

ELECTRIC CHARGE

21

21-1 WHAT IS PHYSICS?

You are surrounded by devices that depend on the physics of electromagnetism, which is the combination of electric and magnetic phenomena. This physics is at the root of computers, television, radio, telecommunications, household lighting, and even the ability of food wrap to cling to a container. This physics is also the basis of the natural world. Not only does it hold together all the atoms and molecules in the world, it also produces lightning, auroras, and rainbows.

The physics of electromagnetism was first studied by the early Greek philosophers, who discovered that if a piece of amber is rubbed and then brought near bits of straw, the straw will jump to the amber. We now know that the attraction between amber and straw is due to an electric force. The Greek philosophers also discovered that if a certain type of stone (a naturally occurring magnet) is brought near bits of iron, the iron will jump to the stone. We now know that the attraction between magnet and iron is due to a magnetic force.

From these modest origins with the Greek philosophers, the sciences of electricity and magnetism developed separately for centuries—until 1820, in fact, when Hans Christian Oersted found a connection between them: an electric current in a wire can deflect a magnetic compass needle. Interestingly enough, Oersted made this discovery, a big surprise, while preparing a lecture demonstration for his physics students.

The new science of electromagnetism was developed further by workers in many countries. One of the best was Michael Faraday, a truly gifted experimenter with a talent for physical intuition and visualization. That talent is attested to by the fact that his collected laboratory notebooks do not contain a single equation. In the mid-nineteenth century, James Clerk Maxwell put Faraday's ideas into mathematical form, introduced many new ideas of his own, and put electromagnetism on a sound theoretical basis.

Our discussion of electromagnetism is spread through the next 16 chapters. We begin with electrical phenomena, and our first step is to discuss the nature of electric charge and electric force.

21-2 Electric Charge

In dry weather, you can produce a spark by walking across certain types of carpet and then bringing one of your fingers near a metal doorknob, metal faucet, or even a friend. You can also produce multiple sparks when you pull, say, a sweater from your body or clothes from a dryer. Sparks and the “static cling” of clothing (similar to what is seen in Fig. 21-1) are usually just annoying. However, if you happen to pull off a sweater and then spark to a computer, the results are more than just annoying.



Fig. 21-1 Static cling, an electrical phenomenon that accompanies dry weather, causes these pieces of paper to stick to one another and to the plastic comb, and your clothing to stick to your body. (*Fundamental Photographs*)

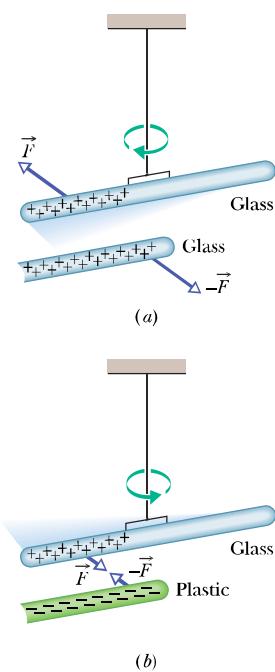


Fig. 21-2 (a) Two charged rods of the same sign repel each other. (b) Two charged rods of opposite signs attract each other. Plus signs indicate a positive net charge, and minus signs indicate a negative net charge.

These examples reveal that we have electric charge in our bodies, sweaters, carpets, doorknobs, faucets, and computers. In fact, every object contains a vast amount of electric charge. **Electric charge** is an intrinsic characteristic of the fundamental particles making up those objects; that is, it is a property that comes automatically with those particles wherever they exist.

The vast amount of charge in an everyday object is usually hidden because the object contains equal amounts of the two kinds of charge: *positive charge* and *negative charge*. With such an equality—or *balance*—of charge, the object is said to be *electrically neutral*; that is, it contains no *net charge*. If the two types of charge are not in balance, then there is a net charge. We say that an object is *charged* to indicate that it has a charge imbalance, or net charge. The imbalance is always much smaller than the total amounts of positive charge and negative charge contained in the object.

Charged objects interact by exerting forces on one another. To show this, we first charge a glass rod by rubbing one end with silk. At points of contact between the rod and the silk, tiny amounts of charge are transferred from one to the other, slightly upsetting the electrical neutrality of each. (We *rub* the silk over the rod to increase the number of contact points and thus the amount, still tiny, of transferred charge.)

Suppose we now suspend the charged rod from a thread to *electrically isolate* it from its surroundings so that its charge cannot change. If we bring a second, similarly charged, glass rod nearby (Fig. 21-2a), the two rods *repel* each other; that is, each rod experiences a force directed away from the other rod. However, if we rub a *plastic* rod with fur and then bring the rod near the suspended glass rod (Fig. 21-2b), the two rods *attract* each other; that is, each rod experiences a force directed toward the other rod.

We can understand these two demonstrations in terms of positive and negative charges. When a glass rod is rubbed with silk, the glass loses some of its negative charge and then has a small unbalanced positive charge (represented by the plus signs in Fig. 21-2a). When the plastic rod is rubbed with fur, the plastic gains a small unbalanced negative charge (represented by the minus signs in Fig. 21-2b). Our two demonstrations reveal the following:



Charges with the same electrical sign repel each other, and charges with opposite electrical signs attract each other.



Fig. 21-3 A carrier bead from a photocopying machine; the bead is covered with toner particles that cling to it by electrostatic attraction. The diameter of the bead is about 0.3 mm. (*Courtesy Xerox*)

In Section 21-4, we shall put this rule into quantitative form as Coulomb's law of *electrostatic force* (or *electric force*) between charges. The term *electrostatic* is used to emphasize that, relative to each other, the charges are either stationary or moving only very slowly.

The “positive” and “negative” labels and signs for electric charge were chosen arbitrarily by Benjamin Franklin. He could easily have interchanged the labels or used some other pair of opposites to distinguish the two kinds of charge. (Franklin was a scientist of international reputation. It has even been said that Franklin's triumphs in diplomacy in France during the American War of Independence were facilitated, and perhaps even made possible, because he was so highly regarded as a scientist.)

The attraction and repulsion between charged bodies have many industrial applications, including electrostatic paint spraying and powder coating, fly-ash collection in chimneys, nonimpact ink-jet printing, and photocopying. Figure 21-3 shows a tiny carrier bead in a photocopying machine, covered with particles of black powder called *toner*, which stick to it by means of electrostatic forces. The negatively charged toner particles are eventually attracted from the carrier bead to a rotating drum, where a positively charged image of the document being copied has formed. A charged sheet of paper then attracts the toner particles from the drum to itself, after which they are heat-fused permanently in place to produce the copy.

21-3 Conductors and Insulators

We can classify materials generally according to the ability of charge to move through them. **Conductors** are materials through which charge can move rather freely; examples include metals (such as copper in common lamp wire), the human body, and tap water. **Nonconductors**—also called **insulators**—are materials through which charge cannot move freely; examples include rubber (such as the insulation on common lamp wire), plastic, glass, and chemically pure water. **Semiconductors** are materials that are intermediate between conductors and insulators; examples include silicon and germanium in computer chips. **Superconductors** are materials that are *perfect* conductors, allowing charge to move without *any* hindrance. In these chapters we discuss only conductors and insulators.

Here is an example of how conduction can eliminate excess charge on an object. If you rub a copper rod with wool, charge is transferred from the wool to the rod. However, if you are holding the rod while also touching a faucet, you cannot charge the rod in spite of the transfer. The reason is that you, the rod, and the faucet are all conductors connected, via the plumbing, to Earth's surface, which is a huge conductor. Because the excess charges put on the rod by the wool repel one another, they move away from one another by moving first through the rod, then through you, and then through the faucet and plumbing to reach Earth's surface, where they can spread out. The process leaves the rod electrically neutral.

In thus setting up a pathway of conductors between an object and Earth's surface, we are said to *ground* the object, and in neutralizing the object (by eliminating an unbalanced positive or negative charge), we are said to *discharge* the object. If instead of holding the copper rod in your hand, you hold it by an insulating handle, you eliminate the conducting path to Earth, and the rod can then be charged by rubbing (the charge remains on the rod), as long as you do not touch it directly with your hand.

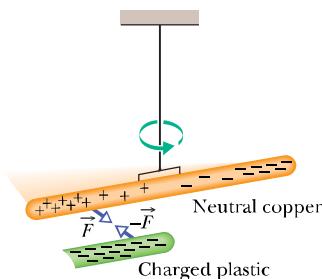
The properties of conductors and insulators are due to the structure and electrical nature of atoms. Atoms consist of positively charged *protons*, negatively charged *electrons*, and electrically neutral *neutrons*. The protons and neutrons are packed tightly together in a central *nucleus*.

The charge of a single electron and that of a single proton have the same magnitude but are opposite in sign. Hence, an electrically neutral atom contains equal numbers of electrons and protons. Electrons are held near the nucleus because they have the electrical sign opposite that of the protons in the nucleus and thus are attracted to the nucleus.

When atoms of a conductor like copper come together to form the solid, some of their outermost (and so most loosely held) electrons become free to wander about within the solid, leaving behind positively charged atoms (*positive ions*). We call the mobile electrons *conduction electrons*. There are few (if any) free electrons in a nonconductor.

The experiment of Fig. 21-4 demonstrates the mobility of charge in a conductor. A negatively charged plastic rod will attract either end of an isolated neutral

Fig. 21-4 A neutral copper rod is electrically isolated from its surroundings by being suspended on a nonconducting thread. Either end of the copper rod will be attracted by a charged rod. Here, conduction electrons in the copper rod are repelled to the far end of that rod by the negative charge on the plastic rod. Then that negative charge attracts the remaining positive charge on the near end of the copper rod, rotating the copper rod to bring that near end closer to the plastic rod.



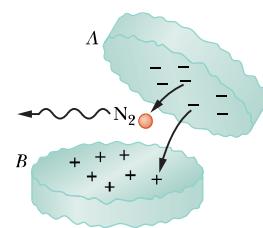


Fig. 21-5 Two pieces of a wintergreen LifeSaver candy as they fall away from each other. Electrons jumping from the negative surface of piece *A* to the positive surface of piece *B* collide with nitrogen (N_2) molecules in the air.

copper rod. What happens is that many of the conduction electrons in the closer end of the copper rod are repelled by the negative charge on the plastic rod. Some of the conduction electrons move to the far end of the copper rod, leaving the near end depleted in electrons and thus with an unbalanced positive charge. This positive charge is attracted to the negative charge in the plastic rod. Although the copper rod is still neutral, it is said to have an *induced charge*, which means that some of its positive and negative charges have been separated due to the presence of a nearby charge.

Similarly, if a positively charged glass rod is brought near one end of a neutral copper rod, conduction electrons in the copper rod are attracted to that end. That end becomes negatively charged and the other end positively charged, so again an induced charge is set up in the copper rod. Although the copper rod is still neutral, it and the glass rod attract each other.

Note that only conduction electrons, with their negative charges, can move; positive ions are fixed in place. Thus, an object becomes positively charged only through the *removal of negative charges*.

Blue Flashes from a Wintergreen LifeSaver

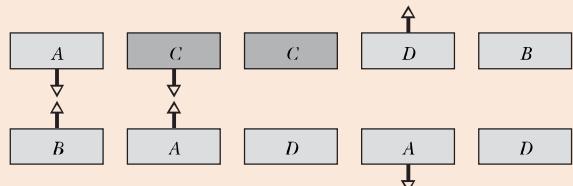
Indirect evidence for the attraction of charges with opposite signs can be seen with a wintergreen LifeSaver (the candy shaped in the form of a marine lifesaver). If you adapt your eyes to darkness for about 15 minutes and then have a friend chomp on a piece of the candy in the darkness, you will see a faint blue flash from your friend's mouth with each chomp. Whenever a chomp breaks a sugar crystal into pieces, each piece will probably end up with a different number of electrons. Suppose a crystal breaks into pieces *A* and *B*, with *A* ending up with more electrons on its surface than *B* (Fig. 21-5). This means that *B* has positive ions (atoms that lost electrons to *A*) on its surface. Because the electrons on *A* are strongly attracted to the positive ions on *B*, some of those electrons jump across the gap between the pieces.

As *A* and *B* fall away from each other, air (primarily nitrogen, N_2) flows into the gap, and many of the jumping electrons collide with nitrogen molecules in the air, causing the molecules to emit ultraviolet light. You cannot see this type of light. However, the wintergreen molecules on the surfaces of the candy pieces absorb the ultraviolet light and then emit blue light, which you *can* see—it is the blue light coming from your friend's mouth.



CHECKPOINT 1

The figure shows five pairs of plates: *A*, *B*, and *D* are charged plastic plates and *C* is an electrically neutral copper plate. The electrostatic forces between the pairs of plates are shown for three of the pairs. For the remaining two pairs, do the plates repel or attract each other?



21-4 Coulomb's Law

If two charged particles are brought near each other, they each exert a force on the other. If the particles have the same sign of charge, they repel each other (Figs. 21-6a and b). That is, the force on each particle is directed away from the other particle, and if the particles can move, they move away from each other. If, instead, the particles have opposite signs of charge, they attract each other (Fig. 21-6c) and, if free to move, they move closer to each other.

This force of repulsion or attraction due to the charge properties of objects is called an **electrostatic force**. The equation giving the force for charged *particles* is called **Coulomb's law** after Charles-Augustin de Coulomb, whose experiments in 1785 led him to it. In terms of the particles in Fig. 21-7, where particle 1 has charge q_1 and particle 2 has charge q_2 , the force on particle 1 is

$$\vec{F} = k \frac{q_1 q_2}{r^2} \hat{r} \quad (\text{Coulomb's law}), \quad (21-1)$$

in which \hat{r} is a unit vector along an axis extending through the two particles, r is the distance between them, and k is a constant. (As with other unit vectors, \hat{r} has a magnitude of exactly 1 and no dimension or unit; its purpose is to point.) If the particles have the same signs of charge, the force on particle 1 is in the direction of \hat{r} ; if they have opposite signs, the force is opposite \hat{r} .

Curiously, the form of Eq. 21-1 is the same as that of Newton's equation (Eq. 13-3) for the gravitational force between two particles with masses m_1 and m_2 that are separated by a distance r :

$$\vec{F} = G \frac{m_1 m_2}{r^2} \hat{r} \quad (\text{Newton's law}), \quad (21-2)$$

in which G is the gravitational constant.

The constant k in Eq. 21-1, by analogy with the gravitational constant G in Eq. 21-2, may be called the *electrostatic constant*. Both equations describe inverse square laws that involve a property of the interacting particles—the mass in one case and the charge in the other. The laws differ in that gravitational forces are always attractive but electrostatic forces may be either attractive or repulsive, depending on the signs of the two charges. This difference arises from the fact that, although there is only one kind of mass, there are two kinds of charge.

Coulomb's law has survived every experimental test; no exceptions to it have ever been found. It holds even within the atom, correctly describing the force between the positively charged nucleus and each of the negatively charged electrons, even though classical Newtonian mechanics fails in that realm and is replaced there by quantum physics. This simple law also correctly accounts for the forces that bind atoms together to form molecules, and for the forces that bind atoms and molecules together to form solids and liquids.

The SI unit of charge is the **coulomb**. For practical reasons having to do with the accuracy of measurements, the coulomb unit is derived from the SI unit **ampere** for *electric current* i . Current is the rate dq/dt at which charge moves past a point or through a region. In Chapter 26 we shall discuss current in detail. Until then we shall use the relation

$$i = \frac{dq}{dt} \quad (\text{electric current}), \quad (21-3)$$

in which i is the current (in amperes) and dq (in coulombs) is the amount of charge moving past a point or through a region in time dt (in seconds). Rearranging Eq. 21-3 tells us that

$$1 \text{ C} = (1 \text{ A})(1 \text{ s}).$$

For historical reasons (and because doing so simplifies many other formulas), the electrostatic constant k of Eq. 21-1 is usually written $1/4\pi\epsilon_0$. Then the magni-

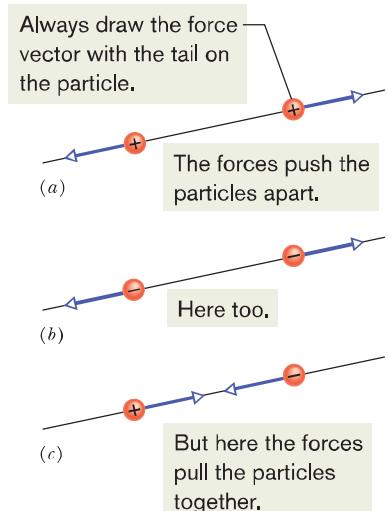


Fig. 21-6 Two charged particles repel each other if they have the same sign of charge, either (a) both positive or (b) both negative. (c) They attract each other if they have opposite signs of charge.

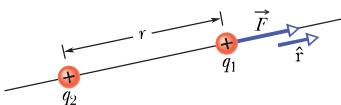


Fig. 21-7 The electrostatic force on particle 1 can be described in terms of a unit vector \hat{r} along an axis through the two particles.

tude of the force in Coulomb's law becomes

$$F = \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_2|}{r^2} \quad (\text{Coulomb's law}). \quad (21-4)$$

The constants in Eqs. 21-1 and 21-4 have the value

$$k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2. \quad (21-5)$$

The quantity ϵ_0 , called the **permittivity constant**, sometimes appears separately in equations and is

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2. \quad (21-6)$$

Still another parallel between the gravitational force and the electrostatic force is that both obey the principle of superposition. If we have n charged particles, they interact independently in pairs, and the force on any one of them, let us say particle 1, is given by the vector sum

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \vec{F}_{15} + \cdots + \vec{F}_{1n}, \quad (21-7)$$

in which, for example, \vec{F}_{14} is the force acting on particle 1 due to the presence of particle 4. An identical formula holds for the gravitational force.

Finally, the shell theorem that we found so useful in our study of gravitation has analogs in electrostatics:

-  A shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell's charge were concentrated at its center.
-  If a charged particle is located inside a shell of uniform charge, there is no net electrostatic force on the particle from the shell.

(In the first theorem, we assume that the charge on the shell is much greater than that of the particle. Then any redistribution of the charge on the shell due to the presence of the particle's charge can be neglected.)

Spherical Conductors

If excess charge is placed on a spherical shell that is made of conducting material, the excess charge spreads uniformly over the (external) surface. For example, if we place excess electrons on a spherical metal shell, those electrons repel one another and tend to move apart, spreading over the available surface until they are uniformly distributed. That arrangement maximizes the distances between all pairs of the excess electrons. According to the first shell theorem, the shell then will attract or repel an external charge as if all the excess charge on the shell were concentrated at its center.

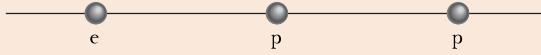
If we remove negative charge from a spherical metal shell, the resulting positive charge of the shell is also spread uniformly over the surface of the shell. For example, if we remove n electrons, there are then n sites of positive charge (sites missing an electron) that are spread uniformly over the shell. According to the first shell theorem, the shell will again attract or repel an external charge as if all the shell's excess charge were concentrated at its center.



CHECKPOINT 2

The figure shows two protons (symbol p) and

one electron (symbol e) on an axis. What is the direction of (a) the electrostatic force on the central proton due to the electron, (b) the electrostatic force on the central proton due to the other proton, and (c) the net electrostatic force on the central proton?



e p p

Sample Problem

Finding the net force due to two other particles

(a) Figure 21-8a shows two positively charged particles fixed in place on an x axis. The charges are $q_1 = 1.60 \times 10^{-19} \text{ C}$ and $q_2 = 3.20 \times 10^{-19} \text{ C}$, and the particle separation is $R = 0.0200 \text{ m}$. What are the magnitude and direction of the electrostatic force \vec{F}_{12} on particle 1 from particle 2?

KEY IDEAS

Because both particles are positively charged, particle 1 is repelled by particle 2, with a force magnitude given by Eq. 21-4. Thus, the direction of force \vec{F}_{12} on particle 1 is *away from* particle 2, in the negative direction of the x axis, as indicated in the free-body diagram of Fig. 21-8b.

Two particles: Using Eq. 21-4 with separation R substituted for r , we can write the magnitude F_{12} of this force as

$$\begin{aligned} F_{12} &= \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_2|}{R^2} \\ &= (8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2) \\ &\quad \times \frac{(1.60 \times 10^{-19} \text{ C})(3.20 \times 10^{-19} \text{ C})}{(0.0200 \text{ m})^2} \\ &= 1.15 \times 10^{-24} \text{ N}. \end{aligned}$$

Thus, force \vec{F}_{12} has the following magnitude and direction (relative to the positive direction of the x axis):

$$1.15 \times 10^{-24} \text{ N} \text{ and } 180^\circ. \quad (\text{Answer})$$

We can also write \vec{F}_{12} in unit-vector notation as

$$\vec{F}_{12} = -(1.15 \times 10^{-24} \text{ N})\hat{i}. \quad (\text{Answer})$$

(b) Figure 21-8c is identical to Fig. 21-8a except that particle 3 now lies on the x axis between particles 1 and 2. Particle 3 has charge $q_3 = -3.20 \times 10^{-19} \text{ C}$ and is at a distance $\frac{3}{4}R$ from particle 1. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 3?

KEY IDEA

The presence of particle 3 does not alter the electrostatic force on particle 1 from particle 2. Thus, force \vec{F}_{12} still acts on particle 1. Similarly, the force \vec{F}_{13} that acts on particle 1 due to particle 3 is not affected by the presence of particle 2. Because particles 1 and 3 have charge of opposite signs, particle 1 is attracted to particle 3. Thus, force \vec{F}_{13} is directed *toward* particle 3, as indicated in the free-body diagram of Fig. 21-8d.

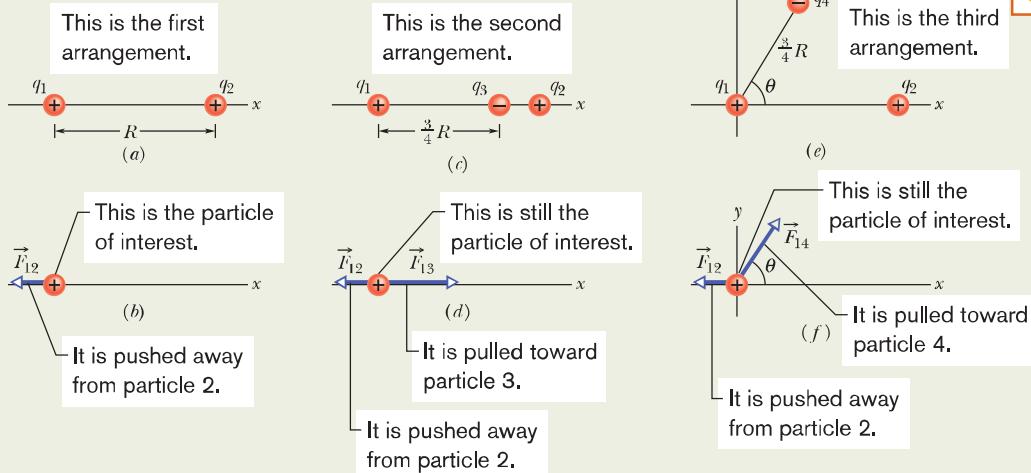
Three particles: To find the magnitude of \vec{F}_{13} , we can rewrite Eq. 21-4 as

$$\begin{aligned} F_{13} &= \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_3|}{(\frac{3}{4}R)^2} \\ &= (8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2) \\ &\quad \times \frac{(1.60 \times 10^{-19} \text{ C})(3.20 \times 10^{-19} \text{ C})}{(\frac{3}{4})^2(0.0200 \text{ m})^2} \\ &= 2.05 \times 10^{-24} \text{ N}. \end{aligned}$$

We can also write \vec{F}_{13} in unit-vector notation:

$$\vec{F}_{13} = (2.05 \times 10^{-24} \text{ N})\hat{i}.$$

Fig. 21-8 (a) Two charged particles of charges q_1 and q_2 are fixed in place on an x axis. (b) The free-body diagram for particle 1, showing the electrostatic force on it from particle 2. (c) Particle 3 included. (d) Free-body diagram for particle 1. (e) Particle 4 included. (f) Free-body diagram for particle 1.



The net force $\vec{F}_{1,\text{net}}$ on particle 1 is the vector sum of \vec{F}_{12} and \vec{F}_{13} ; that is, from Eq. 21-7, we can write the net force $\vec{F}_{1,\text{net}}$ on particle 1 in unit-vector notation as

$$\begin{aligned}\vec{F}_{1,\text{net}} &= \vec{F}_{12} + \vec{F}_{13} \\ &= -(1.15 \times 10^{-24} \text{ N})\hat{i} + (2.05 \times 10^{-24} \text{ N})\hat{i} \\ &= (9.00 \times 10^{-25} \text{ N})\hat{i}. \quad (\text{Answer})\end{aligned}$$

Thus, $\vec{F}_{1,\text{net}}$ has the following magnitude and direction (relative to the positive direction of the x axis):

$$9.00 \times 10^{-25} \text{ N} \quad \text{and} \quad 0^\circ. \quad (\text{Answer})$$

(c) Figure 21-8e is identical to Fig. 21-8a except that particle 4 is now included. It has charge $q_4 = -3.20 \times 10^{-19} \text{ C}$, is at a distance $\frac{3}{4}R$ from particle 1, and lies on a line that makes an angle $\theta = 60^\circ$ with the x axis. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 4?

KEY IDEA

The net force $\vec{F}_{1,\text{net}}$ is the vector sum of \vec{F}_{12} and a new force \vec{F}_{14} acting on particle 1 due to particle 4. Because particles 1 and 4 have charge of opposite signs, particle 1 is attracted to particle 4. Thus, force \vec{F}_{14} on particle 1 is directed toward particle 4, at angle $\theta = 60^\circ$, as indicated in the free-body diagram of Fig. 21-8f.

Four particles: We can rewrite Eq. 21-4 as

$$\begin{aligned}F_{14} &= \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_4|}{(\frac{3}{4}R)^2} \\ &= (8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2) \\ &\quad \times \frac{(1.60 \times 10^{-19} \text{ C})(3.20 \times 10^{-19} \text{ C})}{(\frac{3}{4})^2(0.0200 \text{ m})^2} \\ &= 2.05 \times 10^{-24} \text{ N}.\end{aligned}$$

Then from Eq. 21-7, we can write the net force $\vec{F}_{1,\text{net}}$ on particle 1 as

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{14}.$$

Because the forces \vec{F}_{12} and \vec{F}_{14} are not directed along the same axis, we *cannot* sum simply by combining their magnitudes. Instead, we must add them as vectors, using one of the following methods.



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CHECKPOINT 3

The figure here shows three arrangements of an electron e and two protons p . (a) Rank the arrangements according to the magnitude of the net electrostatic force on the electron due to the protons, largest first. (b) In situation c, is the angle between the net force on the electron and the line labeled d less than or more than 45° ?

Method 1. *Summing directly on a vector-capable calculator.* For \vec{F}_{12} , we enter the magnitude 1.15×10^{-24} and the angle 180° . For \vec{F}_{14} , we enter the magnitude 2.05×10^{-24} and the angle 60° . Then we add the vectors.

Method 2. *Summing in unit-vector notation.* First we rewrite \vec{F}_{14} as

$$\vec{F}_{14} = (F_{14} \cos \theta)\hat{i} + (F_{14} \sin \theta)\hat{j}.$$

Substituting $2.05 \times 10^{-24} \text{ N}$ for F_{14} and 60° for θ , this becomes

$$\vec{F}_{14} = (1.025 \times 10^{-24} \text{ N})\hat{i} + (1.775 \times 10^{-24} \text{ N})\hat{j}.$$

Then we sum:

$$\begin{aligned}\vec{F}_{1,\text{net}} &= \vec{F}_{12} + \vec{F}_{14} \\ &= -(1.15 \times 10^{-24} \text{ N})\hat{i} \\ &\quad + (1.025 \times 10^{-24} \text{ N})\hat{i} + (1.775 \times 10^{-24} \text{ N})\hat{j} \\ &\approx (-1.25 \times 10^{-25} \text{ N})\hat{i} + (1.78 \times 10^{-24} \text{ N})\hat{j}. \quad (\text{Answer})\end{aligned}$$

Method 3. *Summing components axis by axis.* The sum of the x components gives us

$$\begin{aligned}F_{1,\text{net},x} &= F_{12,x} + F_{14,x} = F_{12} + F_{14} \cos 60^\circ \\ &= -1.15 \times 10^{-24} \text{ N} + (2.05 \times 10^{-24} \text{ N})(\cos 60^\circ) \\ &= -1.25 \times 10^{-25} \text{ N}.\end{aligned}$$

The sum of the y components gives us

$$\begin{aligned}F_{1,\text{net},y} &= F_{12,y} + F_{14,y} = 0 + F_{14} \sin 60^\circ \\ &= (2.05 \times 10^{-24} \text{ N})(\sin 60^\circ) \\ &= 1.78 \times 10^{-24} \text{ N}.\end{aligned}$$

The net force $\vec{F}_{1,\text{net}}$ has the magnitude

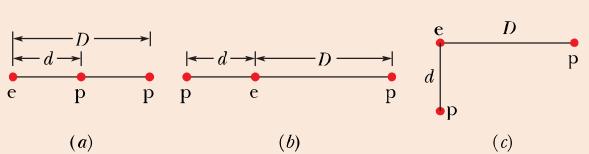
$$F_{1,\text{net}} = \sqrt{F_{1,\text{net},x}^2 + F_{1,\text{net},y}^2} = 1.78 \times 10^{-24} \text{ N}. \quad (\text{Answer})$$

To find the direction of $\vec{F}_{1,\text{net}}$, we take

$$\theta = \tan^{-1} \frac{F_{1,\text{net},y}}{F_{1,\text{net},x}} = -86.0^\circ.$$

However, this is an unreasonable result because $\vec{F}_{1,\text{net}}$ must have a direction between the directions of \vec{F}_{12} and \vec{F}_{14} . To correct θ , we add 180° , obtaining

$$-86.0^\circ + 180^\circ = 94.0^\circ. \quad (\text{Answer})$$



Sample Problem**Equilibrium of two forces on a particle**

Figure 21-9a shows two particles fixed in place: a particle of charge $q_1 = +8q$ at the origin and a particle of charge $q_2 = -2q$ at $x = L$. At what point (other than infinitely far away) can a proton be placed so that it is in *equilibrium* (the net force on it is zero)? Is that equilibrium *stable* or *unstable*? (That is, if the proton is displaced, do the forces drive it back to the point of equilibrium or drive it farther away?)

KEY IDEA

If \vec{F}_1 is the force on the proton due to charge q_1 and \vec{F}_2 is the force on the proton due to charge q_2 , then the point we seek is where $\vec{F}_1 + \vec{F}_2 = 0$. Thus,

$$\vec{F}_1 = -\vec{F}_2. \quad (21-8)$$

This tells us that at the point we seek, the forces acting on the proton due to the other two particles must be of equal magnitudes,

$$F_1 = F_2, \quad (21-9)$$

and that the forces must have opposite directions.

Reasoning: Because a proton has a positive charge, the proton and the particle of charge q_1 are of the same sign, and force \vec{F}_1 on the proton must point away from q_1 . Also, the proton and the particle of charge q_2 are of opposite signs, so force \vec{F}_2 on the proton must point toward q_2 . “Away from q_1 ” and “toward q_2 ” can be in opposite directions only if the proton is located on the x axis.

If the proton is on the x axis at any point between q_1 and q_2 , such as point P in Fig. 21-9b, then \vec{F}_1 and \vec{F}_2 are in the same direction and not in opposite directions as required. If the proton is at any point on the x axis to the left of q_1 , such as point S in Fig. 21-9c, then \vec{F}_1 and \vec{F}_2 are in opposite directions. However, Eq. 21-4 tells us that \vec{F}_1 and \vec{F}_2 cannot have equal magnitudes there: F_1 must be greater than F_2 , because F_1 is produced by a closer charge (with lesser r) of greater magnitude ($8q$ versus $2q$).

Finally, if the proton is at any point on the x axis to the right of q_2 , such as point R in Fig. 21-9d, then \vec{F}_1 and \vec{F}_2 are again in opposite directions. However, because now the charge of greater magnitude (q_1) is *further* away from the proton than the charge of lesser magnitude, there is a point at which F_1 is equal to F_2 . Let x be the coordinate of this point, and let q_p be the charge of the proton.

Calculations: With the aid of Eq. 21-4, we can now rewrite Eq. 21-9 (which says that the forces have equal magnitudes):

$$\frac{1}{4\pi\epsilon_0} \frac{8qq_p}{x^2} = \frac{1}{4\pi\epsilon_0} \frac{2qq_p}{(x-L)^2}. \quad (21-10)$$

(Note that only the charge magnitudes appear in Eq. 21-10. We already decided about the directions of the forces in drawing Fig. 21-9d and do not want to include any positive or negative signs here.) Rearranging Eq. 21-10 gives us

$$\left(\frac{x-L}{x}\right)^2 = \frac{1}{4}.$$

After taking the square roots of both sides, we have

$$\frac{x-L}{x} = \frac{1}{2},$$

which gives us

$$x = 2L. \quad (\text{Answer})$$

The equilibrium at $x = 2L$ is unstable; that is, if the proton is displaced leftward from point R , then F_1 and F_2 both increase but F_2 increases more (because q_2 is closer than q_1), and a net force will drive the proton farther leftward. If the proton is displaced rightward, both F_1 and F_2 decrease but F_2 decreases more, and a net force will then drive the proton farther rightward. In a stable equilibrium, if the proton is displaced slightly, it returns to the equilibrium position.

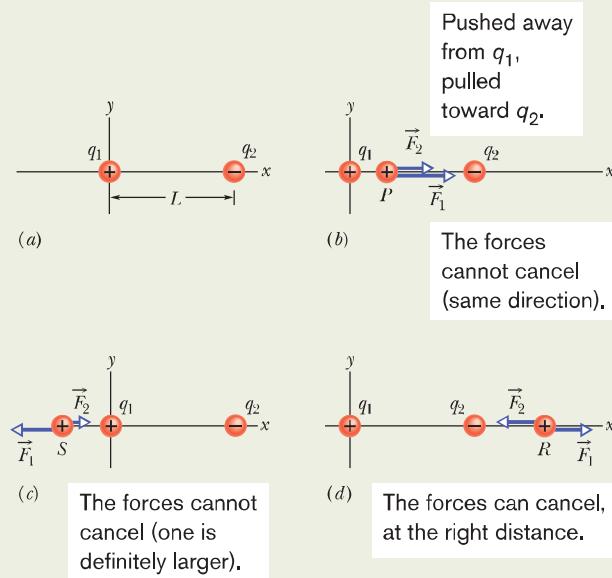


Fig. 21-9 (a) Two particles of charges q_1 and q_2 are fixed in place on an x axis, with separation L . (b)–(d) Three possible locations P , S , and R for a proton. At each location, \vec{F}_1 is the force on the proton from particle 1 and \vec{F}_2 is the force on the proton from particle 2.

Sample Problem**Charge sharing by two identical conducting spheres**

In Fig. 21-10a, two identical, electrically isolated conducting spheres *A* and *B* are separated by a (center-to-center) distance *a* that is large compared to the spheres. Sphere *A* has a positive charge of $+Q$, and sphere *B* is electrically neutral. Initially, there is no electrostatic force between the spheres. (Assume that there is no induced charge on the spheres because of their large separation.)

- (a) Suppose the spheres are connected for a moment by a conducting wire. The wire is thin enough so that any net charge on it is negligible. What is the electrostatic force between the spheres after the wire is removed?

KEY IDEAS

- (1) Because the spheres are identical, connecting them means that they end up with identical charges (same sign and same amount).
- (2) The initial sum of the charges (including the signs of the charges) must equal the final sum of the charges.

Reasoning: When the spheres are wired together, the (negative) conduction electrons on *B*, which repel one another, have a way to move away from one another (along the wire to positively charged *A*, which attracts them—Fig. 21-10b.) As *B* loses negative charge, it becomes positively charged, and as *A* gains negative charge, it becomes less positively charged. The transfer of charge stops when the charge on *B* has increased to $+Q/2$ and the charge on *A* has decreased to $+Q/2$, which occurs when $-Q/2$ has shifted from *B* to *A*.

After the wire has been removed (Fig. 21-10c), we can assume that the charge on either sphere does not disturb the uniformity of the charge distribution on the other sphere, because the spheres are small relative to their separation. Thus, we can apply the first shell theorem to each sphere. By Eq. 21-4

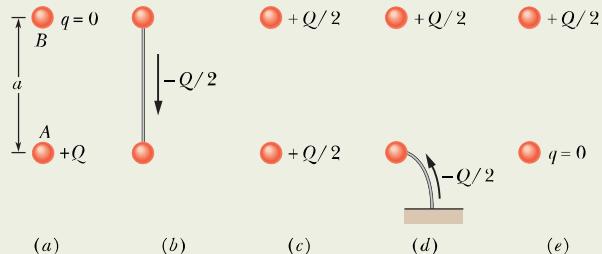


Fig. 21-10 Two small conducting spheres *A* and *B*. (a) To start, sphere *A* is charged positively. (b) Negative charge is transferred from *B* to *A* through a connecting wire. (c) Both spheres are then charged positively. (d) Negative charge is transferred through a grounding wire to sphere *A*. (e) Sphere *A* is then neutral.

with $q_1 = q_2 = Q/2$ and $r = a$,

$$F = \frac{1}{4\pi\epsilon_0} \frac{(Q/2)(Q/2)}{a^2} = \frac{1}{16\pi\epsilon_0} \left(\frac{Q}{a}\right)^2. \quad (\text{Answer})$$

The spheres, now positively charged, repel each other.

- (b) Next, suppose sphere *A* is grounded momentarily, and then the ground connection is removed. What now is the electrostatic force between the spheres?

Reasoning: When we provide a conducting path between a charged object and the ground (which is a huge conductor), we neutralize the object. Were sphere *A* negatively charged, the mutual repulsion between the excess electrons would cause them to move from the sphere to the ground. However, because sphere *A* is positively charged, electrons with a total charge of $-Q/2$ move *from* the ground up onto the sphere (Fig. 21-10d), leaving the sphere with a charge of 0 (Fig. 21-10e). Thus, there is (again) no electrostatic force between the two spheres.



Additional examples, video, and practice available at WileyPLUS

21-5 Charge Is Quantized

In Benjamin Franklin's day, electric charge was thought to be a continuous fluid—an idea that was useful for many purposes. However, we now know that fluids themselves, such as air and water, are not continuous but are made up of atoms and molecules; matter is discrete. Experiment shows that "electrical fluid" is also not continuous but is made up of multiples of a certain elementary charge. Any positive or negative charge *q* that can be detected can be written as

$$q = ne, \quad n = \pm 1, \pm 2, \pm 3, \dots, \quad (21-11)$$

in which *e*, the **elementary charge**, has the approximate value

$$e = 1.602 \times 10^{-19} \text{ C.} \quad (21-12)$$

The elementary charge e is one of the important constants of nature. The electron and proton both have a charge of magnitude e (Table 21-1). (Quarks, the constituent particles of protons and neutrons, have charges of $\pm e/3$ or $\pm 2e/3$, but they apparently cannot be detected individually. For this and for historical reasons, we do not take their charges to be the elementary charge.)

You often see phrases—such as “the charge on a sphere,” “the amount of charge transferred,” and “the charge carried by the electron”—that suggest that charge is a substance. (Indeed, such statements have already appeared in this chapter.) You should, however, keep in mind what is intended: *Particles* are the substance and charge happens to be one of their properties, just as mass is.

When a physical quantity such as charge can have only discrete values rather than any value, we say that the quantity is **quantized**. It is possible, for example, to find a particle that has no charge at all or a charge of $+10e$ or $-6e$, but not a particle with a charge of, say, $3.57e$.

The quantum of charge is small. In an ordinary 100 W lightbulb, for example, about 10^{19} elementary charges enter the bulb every second and just as many leave. However, the graininess of electricity does not show up in such large-scale phenomena (the bulb does not flicker with each electron), just as you cannot feel the individual molecules of water with your hand.



CHECKPOINT 4

Initially, sphere A has a charge of $-50e$ and sphere B has a charge of $+20e$. The spheres are made of conducting material and are identical in size. If the spheres then touch, what is the resulting charge on sphere A?

Table 21-1
The Charges of Three Particles

Particle	Symbol	Charge
Electron	e or e^-	$-e$
Proton	p	$+e$
Neutron	n	0

Sample Problem

Mutual electric repulsion in a nucleus

The nucleus in an iron atom has a radius of about $4.0 \times 10^{-15} \text{ m}$ and contains 26 protons.

- (a) What is the magnitude of the repulsive electrostatic force between two of the protons that are separated by $4.0 \times 10^{-15} \text{ m}$?

KEY IDEA

The protons can be treated as charged particles, so the magnitude of the electrostatic force on one from the other is given by Coulomb's law.

Calculation: Table 21-1 tells us that the charge of a proton is $+e$. Thus, Eq. 21-4 gives us

$$\begin{aligned} F &= \frac{1}{4\pi\epsilon_0} \frac{e^2}{r^2} \\ &= \frac{(8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2)(1.602 \times 10^{-19} \text{ C})^2}{(4.0 \times 10^{-15} \text{ m})^2} \\ &= 14 \text{ N.} \end{aligned} \quad (\text{Answer})$$

No explosion: This is a small force to be acting on a macroscopic object like a cantaloupe, but an enormous force to be

acting on a proton. Such forces should explode the nucleus of any element but hydrogen (which has only one proton in its nucleus). However, they don't, not even in nuclei with a great many protons. Therefore, there must be some enormous attractive force to counter this enormous repulsive electrostatic force.

- (b) What is the magnitude of the gravitational force between those same two protons?

KEY IDEA

Because the protons are particles, the magnitude of the gravitational force on one from the other is given by Newton's equation for the gravitational force (Eq. 21-2).

Calculation: With m_p ($= 1.67 \times 10^{-27} \text{ kg}$) representing the mass of a proton, Eq. 21-2 gives us

$$\begin{aligned} F &= G \frac{m_p^2}{r^2} \\ &= \frac{(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2)(1.67 \times 10^{-27} \text{ kg})^2}{(4.0 \times 10^{-15} \text{ m})^2} \\ &= 1.2 \times 10^{-35} \text{ N.} \end{aligned} \quad (\text{Answer})$$

Weak versus strong: This result tells us that the (attractive) gravitational force is far too weak to counter the repulsive electrostatic forces between protons in a nucleus. Instead, the protons are bound together by an enormous force called (aptly) the *strong nuclear force*—a force that acts between protons (and neutrons) when they are close together, as in a nucleus.

Although the gravitational force is many times weaker

than the electrostatic force, it is more important in large-scale situations because it is always attractive. This means that it can collect many small bodies into huge bodies with huge masses, such as planets and stars, that then exert large gravitational forces. The electrostatic force, on the other hand, is repulsive for charges of the same sign, so it is unable to collect either positive charge or negative charge into large concentrations that would then exert large electrostatic forces.



Additional examples, video, and practice available at WileyPLUS

21-6 Charge Is Conserved

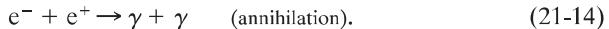
If you rub a glass rod with silk, a positive charge appears on the rod. Measurement shows that a negative charge of equal magnitude appears on the silk. This suggests that rubbing does not create charge but only transfers it from one body to another, upsetting the electrical neutrality of each body during the process. This hypothesis of **conservation of charge**, first put forward by Benjamin Franklin, has stood up under close examination, both for large-scale charged bodies and for atoms, nuclei, and elementary particles. No exceptions have ever been found. Thus, we add electric charge to our list of quantities—including energy and both linear and angular momentum—that obey a conservation law.

Important examples of the conservation of charge occur in the *radioactive decay* of nuclei, in which a nucleus transforms into (becomes) a different type of nucleus. For example, a uranium-238 nucleus (^{238}U) transforms into a thorium-234 nucleus (^{234}Th) by emitting an *alpha particle*. Because that particle has the same makeup as a helium-4 nucleus, it has the symbol ^4He . The number used in the name of a nucleus and as a superscript in the symbol for the nucleus is called the *mass number* and is the total number of the protons and neutrons in the nucleus. For example, the total number in ^{238}U is 238. The number of protons in a nucleus is the *atomic number Z*, which is listed for all the elements in Appendix F. From that list we find that in the decay



the *parent* nucleus ^{238}U contains 92 protons (a charge of $+92e$), the *daughter* nucleus ^{234}Th contains 90 protons (a charge of $+90e$), and the emitted alpha particle ^4He contains 2 protons (a charge of $+2e$). We see that the total charge is $+92e$ before and after the decay; thus, charge is conserved. (The total number of protons and neutrons is also conserved: 238 before the decay and $234 + 4 = 238$ after the decay.)

Another example of charge conservation occurs when an electron e^- (charge $-e$) and its antiparticle, the *positron* e^+ (charge $+e$), undergo an *annihilation process*, transforming into two *gamma rays* (high-energy light):



In applying the conservation-of-charge principle, we must add the charges algebraically, with due regard for their signs. In the annihilation process of Eq. 21-14 then, the net charge of the system is zero both before and after the event. Charge is conserved.

In *pair production*, the converse of annihilation, charge is also conserved. In this process a gamma ray transforms into an electron and a positron:

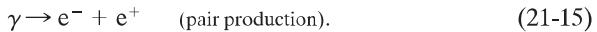


Figure 21-11 shows such a pair-production event that occurred in a bubble cham-

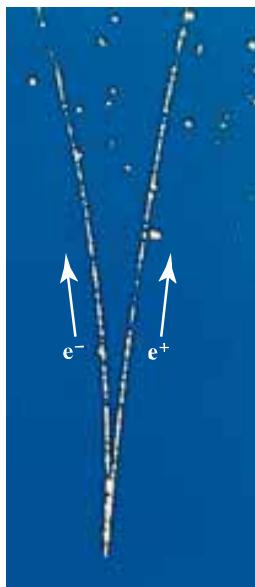


Fig. 21-11 A photograph of trails of bubbles left in a bubble chamber by an electron and a positron. The pair of particles was produced by a gamma ray that entered the chamber directly from the bottom. Being electrically neutral, the gamma ray did not generate a telltale trail of bubbles along its path, as the electron and positron did. (Courtesy Lawrence Berkeley Laboratory)

ber. A gamma ray entered the chamber from the bottom and at one point transformed into an electron and a positron. Because those new particles were charged and moving, each left a trail of tiny bubbles. (The trails were curved because a magnetic field had been set up in the chamber.) The gamma ray, being electrically neutral, left no trail. Still, you can tell exactly where it underwent pair production—at the tip of the curved V, which is where the trails of the electron and positron begin.

REVIEW & SUMMARY

Electric Charge The strength of a particle's electrical interaction with objects around it depends on its **electric charge**, which can be either positive or negative. Charges with the same sign repel each other, and charges with opposite signs attract each other. An object with equal amounts of the two kinds of charge is electrically neutral, whereas one with an imbalance is electrically charged.

Conductors are materials in which a significant number of charged particles (electrons in metals) are free to move. The charged particles in **nonconductors**, or **insulators**, are not free to move.

The Coulomb and Ampere The SI unit of charge is the **coulomb** (C). It is defined in terms of the unit of current, the ampere (A), as the charge passing a particular point in 1 second when there is a current of 1 ampere at that point:

$$1 \text{ C} = (1 \text{ A})(1 \text{ s}).$$

This is based on the relation between current i and the rate dq/dt at which charge passes a point:

$$i = \frac{dq}{dt} \quad (\text{electric current}). \quad (21-3)$$

Coulomb's Law *Coulomb's law* describes the **electrostatic force** between small (point) electric charges q_1 and q_2 at rest (or

nearly at rest) and separated by a distance r :

$$F = \frac{1}{4\pi\epsilon_0} \frac{|q_1||q_2|}{r^2} \quad (\text{Coulomb's law}). \quad (21-4)$$

Here $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2$ is the **permittivity constant**, and $1/4\pi\epsilon_0 = k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$.

The force of attraction or repulsion between point charges at rest acts along the line joining the two charges. If more than two charges are present, Eq. 21-4 holds for each pair of charges. The net force on each charge is then found, using the superposition principle, as the vector sum of the forces exerted on the charge by all the others.

The two shell theorems for electrostatics are

A shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell's charge were concentrated at its center.

If a charged particle is located inside a shell of uniform charge, there is no net electrostatic force on the particle from the shell.

The Elementary Charge Electric charge is **quantized**: any charge can be written as ne , where n is a positive or negative integer and e is a constant of nature called the **elementary charge** ($\approx 1.602 \times 10^{-19} \text{ C}$). Electric charge is **conserved**: the net charge of any isolated system cannot change.

QUESTIONS

- 1 Figure 21-12 shows four situations in which five charged particles are evenly spaced along an axis. The charge values are indicated except for the central particle, which has the same charge in all four situations. Rank the situations according to the magnitude of the net electrostatic force on the central particle, greatest first.

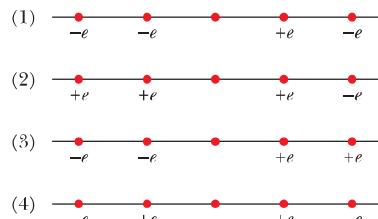


Fig. 21-12 Question 1.

- 2 Figure 21-13 shows three pairs of identical spheres that are to be touched together and then separated. The initial charges on them are indicated. Rank the pairs according to (a) the magnitude of the charge transferred during touching and (b) the charge left on the positively charged sphere, greatest first.

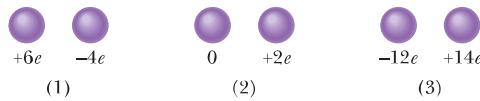


Fig. 21-13 Question 2.

- 3 Figure 21-14 shows four situations in which charged particles are fixed in place on an axis. In which situations is there a point to the left of the particles where an electron will be in equilibrium?

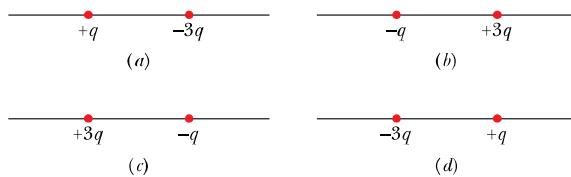


Fig. 21-14 Question 3.

- 4** Figure 21-15 shows two charged particles on an axis. The charges are free to move. However, a third charged particle can be placed at a certain point such that all three particles are then in equilibrium. (a) Is that point to the left of the first two particles, to their right, or between them? (b) Should the third particle be positively or negatively charged? (c) Is the equilibrium stable or unstable?

- 5** In Fig. 21-16, a central particle of charge $-q$ is surrounded by two circular rings of charged particles. What are the magnitude and direction of the net electrostatic force on the central particle due to the other particles? (Hint: Consider symmetry.)

- 6** A positively charged ball is brought close to an electrically neutral isolated conductor. The conductor is then grounded while the ball is kept close. Is the conductor charged positively, charged negatively, or neutral if (a) the ball is first taken away and then the ground connection is removed and (b) the ground connection is first removed and then the ball is taken away?

- 7** Figure 21-17 shows three situations involving a charged particle and a uniformly charged spherical shell. The charges are given, and the radii of the shells are indicated. Rank the situations according to the magnitude of the force on the particle due to the presence of the shell, greatest first.

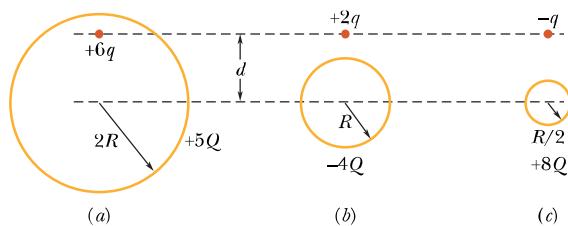


Fig. 21-17 Question 7.

- 8** Figure 21-18 shows four arrangements of charged particles.

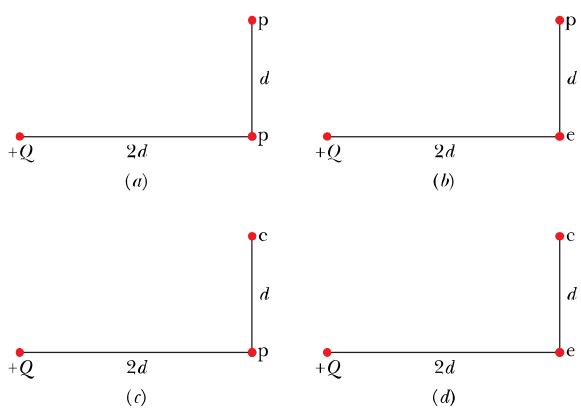


Fig. 21-18 Question 8.



Fig. 21-15 Question 4.

Rank the arrangements according to the magnitude of the net electrostatic force on the particle with charge $+Q$, greatest first.

- 9** Figure 21-19 shows four situations in which particles of charge $+q$ or $-q$ are fixed in place. In each situation, the particles on the x axis are equidistant from the y axis. First, consider the middle particle in situation 1; the middle particle experiences an electrostatic force from each of the other two particles. (a) Are the magnitudes F of those forces the same or different? (b) Is the magnitude of the net force on the middle particle equal to, greater than, or less than $2F$? (c) Do the x components of the two forces add or cancel? (d) Do their y components add or cancel? (e) Is the direction of the net force on the middle particle that of the canceling components or the adding components? (f) What is the direction of that net force? Now consider the remaining situations: What is the direction of the net force on the middle particle in (g) situation 2, (h) situation 3, and (i) situation 4? (In each situation, consider the symmetry of the charge distribution and determine the canceling components and the adding components.)

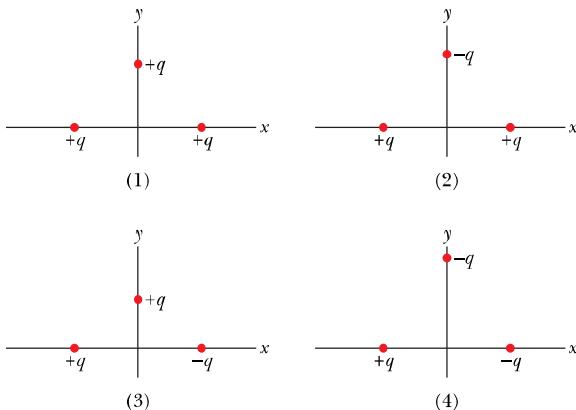


Fig. 21-19 Question 9.

- 10** In Fig. 21-20, a central particle of charge $-2q$ is surrounded by a square array of charged particles, separated by either distance d or $d/2$ along the perimeter of the square. What are the magnitude and direction of the net electrostatic force on the central particle due to the other particles? (Hint: Consideration of symmetry can greatly reduce the amount of work required here.)

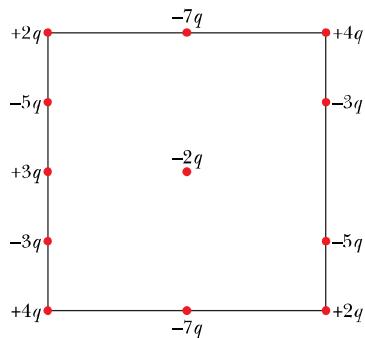


Fig. 21-20 Question 10.

PROBLEMS



Tutoring problem available (at instructor's discretion) in WileyPLUS and WebAssign

Worked-out solution available in Student Solutions Manual

Number of dots indicates level of problem difficulty

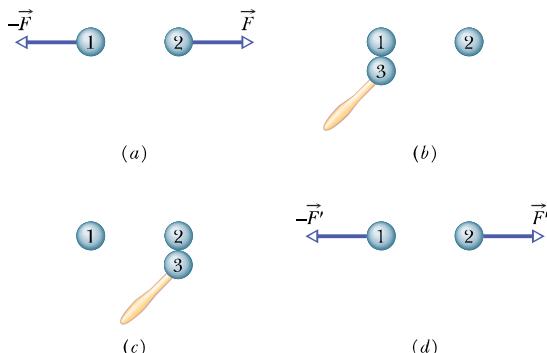
WWW Worked-out solution is at

ILW Interactive solution is at

Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com<http://www.wiley.com/college/halliday>**sec. 21-4 Coulomb's Law**

- 1 SSM ILW** Of the charge Q initially on a tiny sphere, a portion q is to be transferred to a second, nearby sphere. Both spheres can be treated as particles. For what value of q/Q will the electrostatic force between the two spheres be maximized?

- 2** Identical isolated conducting spheres 1 and 2 have equal charges and are separated by a distance that is large compared with their diameters (Fig. 21-21a). The electrostatic force acting on sphere 2 due to sphere 1 is \vec{F} . Suppose now that a third identical sphere 3, having an insulating handle and initially neutral, is touched first to sphere 1 (Fig. 21-21b), then to sphere 2 (Fig. 21-21c), and finally removed (Fig. 21-21d). The electrostatic force that now acts on sphere 2 has magnitude F' . What is the ratio F'/F ?

**Fig. 21-21** Problem 2.

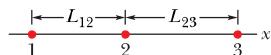
- 3 SSM** What must be the distance between point charge $q_1 = 26.0 \mu\text{C}$ and point charge $q_2 = -47.0 \mu\text{C}$ for the electrostatic force between them to have a magnitude of 5.70 N?

- 4** In the return stroke of a typical lightning bolt, a current of $2.5 \times 10^4 \text{ A}$ exists for $20 \mu\text{s}$. How much charge is transferred in this event?

- 5** A particle of charge $+3.00 \times 10^{-6} \text{ C}$ is 12.0 cm distant from a second particle of charge $-1.50 \times 10^{-6} \text{ C}$. Calculate the magnitude of the electrostatic force between the particles.

- 6 ILW** Two equally charged particles are held $3.2 \times 10^{-3} \text{ m}$ apart and then released from rest. The initial acceleration of the first particle is observed to be 7.0 m/s^2 and that of the second to be 9.0 m/s^2 . If the mass of the first particle is $6.3 \times 10^{-7} \text{ kg}$, what are (a) the mass of the second particle and (b) the magnitude of the charge of each particle?

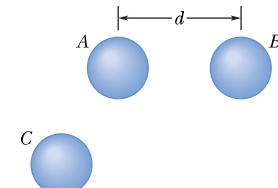
- 7** In Fig. 21-22, three charged particles lie on an x axis. Particles 1 and 2 are fixed in place. Particle 3 is free to move, but the net

**Fig. 21-22** Problems 7 and 40.

electrostatic force on it from particles 1 and 2 happens to be zero. If $L_{23} = L_{12}$, what is the ratio q_1/q_2 ?

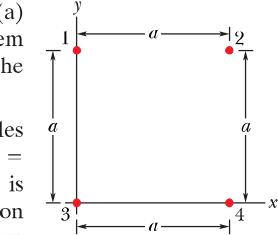
- 8** In Fig. 21-23, three identical conducting spheres initially have the following charges: sphere A , $4Q$; sphere B , $-6Q$; and sphere C , 0. Spheres A and B are fixed in place, with a center-to-center separation that is much larger than the spheres.

Two experiments are conducted. In experiment 1, sphere C is touched to sphere A and then (separately) to sphere B , and then it is removed. In experiment 2, starting with the same initial states, the procedure is reversed: Sphere C is touched to sphere B and then (separately) to sphere A , and then it is removed. What is the ratio of the electrostatic force between A and B at the end of experiment 2 to that at the end of experiment 1?

**Fig. 21-23**

Problems 8 and 65.

- 9 SSM WWW** Two identical conducting spheres, fixed in place, attract each other with an electrostatic force of 0.108 N when their center-to-center separation is 50.0 cm. The spheres are then connected by a thin conducting wire. When the wire is removed, the spheres repel each other with an electrostatic force of 0.0360 N. Of the initial charges on the spheres, with a positive net charge, what was (a) the negative charge on one of them and (b) the positive charge on the other?

**Fig. 21-24**

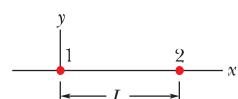
Problems 10, 11, and 70.

- 10** In Fig. 21-24, four particles form a square. The charges are $q_1 = q_4 = Q$ and $q_2 = q_3 = q$. (a) What is Q/q if the net electrostatic force on particles 1 and 4 is zero? (b) Is there any value of q that makes the net electrostatic force on each of the four particles zero? Explain.

- 11 ILW** In Fig. 21-24, the particles have charges $q_1 = -q_2 = 100 \text{ nC}$ and $q_3 = -q_4 = 200 \text{ nC}$, and distance $a = 5.0 \text{ cm}$. What are the (a) x and (b) y components of the net electrostatic force on particle 3?

- 12** Two particles are fixed on an x axis. Particle 1 of charge $40 \mu\text{C}$ is located at $x = -2.0 \text{ cm}$; particle 2 of charge Q is located at $x = 3.0 \text{ cm}$. Particle 3 of charge magnitude $20 \mu\text{C}$ is released from rest on the y axis at $y = 2.0 \text{ cm}$. What is the value of Q if the initial acceleration of particle 3 is in the positive direction of (a) the x axis and (b) the y axis?

- 13** In Fig. 21-25, particle 1 of charge $+1.0 \mu\text{C}$ and particle 2 of charge $-3.0 \mu\text{C}$ are held at separation $L = 10.0 \text{ cm}$ on an x axis. If particle 3 of unknown charge q_3 is to be located such that the net electrostatic force on it from particles 1 and 2 is zero, what must be the (a) x and (b) y coordinates of particle 3?

**Fig. 21-25** Problems 13, 19, 30, 58, and 67.

••14 Three particles are fixed on an x axis. Particle 1 of charge q_1 is at $x = -a$, and particle 2 of charge q_2 is at $x = +a$. If their net electrostatic force on particle 3 of charge $+Q$ is to be zero, what must be the ratio q_1/q_2 when particle 3 is at (a) $x = +0.500a$ and (b) $x = +1.50a$?

••15 The charges and coordinates of two charged particles held fixed in an xy plane are $q_1 = +3.0 \mu\text{C}$, $x_1 = 3.5 \text{ cm}$, $y_1 = 0.50 \text{ cm}$, and $q_2 = -4.0 \mu\text{C}$, $x_2 = -2.0 \text{ cm}$, $y_2 = 1.5 \text{ cm}$. Find the (a) magnitude and (b) direction of the electrostatic force on particle 2 due to particle 1. At what (c) x and (d) y coordinates should a third particle of charge $q_3 = +4.0 \mu\text{C}$ be placed such that the net electrostatic force on particle 2 due to particles 1 and 3 is zero?

••16 In Fig. 21-26a, particle 1 (of charge q_1) and particle 2 (of charge q_2) are fixed in place on an x axis, 8.00 cm apart. Particle 3 (of charge $q_3 = +8.00 \times 10^{-19} \text{ C}$) is to be placed on the line between particles 1 and 2 so that they produce a net electrostatic force $\vec{F}_{3,\text{net}}$ on it. Figure 21-26b gives the x component of that force versus the coordinate x at which particle 3 is placed. The scale of the x axis is set by $x_s = 8.00 \text{ cm}$. What are (a) the sign of charge q_1 and (b) the ratio q_2/q_1 ?

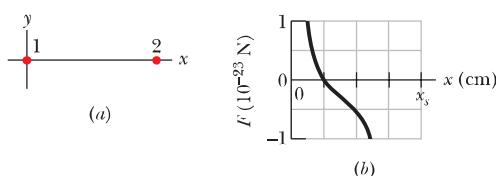


Fig. 21-26 Problem 16.

••17 In Fig. 21-27a, particles 1 and 2 have charge $20.0 \mu\text{C}$ each and are held at separation distance $d = 1.50 \text{ m}$. (a) What is the magnitude of the electrostatic force on particle 1 due to particle 2? In Fig. 21-27b, particle 3 of charge $20.0 \mu\text{C}$ is positioned so as to complete an equilateral triangle. (b) What is the magnitude of the net electrostatic force on particle 1 due to particles 2 and 3?

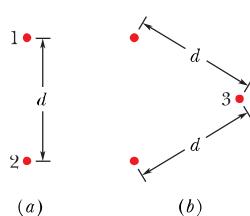


Fig. 21-27 Problem 17.

••18 In Fig. 21-28a, three positively charged particles are fixed on an x axis. Particles B and C are so close to each other that they can be considered to be at the same distance from particle A. The net force on particle A due to particles B and C is $2.014 \times 10^{-23} \text{ N}$ in the negative direction of the x axis. In Fig. 21-28b, particle B has been moved to the opposite side of A but is still at the same distance from it. The net force on A is now $2.877 \times 10^{-24} \text{ N}$ in the negative direction of the x axis. What is the ratio q_C/q_B ?

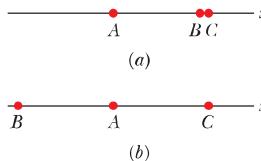


Fig. 21-28 Problem 18.

••19 **SSM WWW** In Fig. 21-25, particle 1 of charge $+q$ and particle 2 of charge $+4.00q$ are held at separation $L = 9.00 \text{ cm}$ on an x axis. If particle 3 of charge q_3 is to be located such that the three particles remain in place when released, what must be the (a) x and (b) y coordinates of particle 3, and (c) the ratio q_3/q ?

••20 Figure 21-29a shows an arrangement of three charged particles separated by distance d . Particles A and C are fixed on the x axis, but particle B can be moved along a circle centered on parti-

cle A. During the movement, a radial line between A and B makes an angle θ relative to the positive direction of the x axis (Fig. 21-29b). The curves in Fig. 21-29c give, for two situations, the magnitude F_{net} of the net electrostatic force on particle A due to the other particles. That net force is given as a function of angle θ and as a multiple of a basic amount F_0 . For example on curve 1, at $\theta = 180^\circ$, we see that $F_{\text{net}} = 2F_0$. (a) For the situation corresponding to curve 1, what is the ratio of the charge of particle C to that of particle B (including sign)? (b) For the situation corresponding to curve 2, what is that ratio?

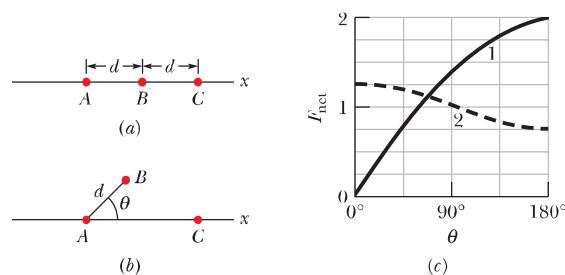


Fig. 21-29 Problem 20.

••21 A nonconducting spherical shell, with an inner radius of 4.0 cm and an outer radius of 6.0 cm , has charge spread nonuniformly through its volume between its inner and outer surfaces. The *volume charge density* ρ is the charge per unit volume, with the unit coulomb per cubic meter. For this shell $\rho = b/r$, where r is the distance in meters from the center of the shell and $b = 3.0 \mu\text{C}/\text{m}^3$. What is the net charge in the shell?

••22 Figure 21-30 shows an arrangement of four charged particles, with angle $\theta = 30.0^\circ$ and distance $d = 2.00 \text{ cm}$. Particle 2 has charge $q_2 = +8.00 \times 10^{-19} \text{ C}$; particles 3 and 4 have charges $q_3 = q_4 = -1.60 \times 10^{-19} \text{ C}$. (a) What is distance D between the origin and particle 2 if the net electrostatic force on particle 1 due to the other particles is zero? (b) If particles 3 and 4 were moved closer to the x axis but maintained their symmetry about that axis, would the required value of D be greater than, less than, or the same as in part (a)?

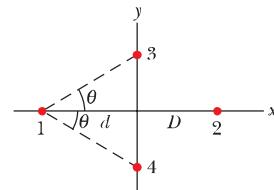


Fig. 21-30 Problem 22.

••23 In Fig. 21-31, particles 1 and 2 of charge $q_1 = q_2 = +3.20 \times 10^{-19} \text{ C}$ are on a y axis at distance $d = 17.0 \text{ cm}$ from the origin. Particle 3 of charge $q_3 = +6.40 \times 10^{-19} \text{ C}$ is moved gradually along the x axis from $x = 0$ to $x = +5.0 \text{ m}$. At what values of x will the magnitude of the electrostatic force on the third particle from the other two particles be (a) minimum and (b) maximum? What are the (c) minimum and (d) maximum magnitudes?

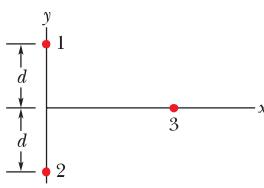


Fig. 21-31 Problem 23.

sec. 21-5 Charge Is Quantized

••24 Two tiny, spherical water drops, with identical charges of $-1.00 \times 10^{-16} \text{ C}$, have a center-to-center separation of 1.00 cm . (a) What is the magnitude of the electrostatic force acting between them? (b) How many excess electrons are on each drop, giving it its charge imbalance?

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•25 ILW How many electrons would have to be removed from a coin to leave it with a charge of $+1.0 \times 10^{-7}$ C?

•26 What is the magnitude of the electrostatic force between a singly charged sodium ion (Na^+ , of charge $+e$) and an adjacent singly charged chlorine ion (Cl^- , of charge $-e$) in a salt crystal if their separation is 2.82×10^{-10} m?

•27 SSM The magnitude of the electrostatic force between two identical ions that are separated by a distance of 5.0×10^{-10} m is 3.7×10^{-9} N. (a) What is the charge of each ion? (b) How many electrons are “missing” from each ion (thus giving the ion its charge imbalance)?

•28 A current of 0.300 A through your chest can send your heart into fibrillation, ruining the normal rhythm of heartbeat and disrupting the flow of blood (and thus oxygen) to your brain. If that current persists for 2.00 min, how many conduction electrons pass through your chest?

•29 In Fig. 21-32, particles 2 and 4, of charge $-e$, are fixed in place on a y axis, at $y_2 = -10.0$ cm and $y_4 = 5.00$ cm. Particles 1 and 3, of charge $-e$, can be moved along the x axis. Particle 5, of charge $+e$, is fixed at the origin. Initially particle 1 is at $x_1 = -10.0$ cm and particle 3 is at $x_3 = 10.0$ cm. (a) To what x value must particle 1 be moved to rotate the direction of the net electric force \vec{F}_{net} on particle 5 by 30° counterclockwise? (b) With particle 1 fixed at its new position, to what x value must you move particle 3 to rotate \vec{F}_{net} back to its original direction?

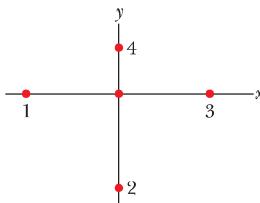


Fig. 21-32 Problem 29.

•30 In Fig. 21-25, particles 1 and 2 are fixed in place on an x axis, at a separation of $L = 8.00$ cm. Their charges are $q_1 = +e$ and $q_2 = -27e$. Particle 3 with charge $q_3 = +4e$ is to be placed on the line between particles 1 and 2, so that they produce a net electrostatic force $\vec{F}_{3,\text{net}}$ on it. (a) At what coordinate should particle 3 be placed to minimize the magnitude of that force? (b) What is that minimum magnitude?

•31 ILW Earth’s atmosphere is constantly bombarded by *cosmic ray protons* that originate somewhere in space. If the protons had passed through the atmosphere, each square meter of Earth’s surface would intercept protons at the average rate of 1500 protons per second. What would be the electric current intercepted by the total surface area of the planet?

•32 Figure 21-33a shows charged particles 1 and 2 that are fixed in place on an x axis. Particle 1 has a charge with a magnitude of $|q_1| = 8.00e$. Particle 3 of charge $q_3 = +8.00e$ is initially on the x axis near particle 2. Then particle 3 is gradually moved in the positive direction of

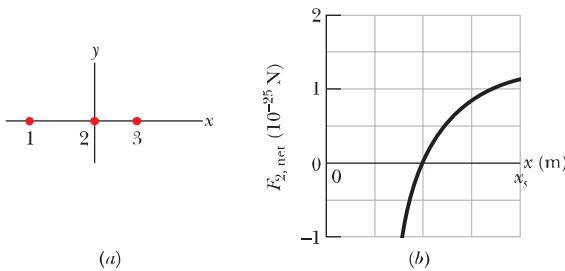


Fig. 21-33 Problem 32.

the x axis. As a result, the magnitude of the net electrostatic force $\vec{F}_{2,\text{net}}$ on particle 2 due to particles 1 and 3 changes. Figure 21-33b gives the x component of that net force as a function of the position x of particle 3. The scale of the x axis is set by $x_s = 0.80$ m. The plot has an asymptote of $F_{2,\text{net}} = 1.5 \times 10^{-25}$ N as $x \rightarrow \infty$. As a multiple of e and including the sign, what is the charge q_3 of particle 3?

•33 Calculate the number of coulombs of positive charge in 250 cm^3 of (neutral) water. (Hint: A hydrogen atom contains one proton; an oxygen atom contains eight protons.)

•34 Figure 21-34 shows electrons 1 and 2 on an x axis and charged ions 3 and 4 of identical charge $-q$ and at identical angles θ . Electron 2 is free to move; the other three particles are fixed in place at horizontal distances R from electron 2 and are intended to hold electron 2 in place. For physically possible values of $q \leq 5e$, what are the (a) smallest, (b) second smallest, and (c) third smallest values of θ for which electron 2 is held in place?

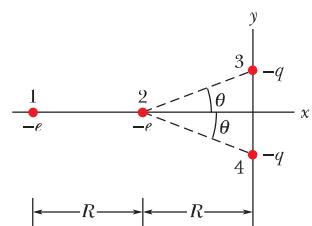


Fig. 21-34 Problem 34.

•35 SSM In crystals of the salt cesium chloride, cesium ions Cs^+ form the eight corners of a cube and a chlorine ion Cl^- is at the cube’s center (Fig. 21-35). The edge length of the cube is 0.40 nm. The Cs^+ ions are each deficient by one electron (and thus each has a charge of $+e$), and the Cl^- ion has one excess electron (and thus has a charge of $-e$). (a) What is the magnitude of the net electrostatic force exerted on the Cl^- ion by the eight Cs^+ ions at the corners of the cube? (b) If one of the Cs^+ ions is missing, the crystal is said to have a *defect*; what is the magnitude of the net electrostatic force exerted on the Cl^- ion by the seven remaining Cs^+ ions?

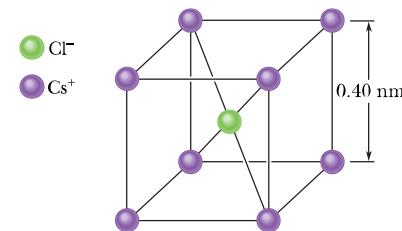


Fig. 21-35 Problem 35.

sec. 21-6 Charge Is Conserved

•36 Electrons and positrons are produced by the nuclear transformations of protons and neutrons known as *beta decay*. (a) If a proton transforms into a neutron, is an electron or a positron produced? (b) If a neutron transforms into a proton, is an electron or a positron produced?

•37 SSM Identify X in the following nuclear reactions: (a) ${}^1\text{H} + {}^9\text{Be} \rightarrow \text{X} + \text{n}$; (b) ${}^{12}\text{C} + {}^1\text{H} \rightarrow \text{X}$; (c) ${}^{15}\text{N} + {}^1\text{H} \rightarrow {}^4\text{He} + \text{X}$. Appendix F will help.

Additional Problems

38 Figure 21-36 shows four identical conducting spheres that are actually well separated from one another. Sphere W (with an initial charge of zero) is touched to sphere

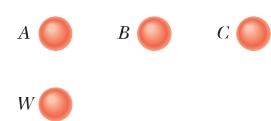


Fig. 21-36 Problem 38.

A and then they are separated. Next, sphere *W* is touched to sphere *B* (with an initial charge of $-32e$) and then they are separated. Finally, sphere *W* is touched to sphere *C* (with an initial charge of $+48e$), and then they are separated. The final charge on sphere *W* is $+18e$. What was the initial charge on sphere *A*?

- 39 [SSM]** In Fig. 21-37, particle 1 of charge $+4e$ is above a floor by distance $d_1 = 2.00 \text{ mm}$ and particle 2 of charge $+6e$ is on the floor, at distance $d_2 = 6.00 \text{ mm}$ horizontally from particle 1. What is the x component of the electrostatic force on particle 2 due to particle 1?

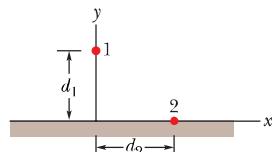


Fig. 21-37 Problem 39.

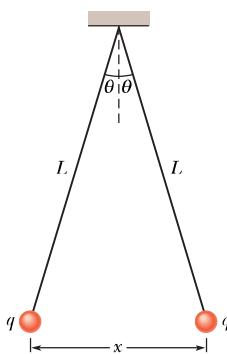
- 40** In Fig. 21-22, particles 1 and 2 are fixed in place, but particle 3 is free to move. If the net electrostatic force on particle 3 due to particles 1 and 2 is zero and $L_{23} = 2.00L_{12}$, what is the ratio q_1/q_2 ?

- 41** (a) What equal positive charges would have to be placed on Earth and on the Moon to neutralize their gravitational attraction? (b) Why don't you need to know the lunar distance to solve this problem? (c) How many kilograms of hydrogen ions (that is, protons) would be needed to provide the positive charge calculated in (a)?

- 42** In Fig. 21-38, two tiny conducting balls of identical mass m and identical charge q hang from nonconducting threads of length L . Assume that θ is so small that $\tan \theta$ can be replaced by its approximate equal, $\sin \theta$. (a) Show that

$$x = \left(\frac{q^2 L}{2\pi\epsilon_0 mg} \right)^{1/3}$$

gives the equilibrium separation x of the balls. (b) If $L = 120 \text{ cm}$, $m = 10 \text{ g}$, and $x = 5.0 \text{ cm}$, what is $|q|$?

Fig. 21-38
Problems 42 and 43.

- 43** (a) Explain what happens to the balls of Problem 42 if one of them is discharged (loses its charge q to, say, the ground). (b) Find the new equilibrium separation x , using the given values of L and m and the computed value of $|q|$.

- 44 [SSM]** How far apart must two protons be if the magnitude of the electrostatic force acting on either one due to the other is equal to the magnitude of the gravitational force on a proton at Earth's surface?

- 45** How many megacoulombs of positive charge are in 1.00 mol of neutral molecular-hydrogen gas (H_2)?

- 46** In Fig. 21-39, four particles are fixed along an x axis, separated by distances $d = 2.00 \text{ cm}$. The charges are $q_1 = +2e$, $q_2 = -e$, $q_3 = +e$, and $q_4 = +4e$, with $e = 1.60 \times 10^{-19} \text{ C}$. In unit-vector notation, what is the net electrostatic force on (a) particle 1 and (b) particle 2 due to the other particles?

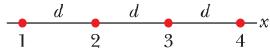
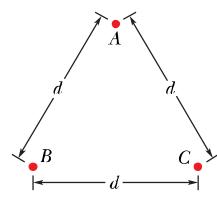


Fig. 21-39 Problem 46.

- 47** (GP) Point charges of $+6.0 \mu\text{C}$ and $-4.0 \mu\text{C}$ are placed on an x axis, at $x = 8.0 \text{ m}$ and $x = 16 \text{ m}$, respectively. What charge must be placed at $x = 24 \text{ m}$ so that any charge placed at the origin would experience no electrostatic force?

- 48** In Fig. 21-40, three identical conducting spheres form an equilateral triangle of side length $d = 20.0 \text{ cm}$. The sphere radii are much smaller than d , and the sphere charges are $q_A = -2.00 \text{ nC}$, $q_B = -4.00 \text{ nC}$, and $q_C = +8.00 \text{ nC}$. (a) What is the magnitude of the electrostatic force between spheres *A* and *C*? The following steps are then taken: *A* and *B* are connected by a thin wire and then disconnected; *B* is grounded by the wire, and the wire is then removed; *B* and *C* are connected by the wire and then disconnected. What now are the magnitudes of the electrostatic force (b) between spheres *A* and *C* and (c) between spheres *B* and *C*?

Fig. 21-40
Problem 48.

- 49** A neutron consists of one "up" quark of charge $+2e/3$ and two "down" quarks each having charge $-e/3$. If we assume that the down quarks are $2.6 \times 10^{-15} \text{ m}$ apart inside the neutron, what is the magnitude of the electrostatic force between them?

- 50** Figure 21-41 shows a long, nonconducting, massless rod of length L , pivoted at its center and balanced with a block of weight W at a distance x from the left end. At the left and right ends of the rod are attached small conducting spheres with positive charges q and $2q$, respectively. A distance h directly beneath each of these spheres is a fixed sphere with positive charge Q . (a) Find the distance x when the rod is horizontal and balanced. (b) What value should h have so that the rod exerts no vertical force on the bearing when the rod is horizontal and balanced?

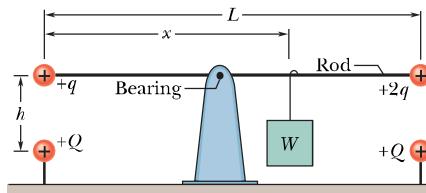


Fig. 21-41 Problem 50.

- 51** A charged nonconducting rod, with a length of 2.00 m and a cross-sectional area of 4.00 cm^2 , lies along the positive side of an x axis with one end at the origin. The volume charge density ρ is charge per unit volume in coulombs per cubic meter. How many excess electrons are on the rod if ρ is (a) uniform, with a value of $-4.00 \mu\text{C}/\text{m}^3$, and (b) nonuniform, with a value given by $\rho = bx^2$, where $b = -2.00 \mu\text{C}/\text{m}^5$?

- 52** A particle of charge Q is fixed at the origin of an xy coordinate system. At $t = 0$ a particle ($m = 0.800 \text{ g}$, $q = 4.00 \mu\text{C}$) is located on the x axis at $x = 20.0 \text{ cm}$, moving with a speed of 50.0 m/s in the positive y direction. For what value of Q will the moving particle execute circular motion? (Neglect the gravitational force on the particle.)

- 53** What would be the magnitude of the electrostatic force between two 1.00 C point charges separated by a distance of (a) 1.00 m and (b) 1.00 km if such point charges existed (they do not) and this configuration could be set up?

- 54** A charge of $6.0 \mu\text{C}$ is to be split into two parts that are then separated by 3.0 mm . What is the maximum possible magnitude of the electrostatic force between those two parts?

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55 Of the charge Q on a tiny sphere, a fraction α is to be transferred to a second, nearby sphere. The spheres can be treated as particles. (a) What value of α maximizes the magnitude F of the electrostatic force between the two spheres? What are the (b) smaller and (c) larger values of α that put F at half the maximum magnitude?

56 If a cat repeatedly rubs against your cotton slacks on a dry day, the charge transfer between the cat hair and the cotton can leave you with an excess charge of $-2.00 \mu\text{C}$. (a) How many electrons are transferred between you and the cat?

You will gradually discharge via the floor, but if instead of waiting, you immediately reach toward a faucet, a painful spark can suddenly appear as your fingers near the faucet. (b) In that spark, do electrons flow from you to the faucet or vice versa? (c) Just before the spark appears, do you induce positive or negative charge in the faucet? (d) If, instead, the cat reaches a paw toward the faucet, which way do electrons flow in the resulting spark? (e) If you stroke a cat with a bare hand on a dry day, you should take care not to bring your fingers near the cat's nose or you will hurt it with a spark. Considering that cat hair is an insulator, explain how the spark can appear.

57 We know that the negative charge on the electron and the positive charge on the proton are equal. Suppose, however, that these magnitudes differ from each other by 0.00010% . With what force would two copper coins, placed 1.0 m apart, repel each other? Assume that each coin contains 3×10^{22} copper atoms. (*Hint:* A neutral copper atom contains 29 protons and 29 electrons.) What do you conclude?

58 In Fig. 21-25, particle 1 of charge $-80.0 \mu\text{C}$ and particle 2 of charge $+40.0 \mu\text{C}$ are held at separation $L = 20.0\text{ cm}$ on an x axis. In unit-vector notation, what is the net electrostatic force on particle 3, of charge $q_3 = 20.0 \mu\text{C}$, if particle 3 is placed at (a) $x = 40.0\text{ cm}$ and (b) $x = 80.0\text{ cm}$? What should be the (c) x and (d) y coordinates of particle 3 if the net electrostatic force on it due to particles 1 and 2 is zero?

59 What is the total charge in coulombs of 75.0 kg of electrons?

60 In Fig. 21-42, six charged particles surround particle 7 at radial distances of either $d = 1.0\text{ cm}$ or $2d$, as drawn. The charges are $q_1 = +2e$, $q_2 = +4e$, $q_3 = +e$, $q_4 = +4e$, $q_5 = +2e$, $q_6 = +8e$, $q_7 = +6e$, with $e = 1.60 \times 10^{-19}\text{ C}$. What is the magnitude of the net electrostatic force on particle 7?

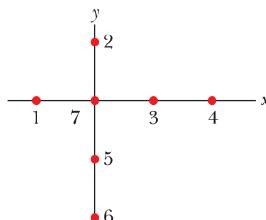


Fig. 21-42 Problem 60.

61 Three charged particles form a triangle: particle 1 with charge $Q_1 = 80.0\text{ nC}$ is at xy coordinates $(0, 3.00\text{ mm})$, particle 2 with charge Q_2 is at $(0, -3.00\text{ mm})$, and particle 3 with charge $q = 18.0\text{ nC}$ is at $(4.00\text{ mm}, 0)$. In unit-vector notation, what is the electrostatic force on particle 3 due to the other two particles if Q_2 is equal to (a) 80.0 nC and (b) -80.0 nC ?

62 In Fig. 21-43, what are the (a) magnitude and (b) direction of the net electrostatic force on particle 4 due to the other three particles? All four particles are fixed in the xy plane, and $q_1 = -3.20 \times 10^{-19}\text{ C}$, $q_2 = +3.20 \times 10^{-19}\text{ C}$, $q_3 = +6.40 \times 10^{-19}\text{ C}$, $q_4 = +3.20 \times 10^{-19}\text{ C}$, $\theta_1 = 35.0^\circ$, $d_1 = 3.00\text{ cm}$, and $d_2 = d_3 = 2.00\text{ cm}$.

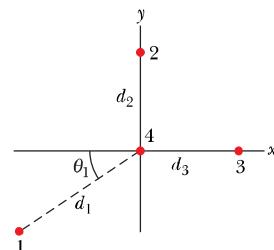


Fig. 21-43 Problem 62.

63 Two point charges of 30 nC and -40 nC are held fixed on an x axis, at the origin and at $x = 72\text{ cm}$, respectively. A particle with a charge of $42 \mu\text{C}$ is released from rest at $x = 28\text{ cm}$. If the initial acceleration of the particle has a magnitude of 100 km/s^2 , what is the particle's mass?

64 Two small, positively charged spheres have a combined charge of $5.0 \times 10^{-5}\text{ C}$. If each sphere is repelled from the other by an electrostatic force of 1.0 N when the spheres are 2.0 m apart, what is the charge on the sphere with the smaller charge?

65 The initial charges on the three identical metal spheres in Fig. 21-23 are the following: sphere A , Q ; sphere B , $-Q/4$; and sphere C , $Q/2$, where $Q = 2.00 \times 10^{-14}\text{ C}$. Spheres A and B are fixed in place, with a center-to-center separation of $d = 1.20\text{ m}$, which is much larger than the spheres. Sphere C is touched first to sphere A and then to sphere B and is then removed. What then is the magnitude of the electrostatic force between spheres A and B ?

66 An electron is in a vacuum near Earth's surface and located at $y = 0$ on a vertical y axis. At what value of y should a second electron be placed such that its electrostatic force on the first electron balances the gravitational force on the first electron?

67 In Fig. 21-25, particle 1 of charge $-5.00q$ and particle 2 of charge $+2.00q$ are held at separation L on an x axis. If particle 3 of unknown charge q_3 is to be located such that the net electrostatic force on it from particles 1 and 2 is zero, what must be the (a) x and (b) y coordinates of particle 3?

68 Two engineering students, John with a mass of 90 kg and Mary with a mass of 45 kg , are 30 m apart. Suppose each has a 0.01% imbalance in the amount of positive and negative charge, one student being positive and the other negative. Find the order of magnitude of the electrostatic force of attraction between them by replacing each student with a sphere of water having the same mass as the student.

69 In the radioactive decay of Eq. 21-13, a ${}^{238}\text{U}$ nucleus transforms to ${}^{234}\text{Th}$ and an ejected ${}^4\text{He}$. (These are nuclei, not atoms, and thus electrons are not involved.) When the separation between ${}^{234}\text{Th}$ and ${}^4\text{He}$ is $9.0 \times 10^{-15}\text{ m}$, what are the magnitudes of (a) the electrostatic force between them and (b) the acceleration of the ${}^4\text{He}$ particle?

70 In Fig. 21-24, four particles form a square. The charges are $q_1 = +Q$, $q_2 = q_3 = q$, and $q_4 = -2.00Q$. What is q/Q if the net electrostatic force on particle 1 is zero?

22

ELECTRIC FIELDS

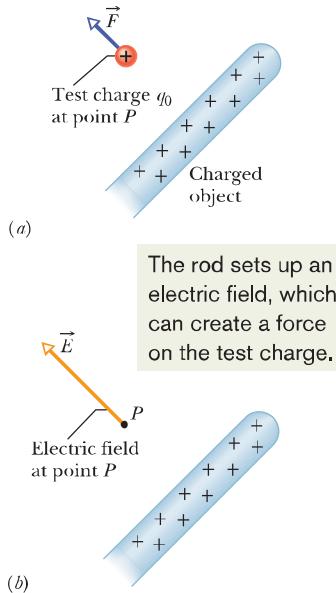


Fig. 22-1 (a) A positive test charge q_0 placed at point P near a charged object. An electrostatic force \vec{F} acts on the test charge. (b) The electric field \vec{E} at point P produced by the charged object.

Table 22-1
Some Electric Fields

Field Location or Situation	Value (N/C)
At the surface of a uranium nucleus	3×10^{21}
Within a hydrogen atom, at a radius of 5.29×10^{-11} m	5×10^{11}
Electric breakdown occurs in air	3×10^6
Near the charged drum of a photocopier	10^5
Near a charged comb	10^3
In the lower atmosphere	10^2
Inside the copper wire of household circuits	10^{-2}

22-1 WHAT IS PHYSICS?

The physics of the preceding chapter tells us how to find the electric force on a particle 1 of charge $+q_1$ when the particle is placed near a particle 2 of charge $+q_2$. A nagging question remains: How does particle 1 “know” of the presence of particle 2? That is, since the particles do not touch, how can particle 2 push on particle 1—how can there be such an *action at a distance*?

One purpose of physics is to record observations about our world, such as the magnitude and direction of the push on particle 1. Another purpose is to provide a deeper explanation of what is recorded. One purpose of this chapter is to provide such a deeper explanation to our nagging questions about electric force at a distance. We can answer those questions by saying that particle 2 sets up an **electric field** in the space surrounding itself. If we place particle 1 at any given point in that space, the particle “knows” of the presence of particle 2 because it is affected by the electric field that particle 2 has already set up at that point. Thus, particle 2 pushes on particle 1 not by touching it but by means of the electric field produced by particle 2.

Our goal in this chapter is to define electric field and discuss how to calculate it for various arrangements of charged particles.

22-2 The Electric Field

The temperature at every point in a room has a definite value. You can measure the temperature at any given point or combination of points by putting a thermometer there. We call the resulting distribution of temperatures a *temperature field*. In much the same way, you can imagine a *pressure field* in the atmosphere; it consists of the distribution of air pressure values, one for each point in the atmosphere. These two examples are of *scalar fields* because temperature and air pressure are scalar quantities.

The electric field is a *vector field*; it consists of a distribution of *vectors*, one for each point in the region around a charged object, such as a charged rod. In principle, we can define the electric field at some point near the charged object, such as point P in Fig. 22-1a, as follows: We first place a *positive* charge q_0 , called a *test charge*, at the point. We then measure the electrostatic force \vec{F} that acts on the test charge. Finally, we define the electric field \vec{E} at point P due to the charged object as

$$\vec{E} = \frac{\vec{F}}{q_0} \quad (\text{electric field}). \quad (22-1)$$

Thus, the magnitude of the electric field \vec{E} at point P is $E = F/q_0$, and the direction of \vec{E} is that of the force \vec{F} that acts on the *positive* test charge. As shown in Fig. 22-1b, we represent the electric field at P with a vector whose tail is at P . To define the electric field within some region, we must similarly define it at all points in the region.

The SI unit for the electric field is the newton per coulomb (N/C). Table 22-1 shows the electric fields that occur in a few physical situations.

22-3 ELECTRIC FIELD LINES

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Although we use a positive test charge to define the electric field of a charged object, that field exists independently of the test charge. The field at point P in Figure 22-1b existed both before and after the test charge of Fig. 22-1a was put there. (We assume that in our defining procedure, the presence of the test charge does not affect the charge distribution on the charged object, and thus does not alter the electric field we are defining.)

To examine the role of an electric field in the interaction between charged objects, we have two tasks: (1) calculating the electric field produced by a given distribution of charge and (2) calculating the force that a given field exerts on a charge placed in it. We perform the first task in Sections 22-4 through 22-7 for several charge distributions. We perform the second task in Sections 22-8 and 22-9 by considering a point charge and a pair of point charges in an electric field. First, however, we discuss a way to visualize electric fields.

22-3 Electric Field Lines

Michael Faraday, who introduced the idea of electric fields in the 19th century, thought of the space around a charged body as filled with *lines of force*. Although we no longer attach much reality to these lines, now usually called **electric field lines**, they still provide a nice way to visualize patterns in electric fields.

The relation between the field lines and electric field vectors is this: (1) At any point, the direction of a straight field line or the direction of the tangent to a curved field line gives the direction of \vec{E} at that point, and (2) the field lines are drawn so that the number of lines per unit area, measured in a plane that is perpendicular to the lines, is proportional to the *magnitude* of \vec{E} . Thus, E is large where field lines are close together and small where they are far apart.

Figure 22-2a shows a sphere of uniform negative charge. If we place a *positive* test charge anywhere near the sphere, an electrostatic force pointing *toward* the center of the sphere will act on the test charge as shown. In other words, the electric field vectors at all points near the sphere are directed radially toward the sphere. This pattern of vectors is neatly displayed by the field lines in Fig. 22-2b, which point in the same directions as the force and field vectors. Moreover, the spreading of the field lines with distance from the sphere tells us that the magnitude of the electric field decreases with distance from the sphere.

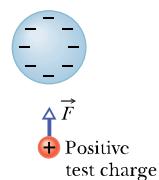
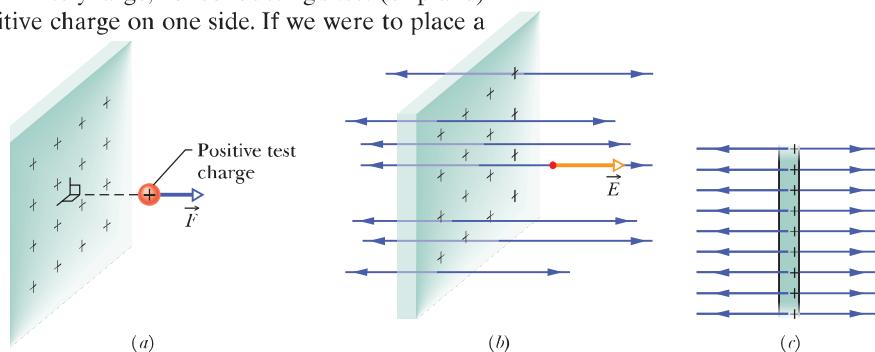
If the sphere of Fig. 22-2 were of uniform *positive* charge, the electric field vectors at all points near the sphere would be directed radially *away from* the sphere. Thus, the electric field lines would also extend radially away from the sphere. We then have the following rule:



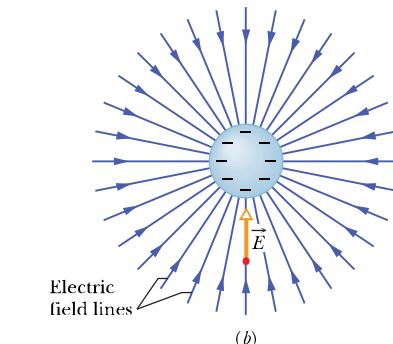
Electric field lines extend away from positive charge (where they originate) and toward negative charge (where they terminate).

Figure 22-3a shows part of an infinitely large, nonconducting *sheet* (or plane) with a uniform distribution of positive charge on one side. If we were to place a

Fig. 22-3 (a) The electrostatic force \vec{F} on a positive test charge near a very large, nonconducting sheet with uniformly distributed positive charge on one side. (b) The electric field vector \vec{E} at the location of the test charge, and the electric field lines in the space near the sheet. The field lines extend *away from* the positively charged sheet. (c) Side view of (b).



(a)



Electric field lines

(b)

Fig. 22-2 (a) The electrostatic force \vec{F} acting on a positive test charge near a sphere of uniform negative charge. (b) The electric field vector \vec{E} at the location of the test charge, and the electric field lines in the space near the sphere. The field lines extend *toward* the negatively charged sphere. (They originate on distant positive charges.)