32
ELECTROSTATICS

Objectives
- Describe the fundamental rule at the base of all electrical phenomena. (32.1)
- Explain how an object becomes electrically charged. (32.2)
- Describe Coulomb's law. (32.3)
- Distinguish between a good conductor and a good insulator. (32.4)
- Describe two ways electric charges can be transferred. (32.5)
- Describe what happens when a charged object is placed near a conducting surface. (32.6)
- Describe what happens when an insulator is in the presence of a charged object. (32.7)

discover!

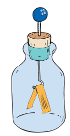
MATERIALS electrophorus, piece of wool, fur, or cloth, electroscope, faucet, paper

EXPECTED OUTCOME Students will charge the metal pie pan of an electrophorus by induction.

ANALYZE AND CONCLUDE

1. There is an electrical interaction between the pan and the electroscope, water, or paper.
2. In theory, the charging of the pie pan could be repeated indefinitely. However, the insulating plate slowly discharges to the surroundings and needs to be charged by contact periodically.
3. Electric charge is the source of the electrical force that causes objects to attract or repel each other.

32 ELECTROSTATICS



THE BIG IDEA Electrostatics involves electric charges, the forces between them, and their behavior in materials.

Electricity in one form or another underlies just about everything around you. It's in the lightning from the sky; it's in the spark beneath your feet when you scuff across a rug; and it's what holds atoms together to form molecules. This chapter is about electrostatics, or electricity at rest. Electrostatics involves electric charges, the forces between them, and their behavior in materials.

An understanding of electricity requires a step-by-step approach, for one concept is the building block for the next. So please study this material with extra care. It is a good idea at this time to lean more heavily on the laboratory part of your course, for *doing* physics is better than only studying physics.

discover!

How Can an Object Become Electrically Charged?

1. Obtain an electrophorus and rub the insulating plate with a piece of wool, fur, or cloth.
2. Lower the pie pan onto the plate.
3. Touch the pie pan with your finger. The pan should now be charged.
4. Bring the pan in contact with an electroscope or hold it near a thin stream of water or small pieces of paper.

Analyze and Conclude

1. **Observing** What evidence do you have that the pie pan was actually charged?
2. **Predicting** How many times do you think you can charge the pie pan without having to once again rub the insulating plate?
3. **Making Generalizations** Based on your experimentation with the electrophorus, how would you define electric charge?

32.1 Electrical Forces and Charges

You are familiar with the force of gravity. It attracts you to Earth, and you call it your weight. Now consider a force acting on you that is billions upon billions of times stronger. Such a force could compress you to a size about the thickness of a piece of paper. But suppose that in addition to this enormous force there is a repelling force that is also billions upon billions of times stronger than gravity. The two forces acting on you would balance each other and have no noticeable effect at all, as shown in Figure 32.1. It so happens that there is a pair of such forces acting on you all the time—electrical forces.

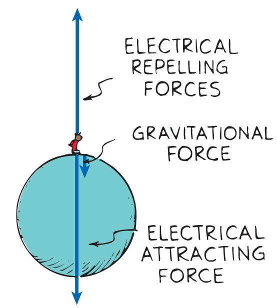


FIGURE 32.1 ▲
The enormous attractive and repulsive electrical forces between the charges in Earth and the charges in your body balance out, leaving the relatively weaker force of gravity, which only attracts. Hence your weight is due only to gravity.

The Atom **Electrical forces** arise from particles in atoms. In the simple model of the atom proposed in the early 1900s by Ernest Rutherford and Niels Bohr, a positively charged nucleus is surrounded by electrons, as illustrated in Figure 32.2. The protons in the nucleus attract the electrons and hold them in orbit. Electrons are attracted to protons, but electrons repel other electrons. The fundamental electrical property to which the mutual attractions or repulsions between electrons or protons is attributed is called **charge.** 32.1 By convention (general agreement), electrons are *negatively* charged and protons *positively* charged. Neutrons have no charge, and are neither attracted nor repelled by charged particles.

Here are some important facts about atoms:

1. Every atom has a positively charged nucleus surrounded by negatively charged electrons.
2. All electrons are identical; that is, each has the same mass and the same quantity of negative charge as every other electron.
3. The nucleus is composed of protons and neutrons. (The common form of hydrogen, which has no neutrons, is the only exception.) All protons are identical; similarly, all neutrons are identical. A proton has nearly 2000 times the mass of an electron, but its positive charge is equal in magnitude to the negative charge of an electron. A neutron has slightly greater mass than a proton and has no charge.
4. Atoms have as many electrons as protons, so a neutral atom has zero *net* charge.

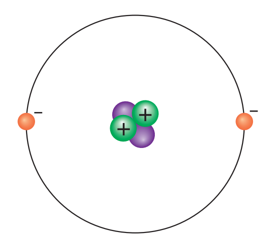


FIGURE 32.2 ▲
The helium nucleus is composed of two protons and two neutrons. The positively charged protons attract two negative electrons.

Attraction and Repulsion Just *why* electrons repel electrons and are attracted to protons is beyond the scope of this book. We simply say that this electric behavior is fundamental, or basic. **The fundamental rule at the base of all electrical phenomena is that like charges repel and opposite charges attract.**

The study of electricity begins with electrostatics, which is best introduced as a series of coordinated demonstrations. After showing charging via fur, rubber rods, etc., and electrostatic attraction and repulsion (Coulomb's law), show (1) the electrophorus (a metal plate charged by induction with a sheet of acrylic glass), (2) the Whimshurst machine (electrostatic generator), and (3) the Van de Graaff generator. The demonstration sequence, 1, 2, and 3, with explanations should make this a great lecture.

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32.1 Electrical Forces and Charges

Key Terms
electrostatics, electrical force, charge

▶ **Teaching Tip** Begin by comparing the strength of the electrical force to gravitational force—the electrical force is billions of billions of times stronger. Acknowledge the fundamental rule of electricity: *Like charges repel and unlike charges attract.* Why? Nobody knows. Hence we say it is fundamental.

Demonstration

Use fur, rubber, glass rods, and suspended pith balls (or their alternatives) to show the effects of transferring charge, i.e., attraction and repulsion. Describe the transfer of electrons in each case.

▶ **Teaching Tip** Explain what it means to say an object is electrically charged. Charging something can be compared to removing bricks from a road and putting them on a sidewalk: There are exactly as many "holes" in the road as there are bricks on the sidewalk.

▶ **Teaching Tip** Explain that electrical effects are due to electric charges, negative for the electron and positive for the proton. Discuss the near balance that exists in common materials, and the slight imbalance when electrons move from one material to another. Explain that different materials have different affinities for electrons. This explains why charge moves from fur to rubber when they are rubbed together. It also explains why it is painful for people with silver fillings in their teeth to chew aluminum foil. Silver has more affinity for electrons than aluminum. The mildly acidic saliva in the mouth facilitates a flow of electrons which, when transmitted to the nerves of the teeth, produce that familiar unpleasant sensation.

CONCEPT CHECK The fundamental rule at the base of all electrical phenomena is that like charges repel and opposite charges attract.

Teaching Resources

- **Reading and Study Workbook**
- **Laboratory Manual** *89, 90*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Conceptual Physics Alive! DVDs** *Electrostatics*

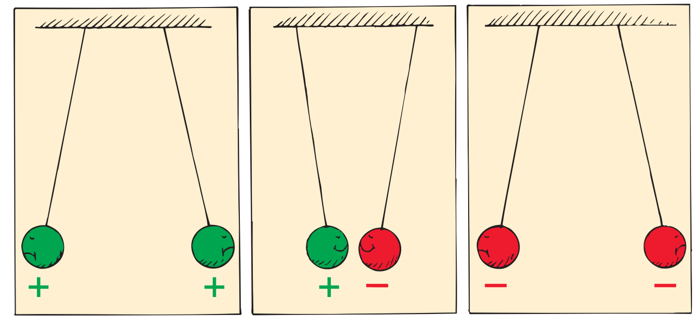
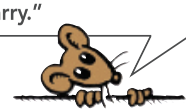


FIGURE 32.3 ▶ The fundamental rule of all electrical phenomena is that like charges repel and opposite charges attract.

The old saying that opposites attract, usually referring to people, was first popularized by public lecturers who traveled about by horse and wagon to entertain people by demonstrating the scientific marvels of electricity. An important part of these demonstrations was the charging and discharging of pith balls. Pith is a light, spongy plant tissue. Balls of pith were coated with aluminum paint so their surfaces would conduct electricity. When suspended from a silk thread, such a ball would be attracted to a rubber rod just rubbed with cat's fur, but when the two made contact, the force of attraction would change to a force of repulsion. Thereafter, the ball would be repelled by the rubber rod but attracted to a glass rod that had just been rubbed with silk. Figure 32.3 shows how a pair of pith balls charged in different ways exhibits both attraction and repulsion forces. The lecturer pointed out that nature provides two kinds of charge, just as it provides two sexes.

Negative and *positive* are just the **names** given to opposite charges. The names chosen could just as well have been "east and west" or "top and down" or "Mary and Larry."



CONCEPT CHECK **What is the fundamental rule at the base of all electrical phenomena?**

32.2 Conservation of Charge

Electrons and protons have electric charge. In a neutral atom, there are as many electrons as protons, so there is no net charge. The total positive charge balances the total negative charge exactly. If an electron is removed from an atom, the atom is no longer neutral. The atom has one more positive charge (proton) than negative charge (electron) and is said to be positively charged.

A charged atom is called an *ion.* A *positive ion* has a net positive charge; it has lost one or more electrons. A *negative ion* has a net negative charge; it has gained one or more extra electrons.

think!

If you scuff electrons onto your shoes while walking across a rug, are you negatively or positively charged?
Answer: 32.2

Electrically Charged Objects Matter is made of atoms, and atoms are made of electrons and protons (and neutrons as well). An object that has equal numbers of electrons and protons has no net electric charge. But if there is an imbalance in the numbers, the object is then electrically charged. An imbalance comes about by adding or removing electrons.

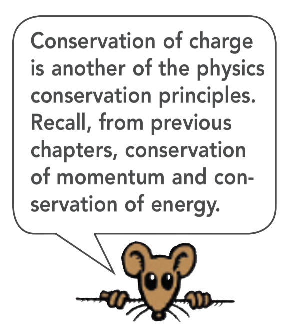
Although the innermost electrons in an atom are bound very tightly to the oppositely charged atomic nucleus, the outermost electrons of many atoms are bound very loosely and can be easily dislodged. How much energy is required to tear an electron away from an atom varies for different substances. The electrons are held more firmly in rubber than in fur, for example. Hence, when a rubber rod is rubbed by a piece of fur, as illustrated in Figure 32.4, electrons transfer from the fur to the rubber rod. The rubber then has an excess of electrons and is negatively charged. The fur, in turn, has a deficiency of electrons and is positively charged. If you rub a glass or plastic rod with silk, you'll find that the rod becomes positively charged. The silk has a greater affinity for electrons than the glass or plastic rod. Electrons are rubbed off the rod and onto the silk.

An object that has unequal numbers of electrons and protons is electrically charged. If it has more electrons than protons, the object is negatively charged. If it has fewer electrons than protons, it is positively charged.

FIGURE 32.4 ▲
When electrons are transferred from the fur to the rod, the rod becomes negatively charged.

Principle of Conservation of Charge The principle that electrons are neither created nor destroyed but are simply transferred from one material to another is known as **conservation of charge.** In every event, whether large-scale or at the atomic and nuclear level, the principle of conservation of charge applies. No case of the creation or destruction of net electric charge has ever been found. The conservation of charge is a cornerstone in physics, ranking with the conservation of energy and momentum.

Any object that is electrically charged has an excess or deficiency of some whole number of electrons—electrons cannot be divided into fractions of electrons. This means that the charge of the object is a whole-number multiple of the charge of an electron. It cannot have a charge equal to the charge of 1.5 or 1000.5 electrons, for example.[32.2] All charged objects to date have a charge that is a whole-number multiple of the charge of a single electron.



CONCEPT CHECK What causes an object to become electrically charged?

32.2 Conservation of Charge

Key Term
conservation of charge

▶ **Teaching Tip** Point out that conservation of charge is another one of the conservation principles. Briefly review conservation of momentum and conservation of energy and point out the similarities among all three.

CONCEPT CHECK An object that has unequal numbers of electrons and protons is electrically charged.

Teaching Resources
- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

Science, Technology and Society

CRITICAL THINKING Students should give examples of static charge, e.g., clinging clothes, static charge experienced after walking across a floor and touching a doorknob, etc. Accept all reasonable responses.

32.3 Coulomb's Law

Key Terms
Coulomb's law, coulomb

Demonstration

Show your students the enormous difference in strength between the forces of electricity and gravity. Use a charged comb to pick up confetti-sized pieces of paper. Then elaborate on what has happened: The huge Earth with its gravitational force is pulling down on the pieces of paper. The small electric charge on the comb is pulling up on the paper. In the battle between the huge Earth and the small comb, the electric charge on the comb wins! The gravitational force is a billion billion times weaker than the electrical force. (The electrical force also has the added advantage of the smaller distance since both forces follow the inverse-square law.)

Science, Technology, and Society

The Threat of Static Charge

Today electronics technicians in high-technology firms that build, test, and repair electronic circuit components follow procedures to guard against static charge, to prevent damage to delicate circuits. Some circuit components are so sensitive that they can be "fried" by static electric sparks. So electronics technicians work in environments free of high-resistance surfaces where static charge can accumulate and wear clothing of special fabric with ground wires between their sleeves and their socks. Some wear special wrist bands that are clipped to a grounded surface, so that any charge that builds up, by movement on a chair for example, is discharged. As electronic components become smaller and circuit elements are placed closer together, the threat of electric sparks producing short circuits becomes greater and greater.

Critical Thinking What effects on your daily life are caused by static charge? What can you do to minimize these effects?

32.3 Coulomb's Law

Recall from Newton's law of gravitation that the gravitational force between two objects of mass m_1 and mass m_2 is proportional to the product of the masses and inversely proportional to the square of the distance d between them:

$$F = G\frac{m_1 m_2}{d^2}$$

where G is the universal gravitational constant.

Force, Charges, and Distance The electrical force between any two objects obeys a similar inverse-square relationship with distance. The relationship among electrical force, charges, and distance, now known as **Coulomb's law,** was discovered by the French physicist Charles Coulomb (1736–1806) in the eighteenth century. ✓ **Coulomb's law states that for charged particles or objects that are small compared with the distance between them, the force between the charges varies directly as the product of the charges and inversely as the square of the distance between them.** Coulomb's law can be expressed as

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

where d is the distance between the charged particles; q_1 represents the quantity of charge of one particle and q_2 the quantity of charge of the other particle; and k is the proportionality constant.

The SI unit of charge is the **coulomb,** abbreviated C. Common sense might say that it is the charge of a single electron, but it isn't. For historical reasons, it turns out that a charge of 1 C is the charge of 6.24 billion billion (6.24×10^{18}) electrons. This might seem like a great number of electrons, but it represents only the amount of charge that passes through a common 100-W lightbulb in about one second.

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The Electrical Proportionality Constant The proportionality constant k in Coulomb's law is similar to G in Newton's law of gravitation. Instead of being a very small number like G, the electrical proportionality constant k is a very large number. Rounded off, it equals

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

or, in scientific notation, $k = 9.0 \times 10^9 \ \mathrm{N \cdot m^2/C^2}$. The units $\mathrm{N \cdot m^2/C^2}$ convert the right side of the equation to the unit of force, the newton (N), when the charges are in coulombs (C) and the distance is in meters (m). Note that if a pair of charges of 1 C each were 1 m apart, the force of repulsion between the two charges would be 9 billion newtons.[32.3.1] That would be more than 10 times the weight of a battleship! Obviously, such amounts of *net* charge do not exist in our everyday environment.

think!

What is the chief significance of the fact that G in Newton's law of gravitation is a small number and k in Coulomb's law is a large number when both are expressed in SI units? *Answer: 32.3.1*

As can be seen in Figure 32.5, Newton's law of gravitation for masses is similar to Coulomb's law for electric charges.[32.3.2] Whereas the gravitational force of attraction between a pair of one-kilogram masses is extremely small, the electrical force between a pair of one-coulomb charges is extremely large. The greatest difference between gravitation and electrical forces is that while gravity only attracts, electrical forces may either attract or repel.

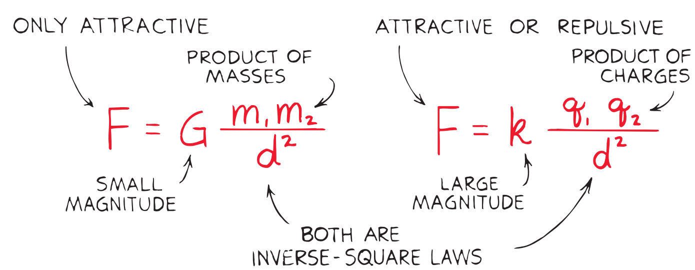

FIGURE 32.5
Newton's law of gravitation is similar to Coulomb's law.

Electrical Forces in Atoms Because most objects have almost exactly equal numbers of electrons and protons, electrical forces usually balance out. Between Earth and the moon, for example, there is no measurable electrical force. In general, the weak gravitational force, which only attracts, is the predominant force between astronomical bodies.

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Although electrical forces balance out for astronomical and everyday objects, at the atomic level this is not always true. Often two or more atoms, when close together, share electrons. The negative electrons of one atom may at times be closer to the neighboring atom's positive nucleus than they are to the average location of the neighbor's electrons. Then the attractive force between these charges is greater than the repulsive force. This is called bonding and leads to the formation of molecules. It would be wise for anyone planning to study chemistry or biology to know something about electricity.

CONCEPT CHECK What does Coulomb's law state?

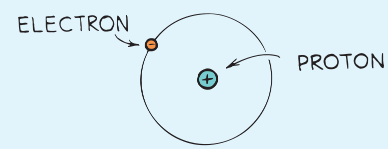
think!

a. If an electron at a certain distance from a charged particle is attracted with a certain force, how will the force compare at twice this distance?
b. Is the charged particle in this case positive or negative?
Answer: 32.3.2

do the math!

How does the electrical force between the proton and the electron in a hydrogen atom compare to the gravitational force between these two particles?

The hydrogen atom's nucleus is a proton (mass 1.7×10^{-27} kg), outside of which there is a single electron (mass 9.1×10^{-31} kg) at an average separation distance (d) of 5.3×10^{-11} m.



To solve for the electrical force, use Coulomb's law, where both the electron charge q_e and the proton charge q_p have the same magnitude (1.6×10^{-19} C).

$$F_e = k\frac{q_e q_p}{d^2} = (9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})\frac{(1.6 \times 10^{-19}\ \mathrm{C})^2}{(5.3 \times 10^{-11}\ \mathrm{m})^2} = 8.2 \times 10^{-8}\ \mathrm{N}$$

The gravitational force F_g between them is $F_g = G\dfrac{m_e m_p}{d^2}$

$$= (6.7 \times 10^{-11}\ \mathrm{N{\cdot}m^2/kg^2})\frac{(9.1 \times 10^{-31}\ \mathrm{kg})(1.7 \times 10^{-27}\ \mathrm{kg})}{(5.3 \times 10^{-11}\ \mathrm{m})^2}$$

$$= 3.7 \times 10^{-47}\ \mathrm{N}$$

A comparison of the two forces is best shown by their ratio:

$$\frac{F_e}{F_g} = \frac{8.2 \times 10^{-8}\ \mathrm{N}}{3.7 \times 10^{-47}\ \mathrm{N}} = 2.2 \times 10^{39}$$

The electrical force between the particles is more than 10^{39} times greater than the gravitational force. In other words, the electric forces that subatomic particles exert on one another are so much stronger than their mutual gravitational forces that gravitation can be completely neglected.

▶ **Teaching Tip** Explain that when a positive and a negative charge are used in Coulomb's law, the answer will be negative, which means a force of attraction. When the charges are either both negative or both positive, the answer will be positive, which means a force of repulsion.

CONCEPT CHECK Coulomb's law states that for charged particles or objects that are small compared with the distance between them, the force between the charges varies directly as the product of the charges and inversely as the square of the distance between them.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *32-1*
- **Problem-Solving Exercises in Physics** *16-1*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *32-1*

32.4 Conductors and Insulators

Electrons are more easily moved in some materials than in others. Outer electrons of the atoms in a metal are not anchored to the nuclei of particular atoms, but are free to roam in the material. Materials through which electric charge can flow are called **conductors.** Metals are good conductors for the motion of electric charges for the same reason they are good conductors of heat: Their electrons are "loose."

Electrons in other materials—rubber and glass, for example—are tightly bound and remain with particular atoms. They are not free to wander about to other atoms in the material. These materials, known as **insulators,** are poor conductors of electricity, for the same reason they are generally poor conductors of heat.

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FIGURE 32.6
It is easier for electric charge to flow through hundreds of kilometers of metal wire than through a few centimeters of insulating material.

Whether a substance is classified as a conductor or an insulator depends on how tightly the atoms of the substance hold their electrons. **Electrons move easily in good conductors and poorly in good insulators.** All substances can be arranged in order of their ability to conduct electric charges. Those at the top of the list are the conductors, and those at the bottom are the insulators. The ends of the list are very far apart. The conductivity of a metal, for example, can be more than a million trillion times greater than the conductivity of an insulator such as glass. In power lines, such as those shown in Figure 32.6, charge flows much more easily through hundreds of kilometers of metal wire than through the few centimeters of insulating material that separates the wire from the supporting tower. In a common appliance cord, charges will flow through several meters of wire to the appliance, and then through its electrical network, and then back through the return wire rather than flow directly across from one wire to the other through the tiny thickness of rubber insulation.

32.4 Conductors and Insulators

Key Terms
conductor, insulator, semiconductor

Common Misconception
Lightning never strikes the same place twice.

FACT Lightning does favor certain spots, mainly high locations. The Empire State Building is struck by lightning about 25 times every year.

CONCEPT CHECK Electrons move easily in good conductors and poorly in good insulators.

Teaching Resources
- Next-Time Question *32-2*

32.5 Charging by Friction and Contact

Common Misconception
Friction is a necessary factor in charging an object.

FACT Electrons can be transferred from one material to another simply by touching.

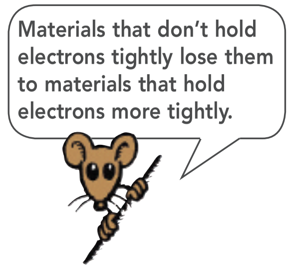
▶ **Teaching Tip** Charge separation can also occur without friction by the simple contact between dissimilar insulating materials. In this case charge simply peels from one material to another, like dust is peeled from a surface when a piece of sticky tape is pulled from it.

Demonstration

In a completely darkened room, quickly pull the tape off a roll of electrician's tape. Your students should see sparks!

CONCEPT CHECK Two ways electric charge can be transferred are by friction and by contact.

Teaching Resources
- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook



Some materials, such as germanium and silicon, are good insulators in their pure crystalline form but increase tremendously in conductivity when even one atom in ten million is replaced with an impurity that adds or removes an electron from the crystal structure. **Semiconductors** are materials that can be made to behave sometimes as insulators and sometimes as conductors. Atoms in a semiconductor hold their electrons until given small energy boosts. This occurs in photovoltaic cells that convert solar energy into electrical energy. Thin layers of semiconducting materials sandwiched together make up *transistors*, which are used in digital media players, computers, and a variety of electrical applications. Transitors amplify electric signals and act as electric switches to control current in circuits—with very little power.

CONCEPT CHECK **What is the difference between a good conductor and a good insulator?**

32.5 Charging by Friction and Contact

Two ways electric charge can be transferred are by friction and by contact. We are all familiar with the electrical effects produced by friction. We can stroke a cat's fur and hear the crackle of sparks that are produced, or comb our hair in front of a mirror in a dark room and see as well as hear the sparks of electricity. We can scuff our shoes across a rug and feel the tingle as we reach for the doorknob, or do the same when sliding across seats while parked in an automobile, as illustrated in Figure 32.7. In all these cases electrons are being transferred by friction when one material rubs against another.

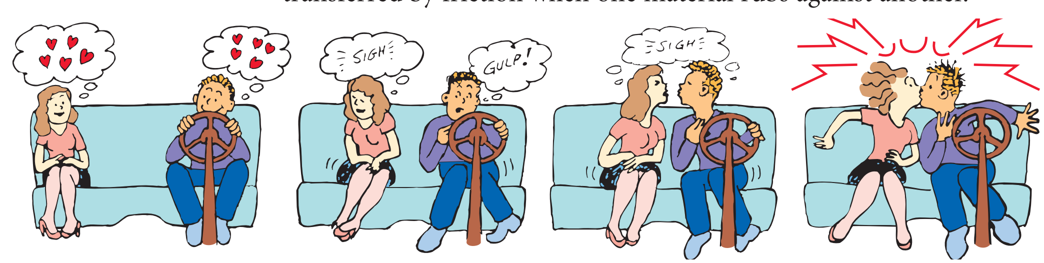


FIGURE 32.7 ▲
If you slide across a seat in an automobile you are in danger of being charged by friction.

Electrons can also be transferred from one material to another by simply touching. When a charged rod is placed in contact with a neutral object, some charge will transfer to the neutral object. This method of charging is simply called *charging by contact.* If the object is a good conductor, the charge will spread to all parts of its surface because the like charges repel each other. If it is a poor conductor, the extra charge will stay close to where the object was touched.

CONCEPT CHECK **What are two ways electric charge can be transferred?**

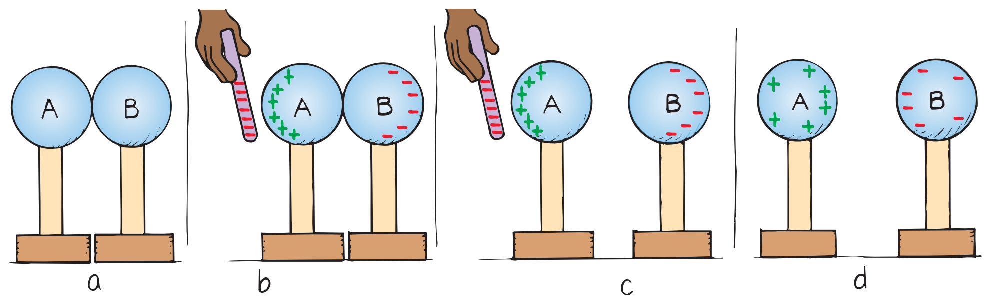


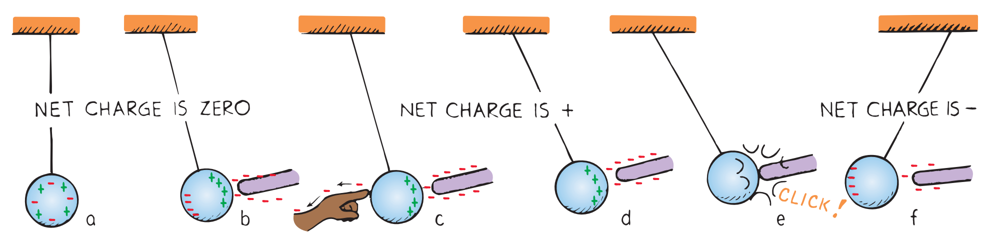
FIGURE 32.8 ▲
Charging by induction can be illustrated using two insulated metal spheres.

32.6 Charging by Induction

If a charged object is brought *near* a conducting surface, even without physical contact, electrons will move in the conducting surface. In Figure 32.8a, the uncharged insulated metal spheres touch each other, so in effect they form a single noncharged conductor. In Figure 32.8b, a negatively charged rod is held near sphere A. Electrons in the metal are repelled by the rod, and excess negative charge has moved onto sphere B, leaving sphere A with excess positive charge. The charge on the two spheres has been redistributed, or **induced.** In Figure 32.8c, the spheres are separated while the rod is still present. In Figure 32.8d, the rod has been removed, and the spheres are charged equally and oppositely. They have been charged by **induction,** which is the charging of an object without direct contact. Since the charged rod never touched them, it retains its initial charge.

A single sphere can be charged similarly by induction. Consider a metal sphere that hangs from a nonconducting string. In Figure 32.9a, the net charge on the metal sphere is zero. In Figure 32.9b, a charge redistribution is induced by the presence of the charged rod. The net charge on the sphere is still zero. In Figure 32.9c, touching the sphere removes electrons by contact. In Figure 32.9d, the sphere is left positively charged. In Figure 32.9e, the sphere is attracted to the negative rod; it swings over to it and touches it. Now electrons move onto the sphere from the rod. The sphere has been negatively charged by contact. In Figure 32.9f, the negative sphere is repelled by the negative rod.

FIGURE 32.9 ▼
Charge induction by grounding can be illustrated using a metal sphere hanging from a nonconducting string.



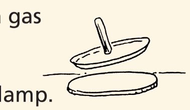
32.6 Charging by Induction

Key Terms
induced, induction, grounding

Ask Why is the charge distribution in Figure 32.8d not uniform? *The charges are closer together in facing halves of the conducting sphere due to induction. If the spheres were much farther apart and induction between them were negligible, the charge distribution on each would be uniform.*

Demonstration

Charge an electrophorus, place an insulated metal disk on top of it, and show that the disk is not charged when removed and brought near a charged pith ball. The insulating surface of the electrophorus has more grab on the electrons than the metal plate. Rest the plate on the electrophorus again and touch the top of the plate. This grounds it. Now bring the plate near the pith ball and show that it is charged by noting the flash of light produced when the charged metal plate is touched to the end of a gas discharge tube or a fluorescent lamp.



Notice that one idea is related to the next in this sequence—very important, as the ideas of electricity are usually difficult to grasp the first time through. Be sure to take care in moving through this sequence of demonstrations and their explanations.

PAUL

When we touch the metal surface with a finger, as illustrated in Figure 32.9c, charges that repel each other have a conducting path to a practically infinite reservoir for electric charge—the ground. When we allow charges to move off (or onto) a conductor by touching it, it is common to say that we are **grounding** it. Chapter 34 returns to this idea of grounding in the discussion of electric currents.

Charging by induction occurs during thunderstorms. The negatively charged bottoms of clouds induce a positive charge on the surface of Earth below, as seen in Figure 32.10. Benjamin Franklin was the first to demonstrate this in his famous kite-flying experiment, in which he proved that lightning is an electrical phenomenon.[32.6] Most lightning is an electrical discharge between oppositely charged parts of clouds. The kind of lightning we are most familiar with is the electrical discharge between the clouds and the oppositely charged ground below.

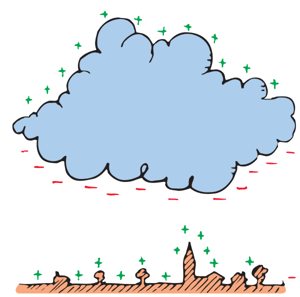


FIGURE 32.10 ▲
The bottom of the negatively charged cloud induces a positive charge at the surface of the ground below.

Franklin also found that charge flows readily to or from sharp points, and fashioned the first lightning rod. If the rod is placed above a building connected to the ground, the point of the rod collects electrons from the air, preventing a large buildup of positive charge on the building by induction. This continual "leaking" of charge prevents a charge buildup that might otherwise lead to a sudden discharge between the cloud and the building. The primary purpose of the lightning rod, then, is to prevent a lightning discharge from occurring. If for any reason sufficient charge does not leak from the air to the rod, and lightning strikes anyway, it may be attracted to the rod and short-circuited to the ground, sparing the building.

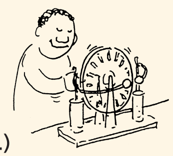
CONCEPT CHECK **What happens when a charged object is placed near a conducting surface?**

think!

Why does the negative rod in Figure 32.8 have the same charge before and after the spheres are charged, but not when charging takes place as in Figure 32.9?
Answer: 32.6

Demonstration

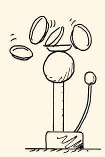
Explain the similarity of a Whimshurst machine (electrostatic generator) to a rotating electrophorus. Show sparks jumping between the spheres of the machine and so forth, and discuss the sizes (radii of curvature) of the spheres in terms of their capacity for storing charge. (The amount of charge that can be stored before discharge into the air is directly proportional to the radius of the sphere.)



▶ **Teaching Tip** Discuss the lightning rod as a preventer of lighting while showing the similar function of the metal points attached to the Whimshurst machine.

Demonstration

When showing the long sparks that jump from the dome of the Van de Graaff generator to the smaller grounded sphere, hold a lightning rod (any sharp pointed conductor) in the vicinity of the dome and the sparking will stop. Bring the lightning rod farther away and the frequent sparking will resume. Set a cup of puffed rice or puffed wheat on top of the Van de Graaff generator. Your students will like the fountain that results when you charge it. Or, place a stack of aluminum pie plates on the dome and watch them levitate and fly away one by one.



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discover!

Is the Water That Comes Out of Your Faucet Charged?

1. Charge a comb by running it through your hair. This will work especially well if the weather is dry.
2. Now bring the comb near some tiny bits of paper. Explain your observations.
3. Next, place the charged comb near a thin stream of water from the faucet.
4. Is there an electrical interaction between the comb and the stream?
5. **Think** Does this mean the stream of water is charged? Why or why not?

32.7 Charge Polarization

Charging by induction is not restricted to conductors. **Charge polarization can occur in insulators that are *near* a charged object.** When a charged rod is brought near an insulator, there are no free electrons to migrate throughout the insulating material. Instead, as shown in Figure 32.11a, there is a rearrangement of the positions of charges within the atoms and molecules themselves. One side of the atom or molecule is induced to be slightly more positive (or negative) than the opposite side, and the atom or molecule is said to be **electrically polarized.** If the charged rod is negative, say, then the positive side of the atom or molecule is toward the rod, and the negative side of the atom or molecule is away from it. The atoms or molecules near the surface all become aligned this way, as seen in Figure 32.11b.

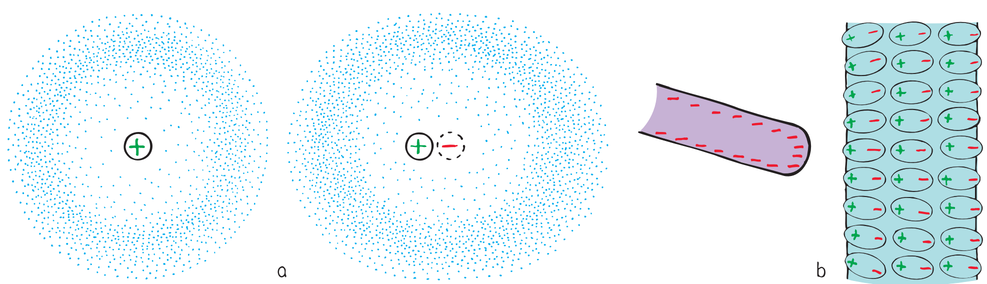


FIGURE 32.11 ▲
a. When an external negative charge is brought closer from the left, the charges within a neutral atom or molecule rearrange.
b. All the atoms or molecules near the surface of the insulator become electrically polarized.

discover!

MATERIALS comb, paper, faucet

EXPECTED OUTCOME Students will observe an electrical interaction between the comb and the stream of water.

THINK The stream of water has a net charge of zero but the charges are rearranged and the stream becomes electrically polarized.

CONCEPT CHECK If a charged object is brought *near* a conducting surface, even without physical contact, electrons will move in the conducting surface.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *32-2*
- **Transparencies** *76, 77*
- **Presentation*EXPRESS***
- **Interactive Textbook**

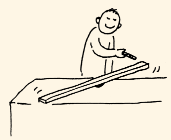
32.7 Charge Polarization

Key Term
electrically polarized

▶ **Teaching Tip** Define polarization by explaining Figures 32.11 through 32.14 in the text. Show the effect of polarization when a charged balloon sticks to a wall.

Demonstration

Show the effects of electrical force and charging by induction by holding a charged rod near the ends of a wooden 2 × 4. The 2 × 4 must be more than a meter long, and it must balance and rotate easily sideways at its midpoint on a protrusion such as the bottom of a metal spoon. You can easily set the massive piece of wood in motion. This is quite impressive!



▶ **Teaching Tip** The demo with the 2 × 4 piece of wood is an example of charge polarization. When the charges are free to move we have induction; when they're only free to reposition in fixed atoms, we have charge polarization.

Demonstration

Rub a balloon on your hair and show that it sticks to the wall. Sketch Figure 32.13 on the board and show that the attracting charges are slightly closer than the repelling charges. Closeness wins and the balloon sticks to the wall!

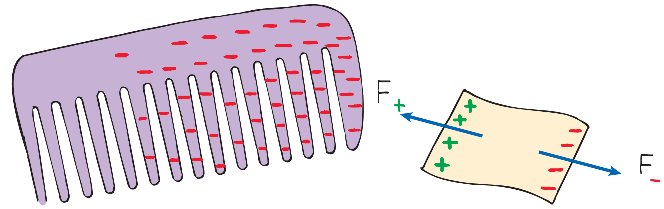
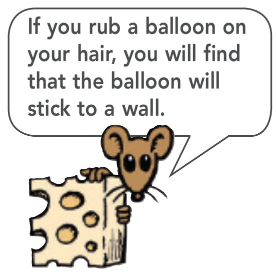


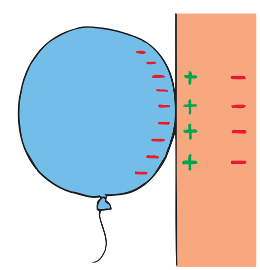
FIGURE 32.12 ▲
A charged comb attracts an uncharged piece of paper because the force of attraction for the closer charge is greater than the force of repulsion for the farther charge.



Examples of Charge Polarization This explains why electrically neutral bits of paper are attracted to a charged object, such as the comb shown in Figure 32.12. Molecules are polarized in the paper, with the oppositely charged sides of molecules closest to the charged object. Closeness wins, and the bits of paper experience a net attraction. Sometimes they will cling to the charged object and suddenly fly off. This indicates that charging by contact has occurred; the paper bits have acquired the same sign of charge as the charged object and are then repelled.

Rub an inflated balloon on your hair and it becomes charged. Place the balloon against the wall and it sticks. As shown in Figure 32.13, the charge on the balloon induces an opposite surface charge on the wall. Closeness wins, for the charge on the balloon is slightly closer to the opposite induced charge than to the charge of the same sign.

FIGURE 32.13 ▶
The negatively charged balloon polarizes molecules in the wooden wall and creates a positively charged surface, so the balloon sticks to the wall.



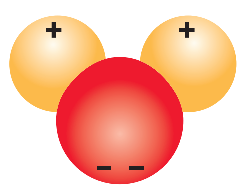


FIGURE 32.14 ▲
An H_2O molecule is an electric dipole.

Electric Dipoles Many molecules—H_2O, for example—are electrically polarized in their normal states. The distribution of electric charge is not perfectly even. As illustrated in Figure 32.14, there is a little more negative charge on one side of the molecule than on the other. Such molecules are said to be *electric dipoles*.

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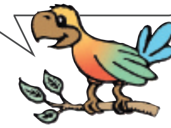
In summary, objects are electrically charged in three ways.

1. By friction, when electrons are transferred by friction from one object to another.
2. By contact, when electrons are transferred from one object to another by direct contact without rubbing. A charged rod placed in contact with an uncharged piece of metal, for example, will transfer charge to the metal.
3. By induction, when electrons are caused to gather or disperse by the presence of nearby charge (even without physical contact). A charged rod held near a metal surface, for example, repels charges of the same sign as those on the rod and attracts opposite charges. The result is a redistribution of charge on the object without any change in its net charge. If the metal surface is discharged by contact, with a finger for example, then a net charge will be left.

If the object is an insulator, on the other hand, then a realignment of charge rather than a migration of charge occurs. This is charge polarization, in which the surface near the charged object becomes oppositely charged. This occurs when you stick a charged balloon to a wall.

CONCEPT CHECK What happens when an insulator is in the presence of a charged object?

Be glad that water is an electric dipole. If its opposite ends didn't attract different ions, almost all the chemistry that occurs in aqueous solutions would be impossible. Three cheers for the electric dipole nature of the water molecule!



Physics in the Kitchen

Microwave Cooking

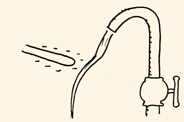
Imagine an enclosure filled with table-tennis balls among a few batons, all at rest. Now imagine the batons suddenly flipping back and forth like semi-rotating propellers, striking neighboring table-tennis balls. Almost immediately most table-tennis balls are energized, vibrating in all directions. A microwave oven works similarly. The batons are water molecules that flip back and forth in rhythm with microwaves in the enclosure. The table-tennis balls are nonwater molecules that make up the bulk of material being cooked.

H_2O molecules are polar, with opposite charges on opposite sides. When an electric field is imposed on them, they align with the field like a compass aligns with a magnetic field. Microwaves are an electric field that oscillates, so H_2O molecules oscillate also—and quite energetically. Food is cooked by a sort of "kinetic friction" as flip-flopping H_2O molecules increase the thermal motion of surrounding food molecules.

A microwave oven wouldn't work without the presence of the electric dipoles in the food (usually, but not always, water). That's why microwaves pass through foam, paper, or ceramic plates with no effect. Microwaves also reflect and bounce off conductors with no effect. They do, however, energize water molecules.

Demonstration

Place a charged rod near a thin stream of falling water. The stream will be attracted to the rod due to the dipole nature of water molecules—they are positive on the hydrogen side and negative on the oxygen side. The water molecules align along the electric field of the charged rod, regardless of its charge.



Conclude the chapter by going back to the Van de Graaff generator. Introduce the idea of electric field—that space near the generator dome is altered, as you can demonstrate by snuffing out a match held near the charged dome. This will be the focus of the next chapter.

PAUL

CONCEPT CHECK Charge polarization can occur in insulators that are *near* a charged object.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *32-3*

32 REVIEW

Teaching Resources

- Teacher*EXPRESS*
- Virtual Physics Lab *29*
- Conceptual Physics Alive! DVDs *Electrostatics*

32 REVIEW

Concept Summary

- Like charges repel and opposite charges attract.
- An object that has unequal numbers of electrons and protons is electrically charged.
- Coulomb's law states that for charged particles or objects that are small compared with the distance between them, the force between the charges varies directly as the product of the charges and inversely as the square of the distance between them.
- Electrons move easily in good conductors and poorly in good insulators.
- Electric charge can be transferred by friction and by contact.
- If a charged object is brought *near* a conducting surface, electrons will move in the conducting surface.
- Charge polarization can occur in insulators that are *near* a charged object.

Key Terms

electrostatics *(p. 644)*
electrical forces *(p. 645)*
charge *(p. 645)*
conservation of charge *(p. 647)*
Coulomb's law *(p. 648)*
coulomb *(p. 649)*
conductor *(p. 651)*
insulator *(p. 651)*
semiconductor *(p. 652)*
induced *(p. 653)*
induction *(p. 653)*
grounding *(p. 654)*
electrically polarized *(p. 655)*

think! Answers

32.2 When your rubber- or plastic-soled shoes drag across the rug, they pick up electrons from the rug in the same way you charge a rubber or plastic rod by rubbing it with a cloth. You have more electrons after you scuff your shoes, so you are negatively charged (and the rug is positively charged).

32.3.1 The small value of G indicates that gravity is a weak force; the large value of k indicates that the electrical force is enormous in comparison.

32.3.2 **a.** In accord with the inverse-square law, at twice the distance the force will be one-fourth as much.
b. Since there is a force of attraction, the charges must be opposite in sign, so the charged particle is positive.

32.6 In the charging process of Figure 32.8, no contact was made between the negative rod and either of the spheres. In the charging process of Figure 32.9, however, the rod touched the sphere when it was positively charged. A transfer of charge by contact reduced the negative charge on the rod.

32 ASSESS

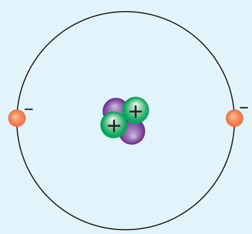
Check Concepts

Section 32.1

1. Which force—gravitational or electrical—repels as well as attracts?

2. Gravitational forces depend on the property called *mass*. What comparable property underlies electrical forces?

3. How do protons and electrons differ in their electric charge?



4. Is an electron in a hydrogen atom the same as an electron in a uranium atom?

5. Which has more mass—a proton or an electron?

6. In a normal atom, how many electrons are there compared with protons?

7. **a.** How do like charges behave toward each other?
   b. How do unlike charges behave toward each other?

Section 32.2

8. How does a negative ion differ from a positive ion?

9. What does it mean to say that charge is conserved?

10. **a.** If electrons are rubbed from cat's fur onto a rubber rod, does the rod become positively or negatively charged?
    b. How about the cat's fur?

Section 32.3

11. **a.** How is Coulomb's law similar to Newton's law of gravitation?
    b. How are the two laws different?

12. The SI unit of mass is the kilogram. What is the SI unit of charge?

13. The proportionality constant k in Coulomb's law is huge in ordinary units, whereas the proportionality constant G in Newton's law of gravity is tiny. What does this mean in terms of the relative strengths of these two forces?

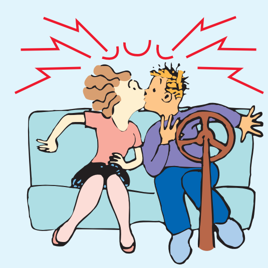
Section 32.4

14. **a.** Why are metals good conductors?
    b. Why are materials such as rubber and glass good insulators?

15. What is a semiconductor?

Section 32.5

16. Which two methods of charging objects involve touching?



32 ASSESS

Check Concepts

1. Electrical; gravitational force only attracts.
2. Charge
3. Same magnitude, but opposite charge
4. Yes, all electrons are identical.
5. Proton—more than 1800 times greater than the electron
6. Same number, no net charge
7. **a.** Repel each other
   b. Attract each other
8. A negative ion has extra electron(s); a positive ion has lost electron(s).
9. It is neither created nor destroyed, only transferred.
10. **a.** Negatively
    b. Positively
11. **a.** Both are inverse-square laws.
    b. One depends on mass, and one depends on charge; Coulomb's law comprises both attractive and repulsive forces.
12. Coulomb
13. Electrical force is relatively much greater.
14. **a.** Free electrons
    b. Bound electrons
15. Material that can behave as either an insulator or a conductor
16. Contact and friction

17. Induction
18. Electrical discharge from cloud to cloud or to ground
19. To prevent discharge and to conduct charge to ground
20. Negative on one side, positive on the other
21. The oppositely charged side is a little closer.
22. A molecule in which the distribution of charge is uneven

Think and Rank

23. A, C, B
24. B = E, C = D, A = F
25. C, B, A

32 ASSESS *(continued)*

Section 32.6

17. Which method of charging objects involves no touching?
18. What is lightning?
19. What is the function of a lightning rod?

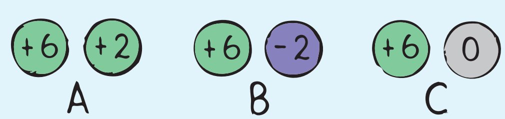
Section 32.7

20. What does it mean to say an object is electrically polarized?
21. When a charged object polarizes another, why is there an attraction between the objects?
22. What is an electric dipole?

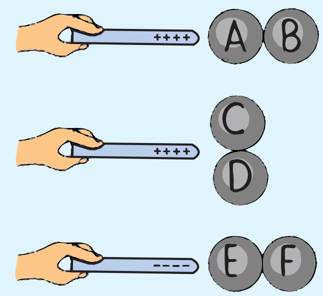
Think and Rank

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

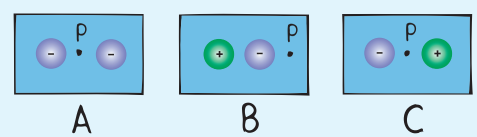
23. The three pairs of metal spheres below are all the same size and have different charges on their surfaces, as indicated. The pairs of spheres are brought into contact with each other. After several moments the spheres are separated. Rank from greatest to least the total amount of charge on the pairs of spheres after separation.



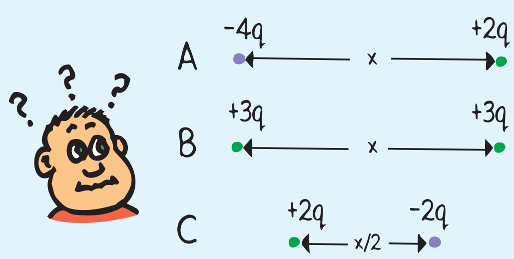
24. Three separate pairs of uncharged metal spheres are in contact. A (positively or negatively) charged rod is brought up to the same distance from each set of spheres. Rank the resulting charge on each sphere from greatest positive to greatest negative.



25. Indicated below are pairs of electric charges in three different arrangements. In each figure, a test charge is located at the point labeled P. The other, much larger, charges all have the same magnitude and lie on a line that passes through P. Note some charges are positive and some are negative. Rank the arrangements on the basis of the strength of the electric force on the test charge, from strongest to weakest.



26. Shown below are three separate pairs of point charges, pairs A, B, and C. Assume the pairs interact only with each other. Rank the magnitudes of the force between the pairs, from largest to smallest.



Think and Explain

27. Electrical forces between charges are enormous relative to gravitational forces. Yet, we normally don't sense electrical forces between us and our environment, while we do sense our gravitational interaction with Earth. Why is this so?

28. Two equally charged particles exert equal forces on each other. Suppose that the charge on one of the particles is doubled. The charge on the other remains the same.
   a. How much stronger is the force between them?
   b. How does the force change if the charges of both particles are doubled?

29. How will the forces between two charged particles compare when one particle has ten times as much charge as the other? Defend your answer.

30. If electrons were positive and protons negative, would Coulomb's law be written the same or differently?

31. If you scuff electrons from your hair onto a comb, are you positively or negatively charged? How about the comb?

32. The five thousand billion billion freely moving electrons in a penny repel one another. Why don't they fly out of the penny?

33. If a glass rod that is rubbed with a plastic dry cleaner's bag acquires a certain charge, why does the plastic bag have exactly the same amount of opposite charge?

34. Why do clothes often cling together after tumbling in a clothes dryer?

35. Why will dust be attracted to a CD wiped with a dry cloth?

36. When one material is rubbed against another, electrons jump readily from one to the other, but protons do not. Why is this? (Think in atomic terms.)

37. Plastic wrap becomes electrically charged when pulled from its container. Does the charged wrap stick better to glass bowls or metal bowls?

38. Explain how an object that is electrically neutral can be attracted to an object that is charged.

26. C, B, A

Think and Explain

27. Charges can cancel, while masses cannot.

28. **a.** Doubling the charge on one of the particles produces twice the force.
b. Doubling the charge on both particles produces 4 times the force.

29. The forces will be equal in magnitude in accord with Newton's third law.

30. The same; Coulomb's law does not distinguish between positive and negative charges.

31. Positive; negative

32. The electrons are attracted to the same number of protons in the penny.

33. Charge is transferred. No *net* charge is ever created or destroyed.

34. Static charge is built up by rubbing.

35. Static charge is built up by rubbing.

36. Protons are locked into the nuclei of atoms but electrons are not.

37. Plastic wrap sticks better to the non-conducting glass. It sticks poorly to the conducting metal.

38. The side having the opposite sign of charge is closer to the charged object. The attraction between the opposite charges is greater than the repulsion between the like charges.

39. The leaves have like charges, and repel each other.

40. No, charging by induction will also charge the leaves.

41. Yes, either a positive or negative charge will polarize and attract the paper.

42. The paint is polarized and attracted to the conducting surface.

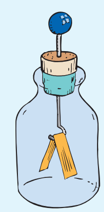
43. Electron; the force on both will be the same but the electron will have more acceleration and therefore more speed because of its lesser mass.

44. Disagree with Jess and agree with Marie. *Acceleration,* not speed, decreases with increasing distance.

45. Sophia is correct about equal forces but not equal accelerations. Sandra is correct and should add that the greater *mass* of the protons means less acceleration for the same force.

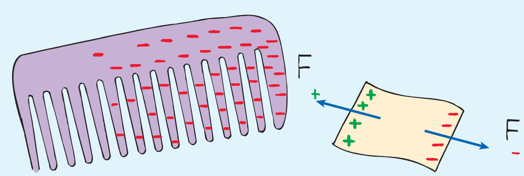
32 ASSESS *(continued)*

39. An electroscope is a simple device. It consists of a metal ball that is attached by a conductor to two fine gold leaves that are protected from air disturbances in a jar, as shown in the sketch. When the ball is touched by a charged object, the leaves that normally hang straight down spring apart. Why? (Electroscopes are useful not only as charge detectors, but also for measuring the amount of charge: the more charge transferred to the ball, the more the leaves diverge.)



40. Would it be necessary for a charged object to actually touch the leaves of an electroscope (see Question 39) for the leaves to diverge? Defend your answer.

41. Figure 32.12 shows a negatively charged plastic comb attracting bits of paper with no net charge. If the comb were positively charged, would it attract the same bits of paper? Defend your answer.



42. When a car is moved into a painting chamber, a mist of paint is sprayed around it. When the body of the car is given a sudden electric charge and the mist of paint is attracted to it, presto—the car is quickly and uniformly painted. What does the phenomenon of polarization have to do with this?

43. Imagine a proton at rest a certain distance from a negatively charged plate. It is released and collides with the plate. Then imagine the similar case of an electron at rest the same distance away from a plate of equal and opposite charge. In which case would the moving particle have the greater speed when the collision occurs? Why?

44. Consider a pair of particles with equal charges. When released, they fly apart from each other. Your teacher asks how the speeds will compare when they are ten times farther apart than when first released. Jess says that since the force on the particles decreases with distance, their speeds will be less. Marie says no, the speed of the repelled particles increases as long as they interact with each other. With whom do you agree or disagree, and why?

45. A pair of isolated protons will fly apart from each other. The same is true for a pair of isolated electrons. Your teacher asks which has the greater initial acceleration if the initial distance between the particles is the same. Sophia says the initial accelerations will be equal because the forces are equal. Sandra says no, that the electrons will accelerate more—but can't explain why. Both look to you for your input. What is your thinking?

Think and Solve

46. The charge on an electron is 1.6×10^{-19} C. How many electrons make a charge of 1 C?

47. By how much is the electrical force between a pair of ions reduced when their separation distance is doubled? Tripled?

48. Two pellets, each with a charge of 1 μC, are separated by a distance of 0.30 m. Show that the electric force between them is 0.1 N.

49. Two identical metal spheres are brought together into contact. Originally one had a charge of $+40$ μC and the other a charge of -10 μC. What is the charge on each after contact?

50. Consider two small charged objects, one with a charge of 15 μC and the other of unknown charge. When they are separated by a distance of 1.2 m, each exerts a force of 2.8 N on the other. What is the charge of the second object?

51. Proportional reasoning: Consider a pair of electrically charged coins suspended from insulating threads, a certain distance from each other. There is a specific amount of electrostatic force between them.

a. If the charge on one coin were halved, what would happen to the force between them?

b. If the charges on both coins were doubled, what would happen to the force between them?

c. If the distance between the coins were tripled, what would happen to the force between them?

d. If the distance between them were reduced to one-fourth the original distance, what would happen to the force between them?

e. If the charge on each object were doubled and the distance between them were doubled, what would happen to the force between them?

52. Two spherical inflated rubber balloons each have the same amount of charge spread uniformly on their surfaces. If the repelling force is 2.5 N and the distance between the balloon centers is 0.30 m, find how much charge is on each balloon.

More Problem-Solving Practice
Appendix F

Think and Solve

46. Total charge ÷ (charge per electron) = (1 C) ÷ (1.6×10^{-19} C) = 6.25×10^{18} electrons

47. To 1/4; to 1/9

48. $F = kq_1q_2/d^2 = (9 \times 10^9\ \text{N·m}^2/\text{C}^2) \times (1 \times 10^{-6}\ \text{C})^2/(0.30\ \text{m})^2 = 0.1\ \text{N}$

49. $+40\ \mu\text{C} - 10\ \mu\text{C} = 30\ \mu\text{C}$; half on each $= 15\ \mu\text{C}$

50. From $F = kq_1q_2/d^2$, $q_2 = Fd^2/kq_1 = (2.8\ \text{N}) \times (1.2\ \text{m})^2/(9 \times 10^9\ \text{N·m}^2/\text{C}^2 \times 15 \times 10^{-6}\ \text{C}) = 3.0 \times 10^{-5}\ \text{C} = 30\ \mu\text{C}$

51. **a.** Force is proportional to each charge, so the force would be halved.
b. Force is proportional to the product of the charges, so the force would be quadrupled.
c. Force is proportional to the inverse of the distance squared, so the force would be 1/9 its original value.
d. Force is proportional to the inverse of the distance squared. The inverse of $(1/4)^2$ is 16, so the force would be 16 times its original value.
e. Doubling both charges would multiply the force by four. Doubling the distance would multiply the force by one-quarter. So there would be no change in force.

52. From $F = kq_1q_2/d^2 = kq^2/d^2$, $q = d \times \sqrt{F/k} = 0.30\ \text{m} \times \sqrt{(2.5\ \text{N})/(9 \times 10^9\ \text{N·m}^2/\text{C}^2)} = 5.0 \times 10^{-6}\ \text{C} = 5.0\ \mu\text{C}$

Teaching Resources

- **Computer Test Bank**
- **Chapter and Unit Tests**