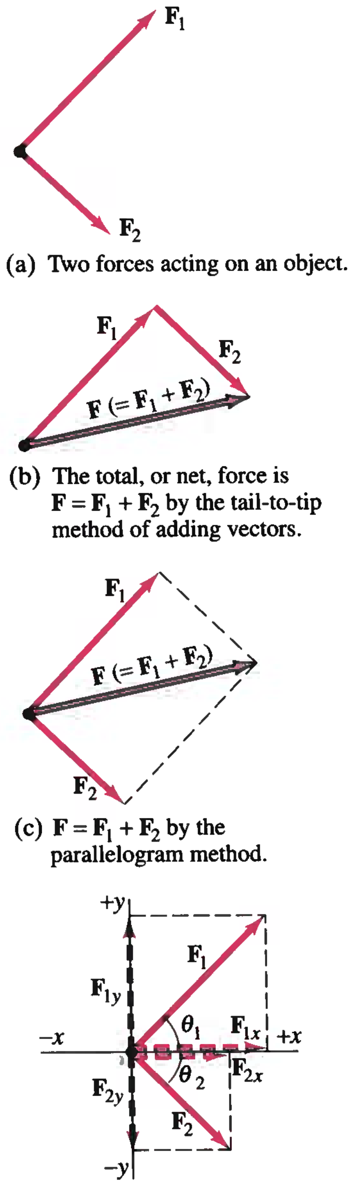
Electric forces add as vectors

16–6 Solving Problems Involving Coulomb's Law and Vectors

The electric force between charged particles at rest (sometimes referred to as the **electrostatic force** or as the **Coulomb force**) is, like all forces, a vector: it has both magnitude and direction. When several forces act on an object (call them $\mathbf{F}_1$, $\mathbf{F}_2$, etc.), the net force $\mathbf{F}_{net}$ on the object is the vector sum of all the forces acting on it:

$$\mathbf{F}_{net} = \mathbf{F}_1 + \mathbf{F}_2 + \cdots.$$

This is sometimes referred to as the principle of superposition for forces). We studied how to add vectors in Chapter 3, and in Chapter 4 we applied the rules for adding vectors to forces. It might be a good idea now to review Sections 3–2, 3–3, 3–4, as well as Section 4–9 on general problem-solving techniques. Here is a brief review of vectors.



(a) Two forces acting on an object.

(b) The total, or net, force is $\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2$ by the tail-to-tip method of adding vectors.

(c) $\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2$ by the parallelogram method.

(d) $\mathbf{F}_1$ and $\mathbf{F}_2$ resolved into their x and y components.

FIGURE 16–17 Review of vector addition.

Given two vector forces, $\mathbf{F}_1$ and $\mathbf{F}_2$, acting on a body (Fig. 16–1 can be added using the tail-to-tip method (Fig. 16–17b) or by the pa gram method (Fig. 16–17c), as discussed in Section 3–2. These two m are useful for *understanding* a given problem (for getting a picture mind of what is going on), but for *calculating* the direction and magn the resultant sum, it is more precise to use the method of adding comp Figure 16–17d shows the components of our $\mathbf{F}_1$ and $\mathbf{F}_2$ resolved into nents along chosen x and y axes (for more details, see Section 3–4). F definitions of the trigonometric functions (Figs. 3–11 and 3–12), we h

$$F_{1x} = F_1 \cos\theta_1 \qquad F_{2x} = F_2 \cos\theta_2$$

$$F_{1y} = F_1 \sin\theta_1 \qquad F_{2y} = -F_2 \sin\theta_2.$$

We add up the x and y components separately to obtain the comp of the resultant force $\mathbf{F}$, which are

$$F_x = F_{1x} + F_{2x} = F_1 \cos\theta_1 + F_2 \cos\theta_2,$$

$$F_y = F_{1y} + F_{2y} = F_1 \sin\theta_1 - F_2 \sin\theta_2.$$

The magnitude of $\mathbf{F}$ is

$$F = \sqrt{F_x^2 + F_y^2}.$$

The direction of $\mathbf{F}$ is specified by the angle θ that $\mathbf{F}$ makes with th which is given by

$$\tan\theta = \frac{F_y}{F_x}.$$

This review has been necessarily brief; a rereading of the appro parts of Chapters 3 and 4 will give more details.

When dealing with several charges, it is often helpful to use sub on each of the forces involved. The first subscript refers to the parti which the force acts; the second refers to the particle that exerts the f For example, if we have three charges, $\mathbf{F}_{31}$ means the force exerted o ticle 3 *by* particle 1.

As in all problem solving, it is very important to draw a diagra particular a free-body diagram for each body (Chapter 4), showing al forces acting on that body. In applying Coulomb's law, we usually with charge magnitudes only (leaving out minus signs) to get the m tude of each force. Then determine the direction of the force phy (like charges repel, unlike attract), and show the force on the di Finally, add the forces on one object together as vectors.

EXAMPLE 16–3 **Three charges in a line.** Three charged partic arranged in a line, as shown in Fig. 16–18a. Calculate the net elect force on particle 3 (the $-4.0\,\mu C$ on the right) due to the other two ch

SOLUTION The net force on particle 3 will be the vector sum o force $\mathbf{F}_{31}$ exerted by particle 1 and the force $\mathbf{F}_{32}$ exerted by parti $\mathbf{F} = \mathbf{F}_{31} + \mathbf{F}_{32}$. The magnitudes of these two forces are

$$F_{31} = \frac{(9.0 \times 10^9\,\mathrm{N\cdot m^2/C^2})(4.0 \times 10^{-6}\,\mathrm{C})(8.0 \times 10^{-6}\,\mathrm{C})}{(0.50\,\mathrm{m})^2}$$

$$F_{32} = \frac{(9.0 \times 10^9\,\mathrm{N\cdot m^2/C^2})(4.0 \times 10^{-6}\,\mathrm{C})(3.0 \times 10^{-6}\,\mathrm{C})}{(0.20\,\mathrm{m})^2}$$

Since we were calculating the magnitudes of the forces, we omitted th the charges; but we must be aware of them to get the direction of each force. Let the line joining the particles be the x axis, and we take it positive to the right. Then, because $\mathbf{F}_{31}$ is repulsive and $\mathbf{F}_{32}$ is attractive, the directions of the forces are as shown in Fig. 16–18b: F_{31} points in the positive x direction and F_{32} points in the negative x direction. The net force on particle 3 is then

$$F = -F_{32} + F_{31} = -2.7\text{ N} + 1.2\text{ N} = -1.5\text{ N}.$$

The magnitude of the net force is 1.5 N, and it points to the left.

Note in this Example that the charge in the middle (Q_2) in no way blocks the effect of the other charge (Q_1); Q_2 does exert its own force, of course.

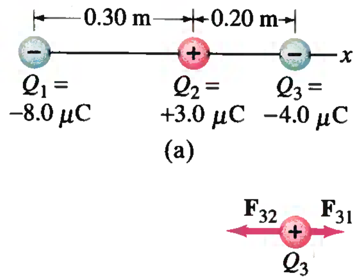


FIGURE 16–18 Diagram for Example 16–3.

EXAMPLE 16–4 **Electric force using vector components.** Calculate the net electrostatic force on charge Q_3 shown in Fig. 16–19a due to the charges Q_1 and Q_2.

SOLUTION The forces $\mathbf{F}_{31}$ and $\mathbf{F}_{32}$ have the directions shown in the diagram since Q_1 exerts an attractive force and Q_2 a repulsive force. The magnitudes of $\mathbf{F}_{31}$ and $\mathbf{F}_{32}$ are (ignoring signs since we know the directions)

$$F_{31} = \frac{(9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(6.5 \times 10^{-5}\ \text{C})(8.6 \times 10^{-5}\ \text{C})}{(0.60\ \text{m})^2} = 140\ \text{N},$$

$$F_{32} = \frac{(9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(6.5 \times 10^{-5}\ \text{C})(5.0 \times 10^{-5}\ \text{C})}{(0.30\ \text{m})^2} = 330\ \text{N}.$$

We resolve $\mathbf{F}_1$ into its components along the x and y axes, as shown:

$$F_{31x} = F_{31} \cos 30° = 120\ \text{N},$$

$$F_{31y} = -F_{31} \sin 30° = -70\ \text{N}.$$

The force $\mathbf{F}_{32}$ has only a y component. So the net force $\mathbf{F}$ on Q_3 has components

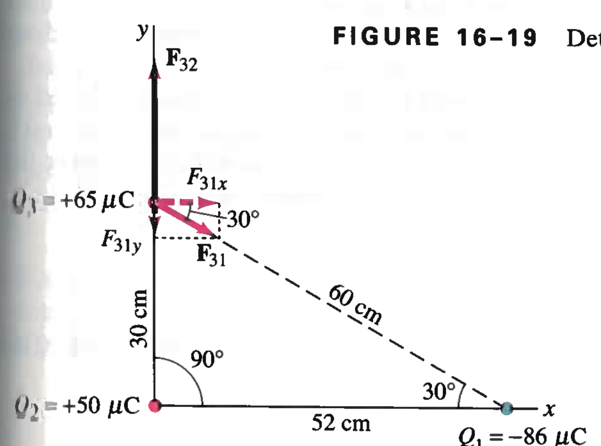
$$F_x = F_{31x} = 120\ \text{N}$$

$$F_y = F_{32} + F_{31y} = 330\ \text{N} - 70\ \text{N} = 260\ \text{N}.$$

Thus the magnitude of the net force is

$$F = \sqrt{F_x^2 + F_y^2} = \sqrt{(120\ \text{N})^2 + (260\ \text{N})^2} = 290\ \text{N};$$

and it acts at an angle θ (see Fig. 16–19b) given by $\tan\theta = F_y/F_x = 260\text{N}/120\text{N} = 2.2$, so $\theta = 65°$.



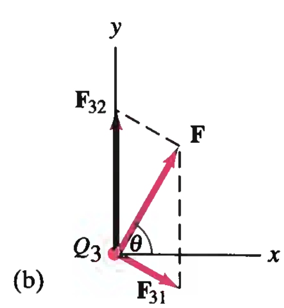


FIGURE 16–19 Determining the forces for Example 16–4.

16–7 The Electric Field

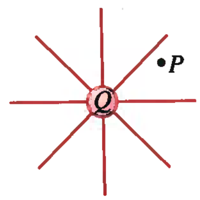
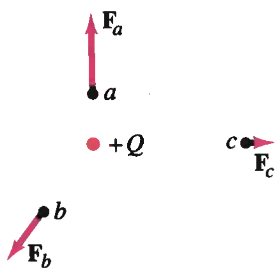


FIGURE 16–20 An electric field surrounds every charge. *P* is an arbitrary point.

FIGURE 16–21 Force exerted by charge $+Q$ on a small test charge, q, placed at points *a*, *b*, and *c*.



Many common forces might be referred to as "contact forces," ... your hands pushing or pulling a cart, or a tennis racket hitting a tenni...

In contrast, both the gravitational force and the electrical fo... over a distance: there is a force even when the two objects are not ... ing. The idea of a force *acting at a distance* was a difficult one fo... thinkers. Newton himself felt uneasy with this idea when he publis... law of universal gravitation. A helpful way to look at the situation ... idea of the **field**, developed by the British scientist Michael F... (1791–1867). In the electrical case, according to Faraday, an *electric fi*... tends outward from every charge and permeates all of space (Fig. 1... When a second charge is placed near the first charge, it feels a fo... cause of the electric field that is there (say, at point *P* in Fig. 16–20)... electric field at the location of the second charge is considered to in... directly with this charge to produce the force. It must be emphasize... ever, that a field, as we think of it here, is *not* a kind of matter.

We can investigate the electric field surrounding a charge or gro... charges by measuring the force on a small positive **test charge**. By ... charge we mean a charge so small that the force it exerts does not ... cantly alter the distribution of the charges that create the field bein... sured. The force on a tiny positive test charge q placed at various lo... in the vicinity of a single positive charge Q would be as show... Fig. 16–21. The force at *b* is less than at *a* because the distance is ... (Coulomb's law); and the force at *c* is smaller still. In each case, th... is directed radially outward from Q. The electric field is defined in ... of the force on such a positive test charge. In particular, the **electric** ... **E**, at any point in space is defined as the force **F** exerted on a tiny p... test charge at that point divided by the magnitude of the test charg...

Definition of electric field

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

Ideally, **E** is defined as the limit of $\mathbf{F}/q$ as q is taken smaller and small... proaching zero. From this definition (Eq. 16–3), we see that the elect... at any point in space is a vector whose direction is the direction of th... on a positive test charge at that point, and whose magnitude is the *f*... *unit charge*. Thus **E** is measured in units of newtons per coulomb (N/...

The reason for defining **E** as $\mathbf{F}/q$ (with $q \rightarrow 0$) is so that **E** d... depend on the magnitude of the test charge q. This means that **E** de... only the effect of the charges creating the electric field at that point.

The electric field at any point in space can be measured, based o... definition, Eq. 16–3. For simple situations involving one or several ... charges, we can calculate what **E** will be. For example, the electric fi... a distance r from a single point charge Q would have magnitude

Electric field due to one point charge

$$E = \frac{kqQ/r^2}{q} = k\frac{Q}{r^2}; \qquad \text{[single point charge]}$$

in terms of ϵ_0 (Eq. 16–2)

$$E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}. \qquad \text{[single point charge]} \qquad \textbf{(16–4b)}$$

This relation for the electric field due to a single point charge is also (in addition to Eq. 16–1) referred to as Coulomb's law. Notice that E is independent of q—that is, it depends only on the charge Q which produces the field and not on the value of the test charge q.

EXAMPLE 16–5 **Electrostatic copier.** An electrostatic copier works by selectively arranging positive charges (in a pattern to be copied) on the surface of a nonconducting drum, then gently sprinkling negatively charged dry toner (ink) particles onto the drum. The toner particles temporarily stick to the pattern on the drum and are later transferred to paper and "melted" to produce the copy. Suppose each toner particle has a mass of 9.0×10^{-16} kg and carries an average of 20 extra electrons to provide an electric charge. Assuming that the electric force on a toner particle must exceed twice its weight in order to ensure sufficient attraction, compute the required electric field strength near the surface of the drum. See Fig. 16–22.

SOLUTION The minimum value of electric field satisfies the relation

$$qE = 2\,mg$$

where $q = 20e$. Hence

$$E = \frac{2\,mg}{q} = \frac{2(9.0 \times 10^{-16}\,\text{kg})(9.8\,\text{m/s}^2)}{20(1.6 \times 10^{-19}\,\text{C})}$$

$$= 5.5 \times 10^{3}\,\text{N/C}.$$

➥ **PHYSICS APPLIED**

Electrostatic copier

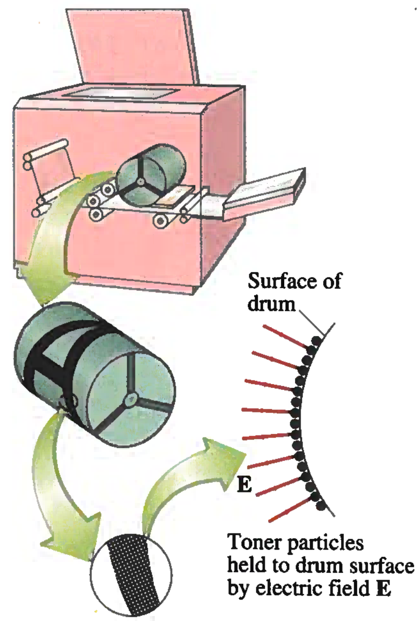


FIGURE 16–22 Example 16–5.

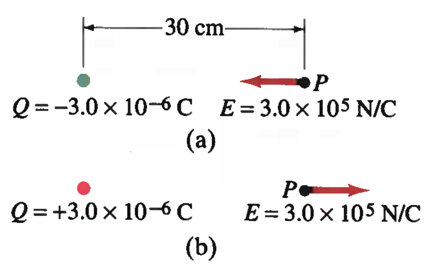
EXAMPLE 16–6 **Electric field of a single point charge.** Calculate the magnitude and direction of the electric field at a point P which is 30 cm to the right of a point charge $Q = -3.0 \times 10^{-6}$ C.

SOLUTION The magnitude of the electric field due to a single point charge is given by Eq. 16–4:

$$E = k\frac{Q}{r^2} = \frac{(9.0 \times 10^{9}\,\text{N}\cdot\text{m}^2/\text{C}^2)(3.0 \times 10^{-6}\,\text{C})}{(0.30\,\text{m})^2} = 3.0 \times 10^{5}\,\text{N/C}.$$

The direction of the electric field is *toward* the charge Q as shown in Fig. 16–23a since we defined the direction as that of the force on a positive test charge. If Q had been positive, the electric field would have pointed away, as in Fig. 16–23b.

FIGURE 16–23 Example 16–6. Electric field at point P (a) due to a negative charge Q, and (b) due to a positive charge Q.



This Example illustrates a general result: The electric field due to a positive charge points away from the charge, whereas **E** due to a negative charge points toward that charge.

If the field is due to more than one charge, the individual fi[...] them $\mathbf{E}_1$, $\mathbf{E}_2$, etc.) due to each charge are added vectorially to get the field at any point:

Superposition principle for electric fields

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 + \cdots .$$

The validity of this **superposition principle** for electric fields is fully [...]firmed by experiment.†

EXAMPLE 16–7 **E in between two point charges.** Two point [...] are separated by a distance of 10.0 cm. One has a charge of $-25\,\mu$[...] the other $+50\,\mu\text{C}$. (*a*) What is the direction and magnitude of the [...] field at a point *P* in between them, that is 2.0 cm from the ne[...] charge (Fig. 16–24a)? (*b*) If an electron is placed at rest at *P*, what wi[...] acceleration (direction and magnitude) be initially?

SOLUTION (*a*) The field will be a combination of two fields [...] pointing to the left: the field due to the negative charge Q_1 points to[...] Q_1, and the field due to the positive charge Q_2 points away from [...] again to the left, Fig. 16–24b. Thus, we can add the magnitudes of the [...] fields together algebraically, ignoring the signs of the charges:

$$E = k\frac{Q_1}{r_1^2} + k\frac{Q_2}{r_2^2} = k\left(\frac{Q_1}{r_1^2} + \frac{Q_2}{r_2^2}\right) = k\frac{Q_1}{r_1^2}\left[1 + \frac{(Q_2/Q_1)}{(r_2^2/r_1^2)}\right]$$

where in the last step we factored out (Q_1/r_1^2). We substitute [...] $r_1 = 2.0\,\text{cm} = 2.0 \times 10^{-2}\,\text{m}$ and $r_2 = 8.0 \times 10^{-2}\,\text{m}$:

$$E = (9.0 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)\frac{(25 \times 10^{-6}\,\text{C})}{(2.0 \times 10^{-2}\,\text{m})^2}\left[1 + \frac{(50/25)}{(8.0/2.0)^2}\right]$$

$$= 5.6 \times 10^8\,[1 + \tfrac{1}{8}]\,\text{N/C} = 6.3 \times 10^8\,\text{N/C}.$$

Notice how factoring out Q_1/r_1^2 on the first line allowed us to see the [...]ative strengths of the two contributing fields—namely that Q_2's is [...] only $\frac{1}{8}$ of Q_1's (or $\frac{1}{9}$ of the total).

(*b*) The electron will feel a force to the ***right*** since it is negatively ch[...] and the acceleration will therefore be to the right, with a magnitude [...]

$$a = \frac{F}{m} = \frac{qE}{m} = \frac{(1.60 \times 10^{-19}\,\text{C})(6.3 \times 10^8\,\text{N/C})}{9.1 \times 10^{-31}\,\text{kg}} = 1.1 \times 10^{[...]}$$

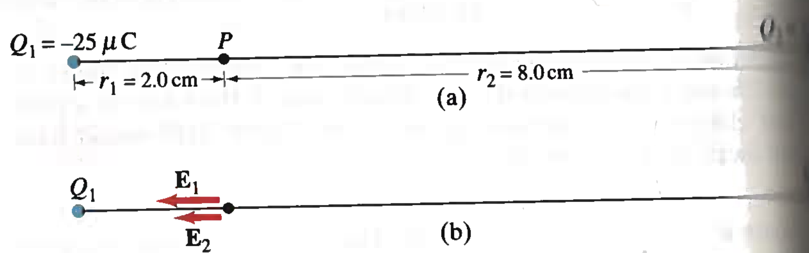


FIGURE 16–24 Example 16–7. In (b), we don't know the relative lengths of $\mathbf{E}_1$ and $\mathbf{E}_2$ until we do the calculation.

†A more general form of Coulomb's law, which allows calculation of the electric field [...] useful situations, is Gauss's law, discussed in Appendix D.

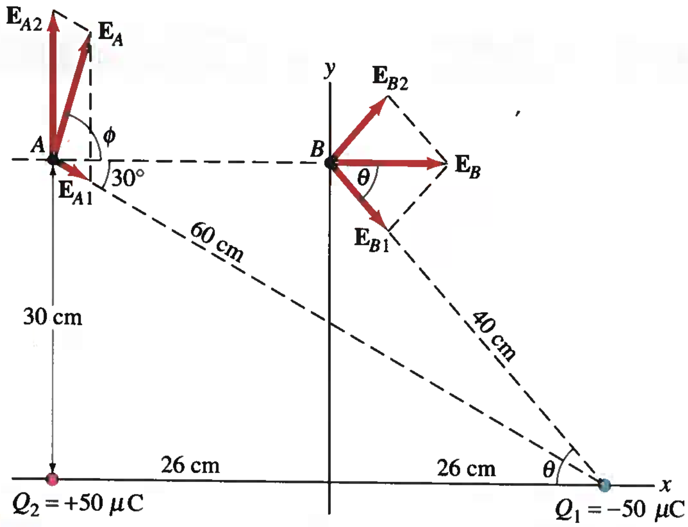


FIGURE 16–25 Calculation of the electric field at points A and B for Example 16–8.

EXAMPLE 16–8 **E above two point charges.** Calculate the total electric field (a) at point A and (b) at point B in Fig. 16–25 due to both charges, Q_1 and Q_2.

SOLUTION (a) The calculation is much like that of Example 16–4, but now we are dealing with electric fields. The electric field at A is the vector sum of the fields $\mathbf{E}_{A1}$ due to Q_1, and $\mathbf{E}_{A2}$ due to Q_2; using Eq. 16–4, $E = kQ/r^2$, they have magnitudes:

PROBLEM SOLVING

Ignore signs of charges and determine direction physically, showing directions on diagram

$$E_{A1} = \frac{(9.0 \times 10^9\,\mathrm{N \cdot m^2/C^2})(50 \times 10^{-6}\,\mathrm{C})}{(0.60\,\mathrm{m})^2} = 1.25 \times 10^6\,\mathrm{N/C},$$

$$E_{A2} = \frac{(9.0 \times 10^9\,\mathrm{N \cdot m^2/C^2})(50 \times 10^{-6}\,\mathrm{C})}{(0.30\,\mathrm{m})^2} = 5.0 \times 10^6\,\mathrm{N/C}.$$

The directions are as shown, so the total electric field at A, $\mathbf{E}_A$, has components

$$E_{Ax} = E_{A1} \cos 30° = 1.1 \times 10^6\,\mathrm{N/C},$$
$$E_{Ay} = E_{A2} - E_{A1} \sin 30° = 4.4 \times 10^6\,\mathrm{N/C}.$$

Thus the magnitude of $\mathbf{E}_A$ is

$$E_A = \sqrt{(1.1)^2 + (4.4)^2} \times 10^6\,\mathrm{N/C} = 4.5 \times 10^6\,\mathrm{N/C},$$

and its direction is ϕ given by $\tan\phi = E_{Ay}/E_{Ax} = 4.4/1.1 = 4.0$, so $\phi = 76°$. (b) Because B is equidistant (40 cm by the Pythagorean theorem) from the two equal charges, the magnitudes of E_{B1} and E_{B2} are the same; that is,

PROBLEM SOLVING

Use symmetry to save work, when possible

$$E_{B1} = E_{B2} = \frac{kQ}{r^2} = \frac{(9.0 \times 10^9\,\mathrm{N \cdot m^2/C^2})(50 \times 10^{-6}\,\mathrm{C})}{(0.40\,\mathrm{m})^2}$$
$$= 2.8 \times 10^6\,\mathrm{N/C}.$$

Also, because of the symmetry, the y components are equal and opposite. Hence the total field E_B is horizontal and equals $E_{B1}\cos\theta + E_{B2}\cos\theta = 2E_{B1}\cos\theta$; from the diagram, $\cos\theta = 26\,\mathrm{cm}/40\,\mathrm{cm} = 0.65$. Then

$$E_B = 2E_{B1}\cos\theta = 2(2.8 \times 10^6\,\mathrm{N/C})(0.65) = 3.6 \times 10^6\,\mathrm{N/C},$$

and the direction of $\mathbf{E}_B$ is along the $+x$ direction.

PROBLEM SOLVING Electrostatics

Solving electrostatics problems follows, to a large extent, the general problem-solving procedure discussed in Section 4–9. In particular,

1. Draw a careful diagram—namely, a free-body diagram for each object, showing all the forces acting on that object, or the electric field at a point due to all sources.
2. Apply Coulomb's law to get the magnitude of each force on a charged object, or the electric field at a point. Deal only with magnitudes of charges (leaving out minus signs), and obt magnitude of each force or electric field determine the direction of each force or el field physically (like charges repel each unlike charges attract). Show and label ea tor force or field on your diagram. Then ad torially all the forces on an object, contributing fields at a point, to get the res
3. Use symmetry (say, in the geometry) wh possible.

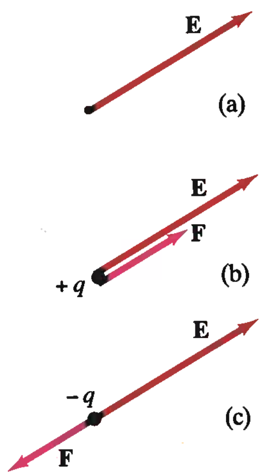


FIGURE 16–26 (a) Electric field at a given point in space. (b) Force on a positive charge. (c) Force on a negative charge.

If we are given the electric field **E** at a given point in space, t can calculate the force **F** on a charge q placed at that point by writi Eq. 16–3):

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

If q is positive, **F** and **E** will point in the same direction. If q is neg and **E** point in opposite directions. See Fig. 16–26.

16–8 Field Lines

Since the electric field is a vector, it is sometimes referred to as a *field*. We could indicate the electric field with arrows at various poi given situation, such as at a, b, and c in Fig. 16–27. The directions $\mathbf{E}_b$, and $\mathbf{E}_c$ are the same as that of the forces shown earlier in Fig but the lengths (magnitudes) are different since we divide by q. Ho the relative lengths of $\mathbf{E}_a$, $\mathbf{E}_b$, and $\mathbf{E}_c$ are the same as for the forc we divide by the same q each time. To indicate the electric field in way at *many* points, however, would result in many arrows, which appear complicated or confusing. To avoid this, we use another tech that of field lines.

In order to visualize the electric field, we draw a series of lines dicate the direction of the electric field at various points in space **electric field lines** (sometimes called *lines of force*) are drawn so th indicate the direction of the force due to the given field on a positiv charge. The lines of force due to a single positive charge are sho Fig. 16–28a and for a single negative charge in Fig. 16–28b. In part

FIGURE 16–27 Electric field vector shown at three points, due to a single point charge Q. (Compare to Fig. 16–21.)

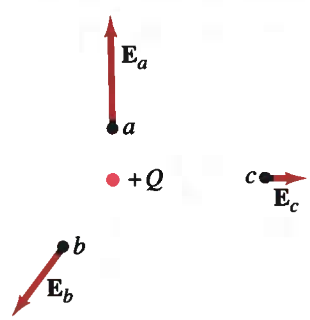
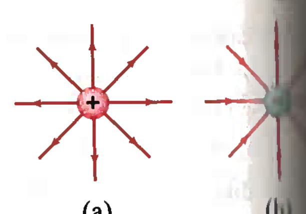


FIGURE 16–28 Ele field lines (a) near a singl positive point charge, (b) n single negative point char



lines point radially outward from the charge, and in part (b) they point radially inward toward the charge because that is the direction the force would be on a positive test charge in each case (as in Fig. 16–23). Only a few representative lines are shown. One could just as well draw lines in between those shown since the electric field exists there as well. However, we can always draw the lines so that the *number of lines starting on a positive charge, or ending on a negative charge, is proportional to the magnitude of the charge.* Notice that near the charge, where the force is greatest, the lines are closer together. This is a general property of electric field lines: *the closer the lines are together, the stronger the electric field in that region.* In fact the lines can always be drawn so that the number of lines crossing unit area perpendicular to **E** is proportional to the magnitude of the electric field.

Figure 16–29a shows the electric field lines surrounding two charges of opposite sign. The electric field lines are curved in this case and they are directed from the positive charge to the negative charge. The direction of the field at any point is directed tangentially as shown by the arrow at point P. To satisfy yourself that this is the correct pattern for the electric field lines, you can make a few calculations such as those done in Example 16–8 for just this case (see Fig. 16–25). Figures 16–29b and c show the electric field lines surrounding two equal positive charges (b), and (c) for unequal charges, $+2Q$ and $-Q$; note that twice as many lines leave $+2Q$ as there are lines entering $-Q$ (number of lines is proportional to magnitude of Q). Finally, in (d), we see the field between two oppositely charged parallel plates. Notice that the electric field lines between the two plates start out perpendicular to the surface of the metal plates (we'll see why this is always true in the next Section) and go directly from one plate to the other, as we expect because a positive test charge placed between the plates would feel a strong repulsion from the positive plate and a strong attraction to the negative plate. The field lines between the plates are parallel and equally spaced, except near the edges. Thus, in the central region, the electric field has the same magnitude at all points and we can write

$$E = \text{constant.} \quad \text{[between two closely spaced parallel plates]} \qquad \textbf{(16–5)}$$

Although the field fringes near the edges (the lines curve), we can often ignore this, particularly if the separation of the plates is small compared to their size. This should be compared to the field of a single point charge, where the field decreases as the square of the distance, Eq. 16–4.

We summarize the properties of field lines as follows:

1. The field lines indicate the direction of the electric field; the field points in the direction tangent to the field line at any point.

2. The lines are drawn so that the magnitude of the electric field, E, is proportional to the number of lines crossing unit area perpendicular to the lines. The closer the lines, the stronger the field.

3. Electric field lines start on positive charges and end on negative charges; and the number starting or ending is proportional to the magnitude of the charge.

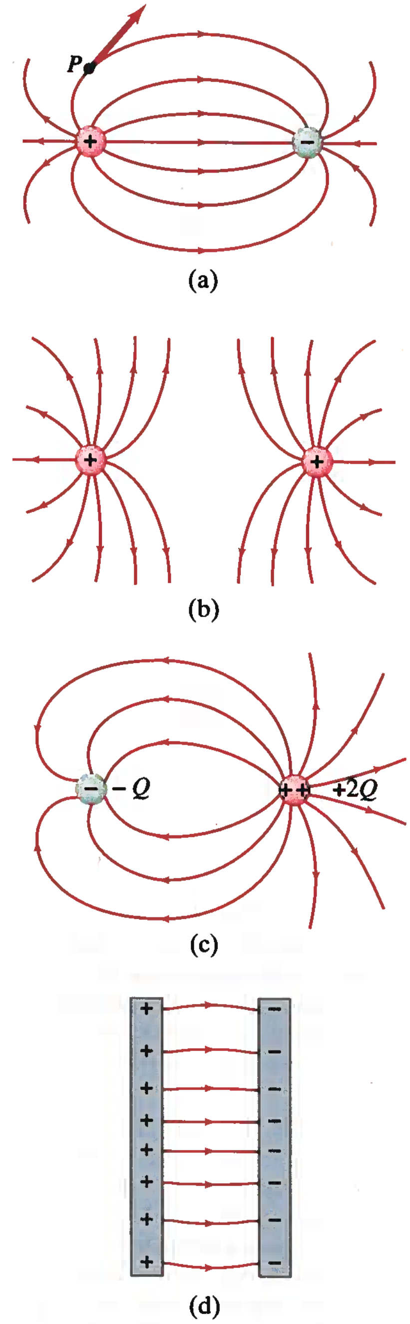


FIGURE 16–29 Electric field lines for four arrangements of charges.

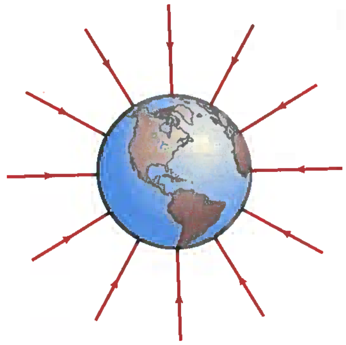


FIGURE 16–30 The Earth's gravitational field.

The field concept can also be applied to the gravitational fo[illegible] can say that a **gravitational field** exists for every object that has ma[illegible] ject attracts another by means of the gravitational field. The Earth, [illegible] ple, can be said to possess a gravitational field (Fig. 16–30) [illegible] responsible for the gravitational force on objects. The *gravitational [illegible] sity* is defined as the *force per unit mass*. The magnitude of the [illegible] tational field intensity at any point is then (GM_E/r^2), where M_E is th[illegible] the Earth, r is the distance of the point from the Earth's center, an[illegible] gravitational constant (Chapter 5). At the Earth's surface, r is sim[illegible] dius of the Earth and the gravitational field intensity is simply equ[illegible] acceleration due to gravity (since $F/m = mg/m = g$). Beyond the [illegible] gravitational field intensity can be calculated at any point as a sum [illegible] due to Earth, Sun, Moon, and other bodies that contribute signific[illegible]

16–9 Electric Fields and Conductors

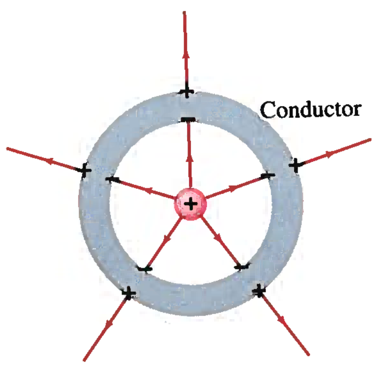


FIGURE 16–31 A charge placed inside a spherical shell. Charges are induced on the conductor surfaces. The electric field exists even beyond the shell but not within the conductor itself.

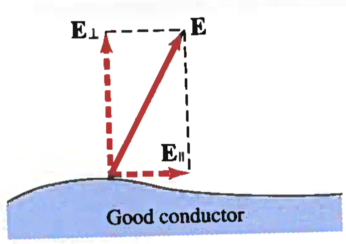
We now discuss some properties of good conductors. First, *the ele[illegible] inside a good conductor is zero in the static situation*—that is, wh[illegible] charges are at rest. If there were an electric field within a conduct[illegible] would be a force on its free electrons since $\mathbf{F} = q\mathbf{E}$. The electron[illegible] move until they reached positions where the electric field, and th[illegible] the electric force on them, did become zero.

This reasoning has some interesting consequences. For one, *any ne[illegible] on a good conductor distributes itself on the surface*. For a negatively [illegible] conductor, you can imagine that the negative charges repel one ano[illegible] race to the surface to get as far from one another as possible. Anoth[illegible] quence is the following. Suppose that a positive charge Q is surround[illegible] isolated uncharged metal conductor whose shape is a spheric[illegible] Fig. 16–31. Because there can be no field within the metal, the lines le[illegible] positive charge must end on negative charges on the inner surfac[illegible] metal. Thus an equal amount of negative charge, $-Q$, is induced on th[illegible] surface of the spherical shell. Then, since the shell is neutral, [illegible] charge, $+Q$, of the same magnitude must exist on the outer surfac[illegible] shell. Thus, although no field exists in the metal itself, an electric fiel[illegible] outside of it, as shown in Fig. 16–31, as if the metal were not even th[illegible]

A related property of static electric fields and conductors is [illegible] *electric field is always perpendicular to the surface outside of a con[illegible]* If there were a component of $\mathbf{E}$ parallel to the surface (Fig. 16–32), [illegible] trons at the surface would move along the surface in response to th[illegible] until they reached positions where no force was exerted on them—[illegible] until the electric field was perpendicular to the surface.

These properties pertain only to conductors. Inside a noncon[illegible] which does not have free electrons, an electric field can exist (Section [illegible] And the electric field outside a nonconductor does not necessarily [illegible] angle of 90° to the surface.

FIGURE 16–32 If the electric field $\mathbf{E}$ at the surface of a conductor had a component parallel to the surface, $\mathbf{E}_{\parallel}$, the latter would accelerate electrons into motion. In the static case (no charges are in motion), $\mathbf{E}_{\parallel}$ must be zero, and so the electric field must be perpendicular to the conductor's surface: $\mathbf{E} = \mathbf{E}_{\perp}$.



CONCEPTUAL EXAMPLE 16–9 **Shielding, and safety in a storm.** A hollow metal box is placed between two parallel charged plates as shown in Fig. 16–33a. What's the field like inside the box?

RESPONSE If our metal box were solid, and not hollow, the electrons in the box, even if it were neutral overall, would redistribute themselves along the surface so that the field lines would not penetrate the conducting metal of the box. For a hollow box, the external field is not changed since the electrons in the metal can move just as freely as before to the surface. Hence we conclude that the field inside the hollow metal box is zero. So the field lines are something like those shown in Fig. 16–33b. A conducting box used in this way is an effective device for shielding delicate instruments and electronic circuits from unwanted external electric fields. We also can see that a relatively safe place to be during a lightning storm is inside a car, surrounded by metal.

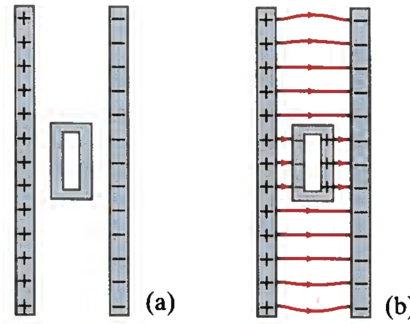


FIGURE 16–33 Example 16–9.

PHYSICS APPLIED

Shielding
Safety in a storm

*16–10 Electric Forces in Molecular Biology: DNA Structure and Replication

The study of the structure and functioning of a living cell at the molecular level is known as molecular biology. It is an important area for application of physics. Since the interior of a cell is mainly water, we can imagine it as a vast sea of molecules continually in motion (as in kinetic theory, Chapter 13), colliding with one another with various amounts of kinetic energy. These molecules interact with one another in various ways—chemical reactions (making and breaking of bonds between atoms) and more brief interactions or unions that occur because of *electrostatic attraction* between molecules.

PHYSICS APPLIED

Inside a cell: Kinetic theory plus electrostatic force

The many processes that occur within the cell are now considered to be the result of *random ("thermal") molecular motion plus the ordering effect of the electrostatic force*. We now use these ideas to analyze some basic cellular processes involving macromolecules (large molecules). The picture we present here has not been seen "in action." Rather, it is a model of what happens based on presently accepted physical theories and a great variety of experimental results.

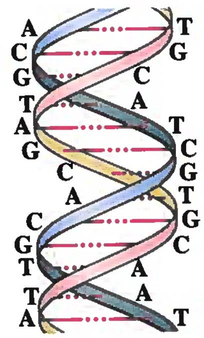
The genetic information that is passed on from generation to generation in all living objects is contained in the chromosomes, which are made up of genes. Each gene contains the information needed to produce a particular type of protein molecule. The genetic information contained in a gene is built into the principal molecule of a chromosome, the DNA (deoxyribonucleic acid). A DNA molecule consists of a long chain of many small molecules known as nucleotide bases. There are only four types of these: adenine (A), cytosine (C), guanine (G), and thymine (T).

The DNA in a chromosome generally consists of two long DNA chains wrapped about one another in the shape of a "double helix." As

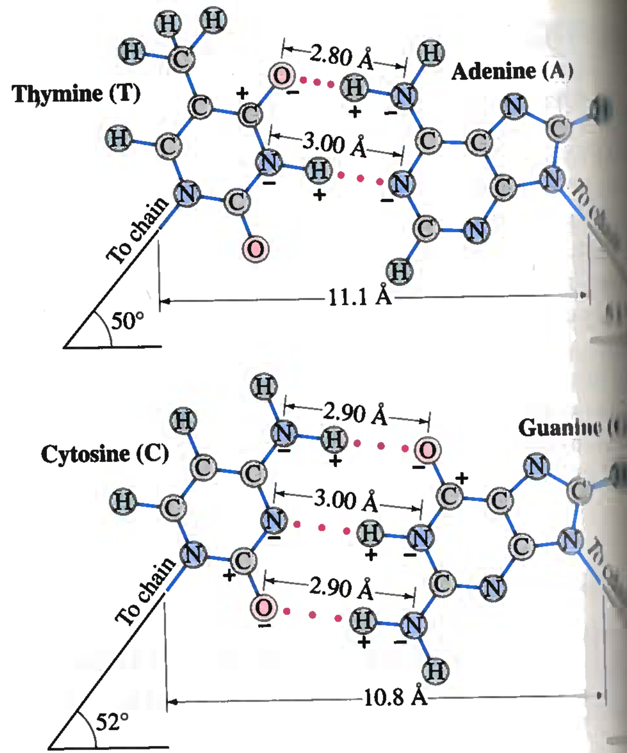
PHYSICS APPLIED

DNA structure

FIGURE 16–34 (a) Section of a DNA double helix. (b) "Close-up" view of the helix, showing how A and T attract each other and how G and C attract each other through electrostatic forces, to hold the double helix together. The red dots are used to indicate the electrostatic attraction (often called a "weak bond" or "hydrogen bond"). Note that there are two weak bonds between A and T, and three between C and G. The distance unit is the angstrom ($1\ \text{Å} = 10^{-10}\ \text{m}$).



(a)



(b)

shown in Fig. 16–34, the two strands are held together by elec[...] forces—that is, by the attraction of positive charges to negative [...]. We see in part (a) that an A (adenine) on one strand is always op[...] T on the other strand; similarly, a G is always opposite a C. This h[...] because the shapes of the four molecules A, T, C, and G are such th[...] fits closely only into an A, and a G into a C; and only in the case o[...] close proximity of the charged portions is the electrostatic force [...] enough to hold them together even for a short time (Fig. 16–34b), f[...] what are often referred to as "weak bonds." The electrostatic fo[...] tween A and T, and between C and G, exists because these molecule[...] charged parts due to some electrons in each of these molecules sp[...] more time orbiting one atom than another. For example, the electr[...] mally on the H atom of adenine spends some of its time orbiting th[...] cent N atom (more on this in Chapter 29), so the N has a net ne[...] charge and the H a positive charge (upper part of Fig. 16–34b). Th[...] atom of adenine is then attracted to the O^- atom of thymine.

➡ PHYSICS APPLIED

DNA replication

How does the arrangement shown in Fig. 16–34 come about? It [...] when the chromosome replicates (duplicates) itself just before cell di[...]. Indeed, the arrangement of A opposite T and G opposite C ensure[...] the genetic information is passed on accurately to the next generation[...] process of replication is shown in a simplified form in Fig. 16–35. Th[...] strands of the DNA chain separate (with the help of enzymes, which [...] operate via the electrostatic force), leaving the charged parts of th[...] exposed. Without going into the details of how replication starts, let [...] how the correct order of bases occurs by focusing our attention on th[...] molecule indicated by the arrow on the lowest strand in the figure. Th[...] are many unattached nucleotide bases of all four kinds bouncing aro[...] the cellular fluid. The only one of the four bases that will experie[...]

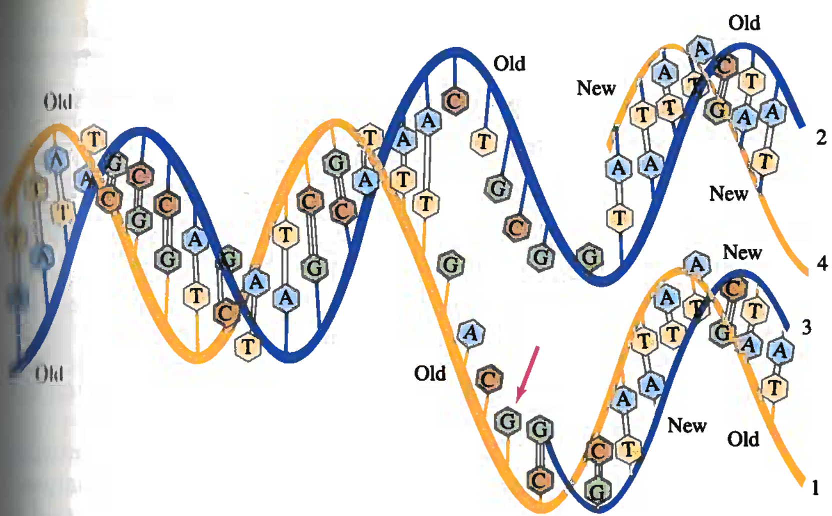


FIGURE 16–35 Replication of DNA.

attraction to our G, if it bounces close to it, will be a C. The charges on the other three bases are not arranged so that they can get close to those on the G, and thus there will be no significant attractive force exerted on them—remember that the force decreases rapidly with distance. Because the G attracts an A, T, or G almost not at all, an A, T, or G will be knocked away by collisions with other molecules before enzymes can attach it to the growing (number 3) chain. But the electrostatic force will often hold a C opposite our G long enough so that an enzyme can attach the C to the growing end of the new chain.

Thus we see that electrostatic forces not only hold the two chains together, electrostatic forces also operate to select the bases in the proper order during replication, so the genetic information is passed on accurately to the next generation. Note in Fig. 16–35 that the new number 4 strand has the same order of bases as the old number 1 strand; and the new number 3 strand is the same as the old number 2. So the two new helixes, 1–3 and 2–4, are identical to the original 1–2 helix. The error rate—say a T being incorporated in a new chain opposite a G—is on the order of 1 in 10^4 [and is kept even lower (1 in 10^8 to 10^9) with the aid of special enzymatic "proofreading and repair" mechanisms]. Such an error constitutes a spontaneous mutation and a possible change in some characteristic of the organism. It is important for the survival of the organism that the error rate be low, but it cannot be zero if evolution (which can only occur through mutation) is to take place.

This process of DNA replication is often presented as if it occurred in clockwork fashion—as if each molecule knew its role and went to its assigned place, like bees in a hive. But this is not the case. The forces of attraction between the electric charges of the molecules are rather weak and become significant only when the molecules can come close together and several "weak bonds" can be made. Indeed, if the shapes are not just right, there is almost no electrostatic attraction, which is why there are few mistakes. The point is that there are many molecules in the cell, all jostling about, but only that one type which has the proper shape will be attracted sufficiently so as to remain long enough to become attached to the growing chain. Thus, out of the random motion of the molecules, the electrostatic force acts to bring order out of chaos.

SUMMARY

There are two kinds of **electric charge**, positive and negative. These designations are to be taken algebraically—that is, any charge is plus or minus so many coulombs (C), in SI units.

Electric charge is **conserved**: if a certain amount of one type of charge is produced in a process, an equal amount of the opposite type is also produced; thus the *net* charge produced is zero.

According to the atomic theory, electricity originates in the atom, which consists of a positively charged nucleus surrounded by negatively charged electrons. Each electron has a charge $-e = -1.6 \times 10^{-19}$ C.

Conductors are those materials in which many electrons are relatively free to move, whereas electric **insulators** are those in which very few electrons are free to move.

An object is negatively charged when it has an excess of electrons, and positively charged when it has less than its normal amount of electrons. The charge on any object is thus a whole number times $+e$ or $-e$; that is, charge is **quantized.**

An object can become charged by rubbing (in which electrons are transferred from one material to another), by conduction (which is transfer of charge from one charged object to another by touching), or by induction (the separation of charge within an object because of the close approach of another charged object but without touching).

Electric charges exert a force on each other. If two charges are of opposite types, one positive and one negative, they each exert an attractive force on the other. If the two charges are the same ty[pe], each repels the other.

The magnitude of the force one point ch[arge] exerts on another is proportional to the pro[duct of] their charges, and inversely proportional to [the] square of the distance between them:

$$F = k\frac{Q_1 Q_2}{r^2};$$

this is **Coulomb's law.** In SI units, k is often w[ritten] as $1/4\pi\epsilon_0$.

We think of an **electric field** as existing [in] space around any charge or group of charges. [The] force on another charged object is then said to [be] due to the electric field present at its location.

The *electric field*, **E**, at any point in sp[ace due] to one or more charges, is defined as the for[ce per] unit charge that would act on a test ch[arge] placed at that point:

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

Electric fields are represented by **electric [field] lines** that start on positive charges and end on [nega]tive charges. Their direction indicates the direction [the] force would be on a tiny positive test charge pl[aced at] a point. The lines can be drawn so that the nu[mber] per unit area is proportional to the magnitude of [E].

The static electric field (that is, no ch[arges] moving) inside a good conductor is zero, an[d the] electric field lines just outside a charged cond[uctor] are perpendicular to its surface.

QUESTIONS

1. If you charge a pocket comb by rubbing it with a silk scarf, how can you determine if the comb is positively or negatively charged?
2. Why does a shirt or blouse taken from a clothes dryer sometimes cling to your body?
3. Explain why fog or rain droplets tend to form around ions or electrons in the air.
4. A positively charged rod is brought close to a neutral piece of paper, which it attracts. Draw a diagram showing the separation of charge and explain why attraction occurs.
5. Why does a plastic ruler that has been rubbed with a cloth have the ability to pick up small pieces of paper? Why is this difficult to do on a humid day?
6. Contrast the *net charge* on a conductor to the "free charges" in the conductor.
7. Figures 16–7 and 16–8 show how a charged [rod] placed near an uncharged metal object can at[tract] (or repel) electrons. There are a great many [elec]trons in the metal, yet only some of them m[ove as] shown. Why not all of them?
8. When an electroscope is charged, the two le[aves] repel each other and remain at an angle. Wh[at bal]ances the electric force of repulsion so th[at the] leaves don't separate further?
9. The form of Coulomb's law is very similar to th[at for] Newton's law of universal gravitation. What ar[e the] differences between these two laws? Compare [also] gravitational mass and electric charge.
10. We are not normally aware of the gravitational [or] electrical force between two ordinary objects. W[hat] is the reason in each case? Give an example wh[ere] we are aware of each one and why.

11. Is the electric force a conservative force? Why or why not? (See Chapter 6.)

12. What experimental observations mentioned in the text rule out the possibility that the numerator in Coulomb's law contains the sum $(Q_1 + Q_2)$ rather than the product Q_1Q_2?

13. When a charged ruler attracts small pieces of paper, sometimes a piece jumps quickly away after touching the ruler. Explain.

14. Explain why we use *small* test charges when measuring electric fields.

15. When determining an electric field, must we use a *positive* test charge, or would a negative one do as well? Explain.

16. Draw the electric field lines surrounding two negative electric charges a distance l apart.

17. Assume that the two opposite charges in Fig. 16–29a are 12.0 cm apart. Consider the magnitude of the electric field 2.5 cm from the positive charge. On which side of this charge—top, bottom, left, or right—is the electric field the strongest? The weakest?

18. Consider the electric field at the three points indicated by the letters A, B, and C in Fig. 16–36. First draw an arrow at each point indicating the direction of the net force that a positive test charge would experience if placed at that point, then list the letters in order of *decreasing* field strength (strongest first).

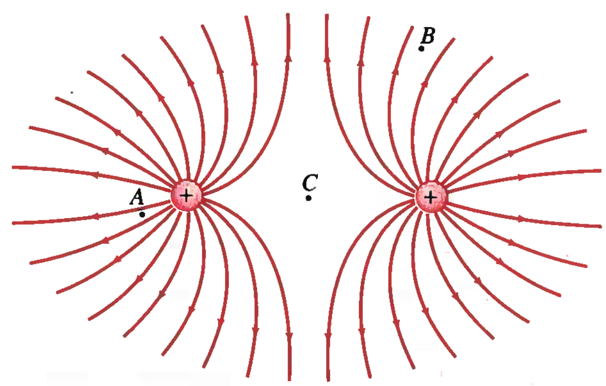


FIGURE 16–36 Question 18.

19. Why can electric field lines never cross?

20. Consider a small positive test charge located on an electric field line at some point, such as point P in Fig. 16–29a. Is the direction of the velocity and/or acceleration of the test charge along this line? Discuss.

21. We wish to determine the electric field at a point near a positively charged metal sphere (a good conductor). We do so by bringing a small test charge, q_0, to this point and measure the force F_0 on it. Will F_0/q_0 be greater than, less than, or equal to, the electric field **E** as it was at that point before the test charge was present?

PROBLEMS

SECTIONS 16–5 AND 16–6

1. (I) How many electrons make up a charge of $-30.0\ \mu C$?

2. (I) Two charged smoke particles exert a force of 4.2×10^{-2} N on each other. What will be the force if they are moved so they are only one eighth as far apart?

3. (I) Two charged balls are 20.0 cm apart. They are moved, and the force on each of them is found to have been tripled. How far apart are they now?

4. (I) Two charged Ping-Pong balls separated by a distance of 1.50 m exert an electric force of 0.0200 N on each other. What will be the force if the objects are brought closer, to a separation of only 30.0 cm?

5. (I) What is the magnitude of the electric force of attraction between an iron nucleus ($q = +26e$) and its innermost electron if the distance between them is 1.5×10^{-12} m?

6. (I) What is the repulsive electrical force between two protons in a nucleus that are 5.0×10^{-15} m apart from each other?

7. (I) What is the magnitude of the force a $+15\text{-}\mu C$ charge exerts on a $+3.0\text{-mC}$ charge 40 cm away? ($1\ \mu C = 10^{-6}$ C, 1 mC $= 10^{-3}$ C.)

8. (II) A person scuffing her feet on a wool rug on a dry day accumulates a net charge of $-60\ \mu C$. How many excess electrons does this person get, and by how much does her mass increase?

9. (II) Imagine that space invaders could deposit extra electrons in equal amounts on the Earth and on your car, which has a mass of 1050 kg. Note that the rubber tires would provide some insulation. How much charge Q would need to be placed on your car (same amount on the Earth) in order to levitate it (overcome gravity)? [*Hint*: Assume that the Earth's charge is spread uniformly so it acts as if it were located at the Earth's center, and then the separation distance is the radius of the Earth.]

10. (II) What is the total charge of all the electrons in 1.0 kg of H_2O?

11. (II) Particles of charge +70, +48, and $-80\ \mu C$ are placed in a line (Fig. 16–37). The center one is 0.35 m from each of the others. Calculate the net force on each charge due to the other two.

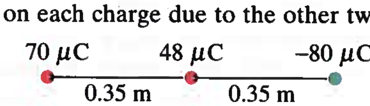


FIGURE 16–37 Problem 11.

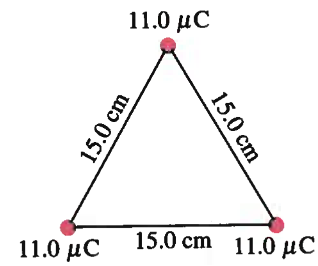


FIGURE 16–38 Problem 12.

12. (II) Three positive particles of charges 11.0 μC are located at the corners of an equilateral triangle of side 15.0 cm (Fig. 16–38). Calculate the magnitude and direction of the net force on each particle.

13. (II) A charge of 6.00 mC is placed at each corner of a square 1.00 m on a side. Determine the magnitude and direction of the force on each charge.

14. (II) Repeat Problem 13 for the case when two of the positive charges, on opposite corners, are replaced by negative charges of the same magnitude (Fig. 16–39).

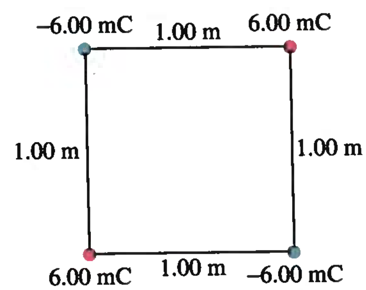


FIGURE 16–39 Problem 14.

15. (II) Compare the electric force holding the electron in orbit around the proton ($r = 0.53 \times 10^{-10}$ m) in the hydrogen nucleus with the gravitational force between the same electron and proton. What is the ratio of these two forces?

16. (II) Suppose that electrical attraction, rather than gravity, were responsible for holding the Moon in orbit around the Earth. If equal and opposite charges Q were placed on the Earth and the Moon, what should be the value of Q to maintain the present orbit? Use these data: mass of Earth = 5.97×10^{24} kg, mass of Moon = 7.35×10^{22} kg, radius of orbit = 3.84×10^{8} m. Treat the Earth and Moon as point particles.

17. (II) Two positive point charges are a fixed distance apart. The sum of their charges is Q_T. What charge must each have in order to (*a*) maximize the electric force between them, and (*b*) minimize it?

18. (II) In one model of the hydrogen atom, the electron revolves in a circular orbit around the proton with a speed of 1.1×10^{6} m/s. Determine the radius of the electron's orbit.

19. (III) A +5.7 μC and a −3.5 μC charge are [illegible] 25 cm apart. Where can a third charge be pl[illegible] that it experiences no net force?

20. (III) Two small nonconducting spheres have [illegible] charge of 80.0 μC. When placed 1.06 m apart [illegible] force each exerts on the other is 12.0 N and is [illegible] sive. What is the charge on each? What if the [illegible] were attractive?

SECTIONS 16–7 AND 16–8

21. (I) What is the magnitude of the acceleration [illegible] enced by an electron in an electric field of [illegible] How does the direction of the acceleration [illegible] on the direction of the field at that point? How [illegible] the direction of the acceleration depend on the [illegible] tron's velocity at that point?

22. (I) What is the magnitude and direction of the [illegible] tric force on an electron in a uniform electric [illegible] strength 3500 N/C that points due east?

23. (I) A proton is released in a uniform electric [illegible] and it experiences an electric force of 3.2 × [illegible] toward the south. What are the magnitude and [illegible] tion of the electric field?

24. (I) A force of 8.4 N is exerted on a −8.8-μC [illegible] in a downward direction. What is the magnitude [illegible] direction of the electric field at this point?

25. (I) What is the magnitude and direction of the [illegible] tric field 30.0 cm directly above a 33.0 × [illegible] charge?

26. (II) What is the magnitude and direction of the [illegible] tric field at a point midway between a −8.0-μ[illegible] a +6.0-μC charge 4.0 cm apart?

27. (II) An electron is released from rest in a [illegible] electric field and accelerates to the north at a [illegible] 125 m/s². What is the magnitude and direction [illegible] electric field?

28. (II) The electric field midway between two equ[illegible] opposite point charges is 1750 N/C, and the d[illegible] between the charges is 16.0 cm. What is the m[illegible] tude of the charge on each?

29. (II) Determine the direction and magnitude [illegible] electric field at the point P shown in Fig. 16–40. [illegible] two charges are separated by a distance of [illegible] the point P is a distance x out on the perpen[illegible] bisector of the line joining them. Express y[illegible] swers in terms of Q, x, a, and k.

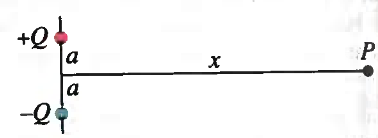


FIGURE 16–40 Problem 29.

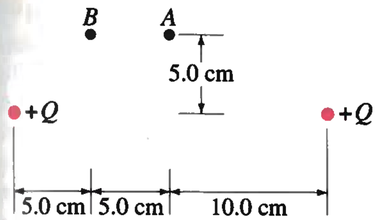


FIGURE 16–41 Problem 30.

30. (II) Use Coulomb's law to determine the magnitude and direction of the electric field at points A and B in Fig. 16–41 due to the two positive charges ($Q = 9.0\ \mu C$) shown. Is your result consistent with Fig. 16–29b?

31. (II) Calculate the electric field at the center of a square 60 cm on a side if one corner is occupied by a $+45.0\text{-}\mu C$ charge and the other three are occupied by $-31.0\text{-}\mu C$ charges.

32. (II) Calculate the electric field at one corner of a square 1.00 m on a side if the other three corners are occupied by 2.80×10^{-6}-C charges.

33. (II) (*a*) Determine the electric field **E** at the origin 0 in Fig. 16–42 due to the two charges at A and B. (*b*) Repeat, but let the charge at B be reversed in sign.

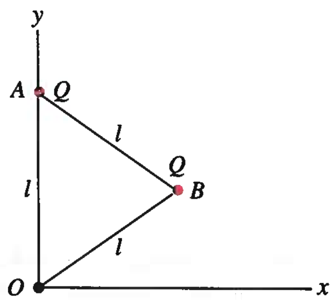


FIGURE 16–42 Problem 33.

34. (II) Draw, approximately, the electric field lines about two point charges, $+Q$ and $-3Q$, which are a distance l apart.

35. (II) What is the electric field strength at a point in space where a proton ($m = 1.67 \times 10^{-27}$ kg) experiences an acceleration of 1 million "g's"?

36. (II) A spacecraft makes a trip from the Earth to the Moon, 380,000 km away. At what point in the trip will the gravitational field be zero? The mass of the Moon is about $\frac{1}{81}$ that of the Earth.

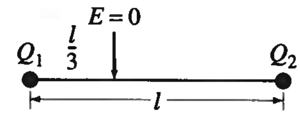


FIGURE 16–43 Problem 37.

37. (III) You are given two unknown point charges, Q_1 and Q_2. At a point on the line joining them, one third of the way from Q_1 to Q_2, the electric field is zero (Fig. 16–43). What can you say about these two charges?

38. (III) An electron (mass $m = 9.11 \times 10^{-31}$ kg) is accelerated in the uniform field **E** ($E = 1.85 \times 10^4$ N/C) between two parallel charged plates. The separation of the plates is 1.20 cm. The electron is accelerated from rest near the negative plate and passes through a tiny hole in the positive plate, Fig. 16–44. (*a*) With what speed does it leave the hole? (*b*) Show that the gravitational force can be ignored.

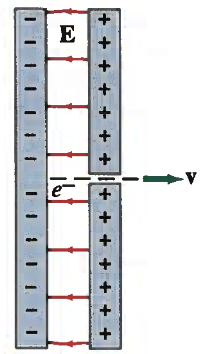


FIGURE 16–44 Problem 38.

39. (III) An electron moving at 1 percent the speed of light to the right enters a uniform electric field region where the field is known to be parallel to its direction of motion. If the electron is to be brought to rest in the space of 5.0 cm, (*a*) what direction is required for the electric field, and (*b*) what is the strength of the field?

*SECTION 16–10

*40. (III) The two strands of the helix-shaped DNA molecule are held together by electrostatic forces as shown in Fig. 16–34. Assume that the net average charge indicated on H and N atoms is $0.2e$, and on the indicated C and O atoms is $0.4e$, that atoms on each molecule are separated by 1.0×10^{-10} m, and that all relevant angles are 120°. Estimate the net force between: (*a*) a thymine and an adenine; and (*b*) a cytosine and a guanine. (*c*) Estimate the total force for a DNA molecule containing 10^5 pairs of such molecules.

GENERAL PROBLEMS

41. How close must two electrons be if the electric force between them is equal to the weight of either at the Earth's surface?

42. A 3.0-g copper penny has a positive charge of 42 μC. What fraction of its electrons has it lost?

43. A proton ($m = 1.67 \times 10^{-27}$ kg) is suspended at rest in a uniform electric field **E**. Take into account gravity and determine **E**.

44. Measurements indicate that there is an electric field surrounding the Earth. Its magnitude is about 150 N/C at the Earth's surface and points inward toward the Earth's center. What is the magnitude of the electric charge on the Earth? Is it positive or negative? [*Hint*: The electric field outside a uniformly charged sphere is the same as if all the charge were concentrated at its center.]

45. A water droplet of radius 0.018 mm remains stationary in the air. If the electric field of the Earth is 150 N/C, how many excess electron charges must the water droplet have?

46. Calculate the magnitude of the electric field at the center of a square with sides 25 cm long if the corners, taken in rotation, have charges of 1.0 μC, 2.0 μC, 3.0 μC, and 4.0 μC (all positive).

47. Estimate the net force between the CO group and the HN group shown in Fig. 16–45. The C and O have charges $\pm 0.40e$ and the H and N have charges $\pm 0.20e$ where $e = 1.6 \times 10^{-19}$ C. [*Hint*: Do not include the "internal" forces between C and O, or between H and N.]

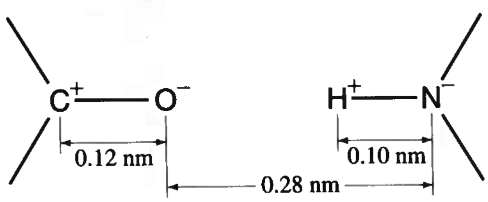


FIGURE 16–45 Problem 47.

48. Two charges, $-Q_0$ and $-3Q_0$, are a distance l apart. These two charges are free to move along the line passing through them both, but do not because there is a third charge nearby. What must be the magnitude of the third charge and its placement in order for the first two to be in equilibrium?

49. A point charge ($m = 1.0$ g) at the end of an insulating string of length 50 cm (Fig. 16–46) is observed to be in equilibrium in a known uniform horizontal electric field, $E = 9200$ N/C, when the pendulum has swung so it is 1.0 cm high. If the field points to the right in Fig. 16–46, determine the magnitude and sign of the point charge.

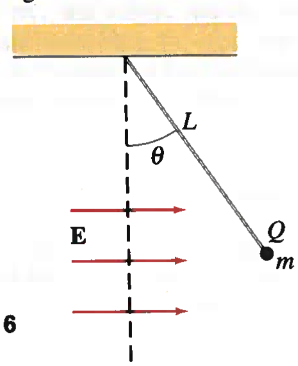


FIGURE 16–46
Problem 49.

50. A positive point charge $Q_1 = 2.5 \times 10^{-5}$ C [illegible] at the origin of coordinates, and a negativ[illegible] $Q_2 = -5.0 \times 10^{-6}$ C is fixed to the [illegible] $x = +2.0$ m. Find the location of the place[illegible] the x axis where the electric field due to th[illegible] charges is zero.

51. An electron with speed $v_0 = 1.5 \times 10^6$ m/s [illegible] ing parallel to an electric field ($\mathbf{v}_0 \parallel \mathbf{E}$) of [illegible] tude $E = 7.7 \times 10^3$ N/C. (*a*) How far will [illegible] before it stops? (*b*) How much time will [illegible] fore it returns to its starting point?

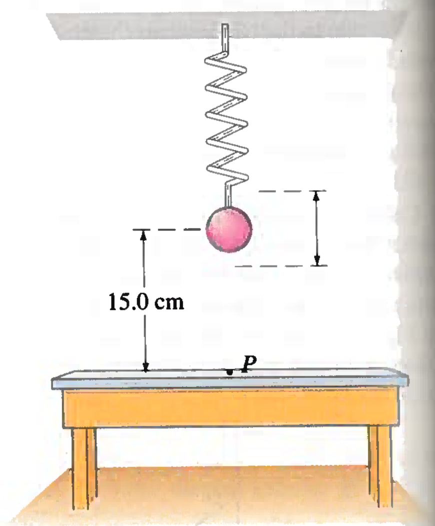


FIGURE 16–47 Problem 52.

52. A small lead ball is encased in insulating pla[illegible] suspended vertically from an ideal sprin[illegible] 126 N/m) above a lab table, Fig. 16–47. Th[illegible] mass of the coated ball is 0.800 kg, and its ce[illegible] 15.0 cm above the tabletop when in equilibri[illegible] ball is pulled down 5.00 cm below equilibri[illegible] electric charge $Q = -3.00 \times 10^{-6}$ C is dep[illegible] the ball, and the system is released. Using wh[illegible] know about harmonic oscillation, write [illegible] sion for the electric field strength as a func[illegible] time that would be measured at the point [illegible] tabletop (P) directly below the ball.

53. A large electroscope is made with "leaves" [illegible] 70-cm-long wires with 24-g balls at the end[illegible] charged, nearly all the charge resides on the [illegible] the wires each make a 30° angle with the [illegible] (Fig. 16–48), what total charge Q must have [illegible] plied to the electroscope?

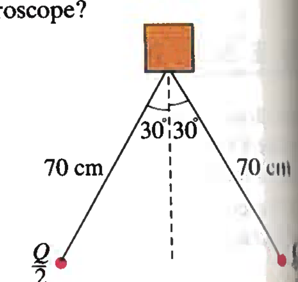


FIGURE 16–48
Problem 53.

55. (II) Dry air will break down and generate a spark if the electric field exceeds about 3×10^6 N/C. How much charge could be packed onto a green pea (diameter 0.75 cm) before the pea spontaneously discharges? [*Hint*: Eq. 16–4 works outside a sphere if r is measured from its center.]

(II) Two point charges, $Q_1 = -6.7\ \mu C$ and $Q_2 = 1.3\ \mu C$ are located between two oppositely charged parallel plates, as shown in Fig. 16–49. The two point charges are separated by a distance of $x = 0.34$ m. Assume that the electric field produced by the charged plates is uniform and equal to $E = 73{,}000$ N/C. Calculate the net electrostatic force on Q_1 and give its direction.

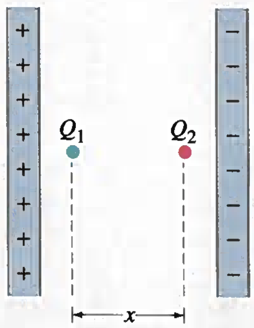


FIGURE 16–49 Problem 55.

56. A point charge of mass 0.210 kg, and net charge $+0.340\ \mu C$, hangs at rest at the end of an insulating string above a single sheet of charge. The horizontal sheet of charge creates a uniform vertical electric field in the vicinity of the point charge. The tension in the string is measured to be 5.67 N. Calculate the magnitude and direction of the electric field due to the sheet of charge (Fig. 16–50).

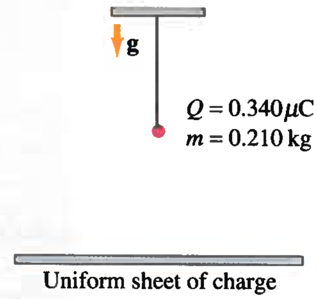


FIGURE 16–50 Problem 56.