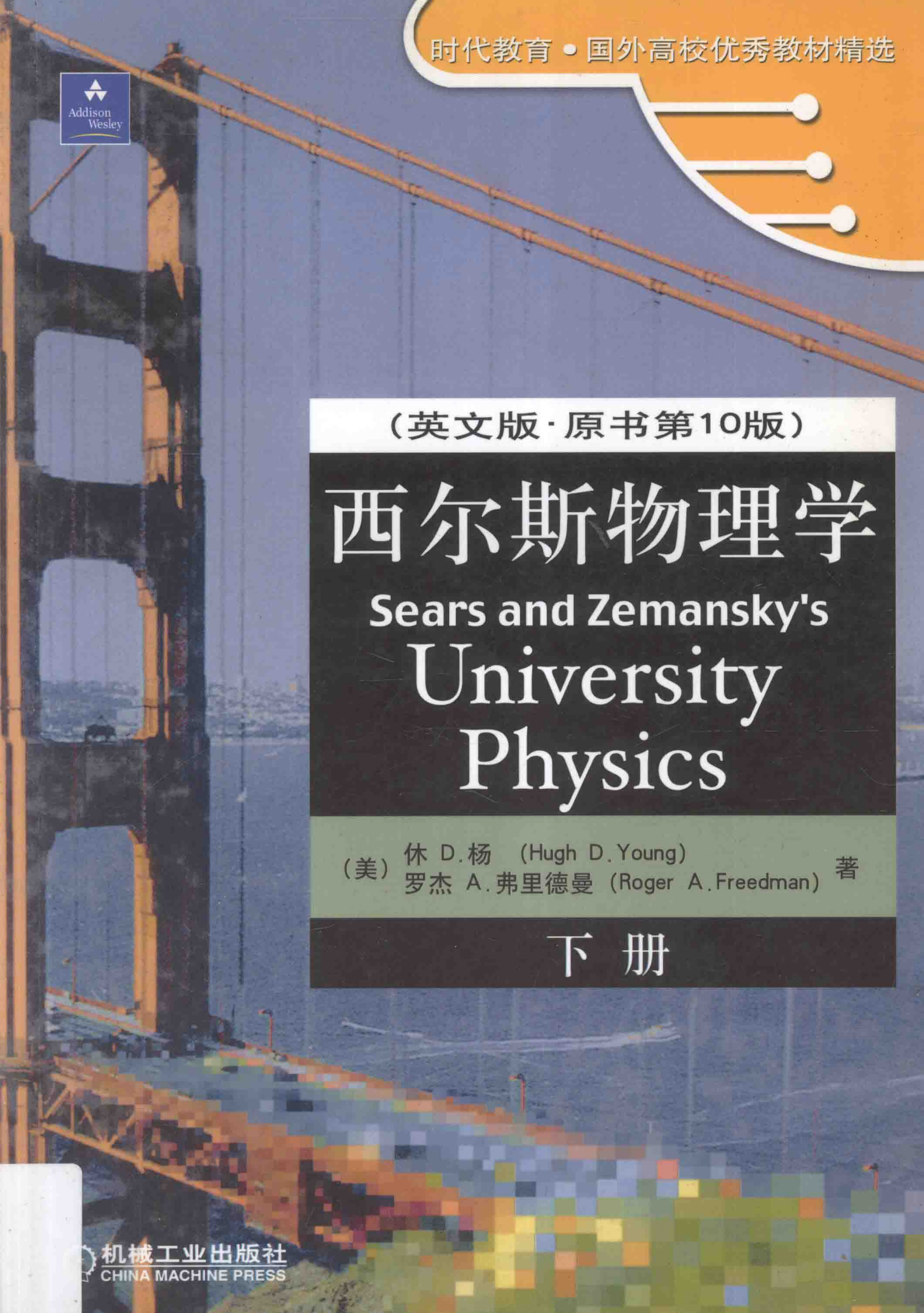

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西尔斯物理学

Sears and Zemansky's University Physics

（美） 休 D. 杨 （Hugh D. Young）
罗杰 A. 弗里德曼 （Roger A. Freedman） 著

下 册

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机械工业出版社(北京市百万庄大街22号　邮政编码　100037)
责任编辑：刘小慧
封面设计：鞠　杨　　责任印制：陶　湛
北京铭成印刷有限公司印刷·新华书店北京发行所发行
2005年3月第1版第3次印刷
787mm×1092mm 1/16·82印张·4插页·2028千字
定价：80.00元（上、下册）
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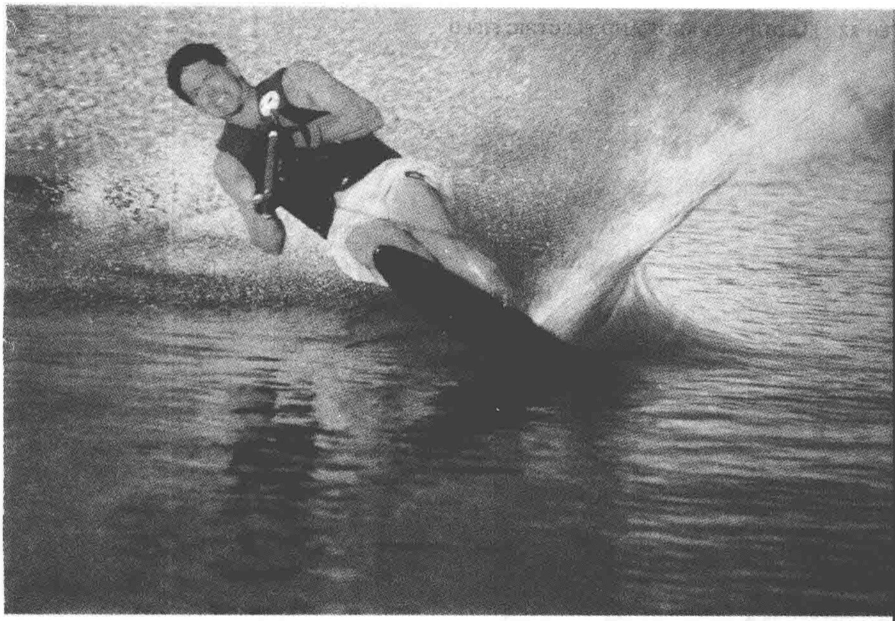


Most of the forces on this water skier are electric. Electric interactions between adjacent molecules give rise to the force of the water on the ski, the tension in the tow rope, and the resistance of the air on the skier's body. They also hold the skier's body together! Only one wholly nonelectric force acts on the skier: the force of gravity.

22

Electric Charge and Electric Field

22-1 INTRODUCTION

When you scuff your shoes across a carpet and then reach for a metal doorknob, you can get zapped by an annoying spark of static electricity. Why does this happen, and why is it more likely to happen on a dry day than on a humid one? The atoms in your body hold together and don't break apart, even though the particles that make up those atoms can be moving at very high speeds. Why? What really happens in an electric circuit? How do electric motors and generators work? And what is light, anyway?

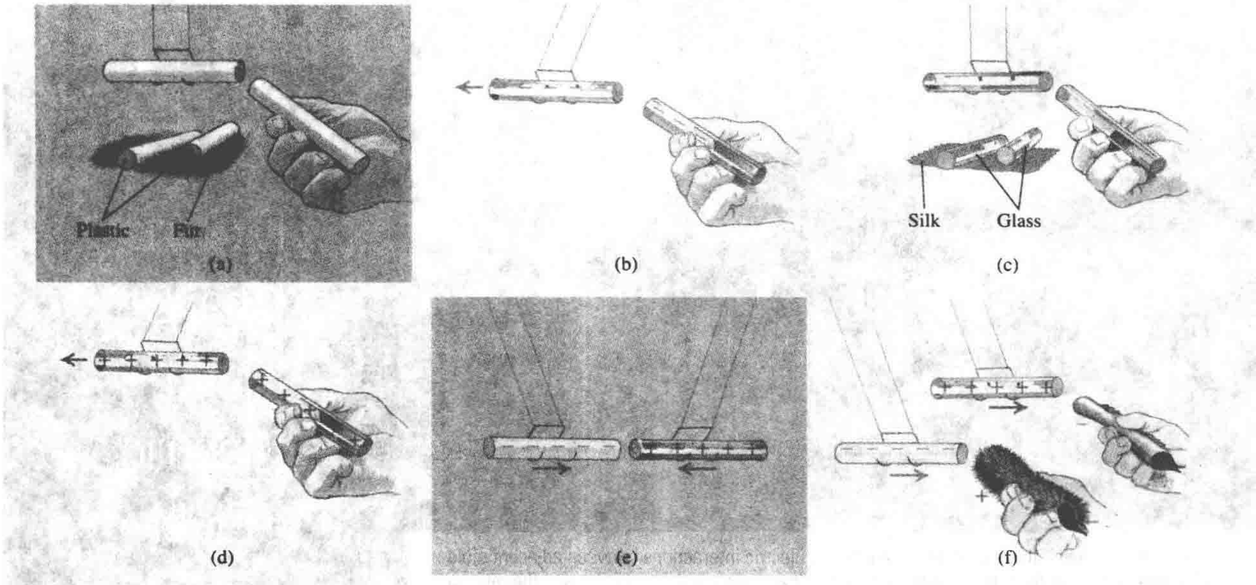
The answers to all these questions come from a fundamental branch of physics known as *electromagnetism,* the study of electric and magnetic interactions. These interactions involve particles that have a property called *electric charge,* an attribute of matter that is as fundamental as mass. Our exploration of electromagnetic phenomena will occupy our attention for most of the remainder of this book.

We begin our study of electromagnetism in this chapter by examining the nature of electric charge. We'll find that electric charge is quantized and that it obeys a conservation principle. We then turn to a discussion of the interactions of electric charges that are at rest in our frame of reference, called *electrostatic* interactions. Such interactions are exceedingly important: They hold atoms, molecules, and our bodies together and have numerous technological applications. Electrostatic interactions are governed by a simple relationship known as *Coulomb's law* and are most conveniently described by using the concept of *electric field.* We'll explore all these concepts in this chapter and expand on them in the three chapters that follow. In later chapters we'll expand our discussion to include electric charges in motion.

While the key ideas of electromagnetism are conceptually simple, applying them to practical problems will make use of many of your mathematical skills, especially your knowledge of geometry and integral calculus. For this reason you may find this chapter and those that follow to be more mathematically demanding than previous chapters. The reward for your extra effort will be a deeper understanding of principles that are at the heart of modern physics and technology.

22-2 ELECTRIC CHARGE

We can't say what electric charge *is;* we can only describe its properties and its behavior. The ancient Greeks discovered as early as 600 B.C. that when they rubbed amber with wool, the amber could then attract other objects. Today we say that the amber has acquired a net **electric charge**, or has become *charged*. The word "electric" is derived from the Greek word *elektron,* meaning amber. When you scuff your shoes across a nylon carpet, you become electrically charged, and you can charge a comb by passing it through dry hair.



22–1 (a, b) After being rubbed with fur, two plastic rods repel each other. (c, d) After being rubbed with silk, two glass rods repel each other. (e) The charged plastic rod from (b) attracts the charged glass rod from (d). (f) The fur attracts the charged plastic rod, and the silk attracts the charged glass rod.

Plastic rods and fur (real or fake) are particularly good for demonstrating the phenomena of **electrostatics,** the interactions between electric charges that are at rest (or nearly so). Figure 22–1a shows two plastic rods and a piece of fur. After we charge each rod by rubbing it with the piece of fur, we find that the rods repel each other (Fig. 22–1b). When we rub glass rods (Fig. 22–1c) with silk, the glass rods also become charged and repel each other (Fig. 22–1d). But a charged plastic rod *attracts* a charged glass rod (Fig. 22–1e). Furthermore, the plastic rod and the fur attract each other, and the glass rod and the silk attract each other (Fig. 22–1f).

These experiments and many others like them have shown that there are exactly two kinds of electric charge: the kind on the plastic rod rubbed with fur and the kind on the glass rod rubbed with silk. Benjamin Franklin (1706–1790) suggested calling these two kinds of charge *negative* and *positive,* respectively, and these names are still used. The plastic rod and the silk have negative charge; the glass rod and the fur have positive charge. **Two positive charges or two negative charges repel each other. A positive charge and a negative charge attract each other.**

CAUTION ▶ The attraction and repulsion of two charged objects is sometimes summarized as "Like charges repel, and opposite charges attract." But keep in mind that the phrase "like charges" does *not* mean that the two charges are exactly identical, only that both charges have the same algebraic *sign* (both positive or both negative). "Opposite charges" means that both objects have an electric charge, and those charges have different signs (one positive and the other negative). ◀

One technological application of forces between charged bodies is in a photocopy machine. Positively charged regions of the machine's imaging drum attract negatively charged particles of toner. When a piece of paper is placed in contact with the drum, the toner particles stick to the paper and form an image.

22-3 ELECTRIC CHARGE AND THE STRUCTURE OF MATTER

Electric charge, like mass, is one of the fundamental attributes of the particles of which matter is made. The interactions responsible for the structure and properties of atoms and molecules are primarily *electric* interactions between electrically charged particles. The same is true for the structure and properties of ordinary matter, which is made up of atoms and molecules. The normal force exerted on you by the chair in which you're sitting, the tension force in a stretched string, and the adhesive force of glue are all fundamentally electric in nature, arising from the electric forces between charged particles in adjacent atoms.

The structure of atoms can be described in terms of three particles: the negatively charged **electron,** the positively charged **proton,** and the uncharged **neutron.** The proton and neutron are combinations of other entities called *quarks,* which have charges of $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$ times the electron charge. Isolated quarks have not been observed, and there are theoretical reasons to believe that it is impossible in principle to observe a quark in isolation.

The electron—the first constituent of the atom to be isolated—was discovered in 1897 by the English physicist J. J. Thomson. This discovery revolutionized our understanding of the structure of matter, and led to the later discoveries of the proton and neutron. Thomson was awarded the 1906 Nobel Prize in physics and was knighted in 1908.

The protons and neutrons in an atom make up a small, very dense core called the **nucleus,** with dimensions of the order of 10^{-15} m. Surrounding the nucleus are the electrons, extending out to distances of the order of 10^{-10} m from the nucleus. If an atom were a few kilometers across, its nucleus would be the size of a tennis ball. The negatively charged electrons are held within the atom by the attractive electric forces exerted on them by the positively charged nucleus. (The protons and neutrons are held within the stable atomic nuclei by an attractive interaction, called the *nuclear force,* that overcomes the electric repulsion of the protons. The nuclear force has a short range, of the order of nuclear dimensions, and its effects do not extend far beyond the nucleus.)

The masses of the individual particles, to the precision that they are presently known, are

$$\text{Mass of electron} = m_e = 9.1093897(54) \times 10^{-31}\ \text{kg},$$

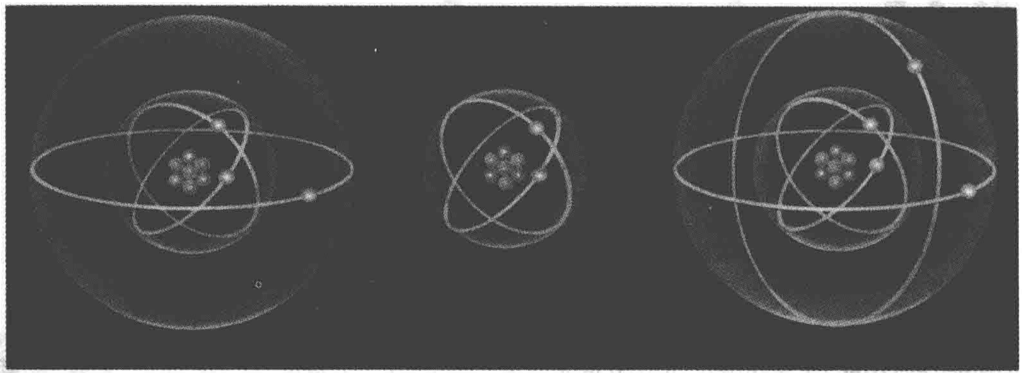
$$\text{Mass of proton} = m_p = 1.6726231(10) \times 10^{-27}\ \text{kg},$$

$$\text{Mass of neutron} = m_n = 1.6749286(10) \times 10^{-27}\ \text{kg}.$$

The numbers in parentheses are the uncertainties in the last two digits. Note that the masses of the proton and neutron are nearly equal and are roughly 2000 times the mass of the electron. Over 99.9% of the mass of any atom is concentrated in its nucleus.

The negative charge of the electron has (within experimental error) *exactly* the same magnitude as the positive charge of the proton. In a neutral atom the number of electrons equals the number of protons in the nucleus, and the net electric charge (the algebraic sum of all the charges) is exactly zero (Fig. 22–2a; see page 672). The number of protons or electrons in a neutral atom of an element is called the **atomic number** of the element. If one or more electrons are removed, the remaining positively charged structure is called a **positive ion** (Fig. 22–2b). A **negative ion** is an atom that has *gained* one or more electrons (Fig. 22–2c). This gaining or losing of electrons is called **ionization.**

When the total number of protons in a macroscopic body equals the total number of electrons, the total charge is zero and the body as a whole is electrically neutral. To give a body an excess negative charge, we may either *add negative* charges to a neutral body or *remove positive* charges from that body. Similarly, we can create an excess positive charge by either *adding positive* charge or *removing negative* charge. In most cases, negatively charged (and highly mobile) electrons are added or removed, and a "positively charged body" is one that has lost some of its normal complement of electrons. When we speak of the charge of a body, we always mean its *net* charge. The net charge is



22–2 (a, left) The neutral lithium atom has three protons in its nucleus and three electrons surrounding the nucleus. (b, center) A positive lithium ion is made by removing an electron from a neutral atom. (c, right) A negative lithium ion is made by adding an electron to a neutral atom. (The electron "orbits" are a schematic representation of the actual electron distribution, which is a diffuse cloud many times larger than the nucleus.)

always a very small fraction (typically no more than 10^{-12}) of the total positive charge or negative charge in the body.

Implicit in the foregoing discussion are two very important principles. First is the **principle of conservation of charge: The algebraic sum of all the electric charges in any closed system is constant.** If we rub together a plastic rod and a piece of fur, both initially uncharged, the rod acquires a negative charge (since it takes electrons from the fur) and the fur acquires a positive charge of the *same* magnitude (since it has lost as many electrons as the rod has gained). Hence the total electric charge on the two bodies together does not change. In any charging process, charge is not created or destroyed; it is merely *transferred* from one body to another.

Conservation of charge is believed to be a *universal* conservation law, and there is no experimental evidence for any violation of this principle. Even in high-energy interactions in which particles are created and destroyed, such as the creation of electron-positron pairs, the total charge of any closed system is exactly constant.

The second important principle is that the magnitude of charge of the electron or proton is a natural unit of charge. Every observable amount of electric charge is always an integer multiple of this basic unit. We say that charge is *quantized.* A familiar example of quantization is money. When you pay cash for an item in a store, you have to do it in one-cent increments. Cash can't be divided into amounts smaller than one cent, and electric charge can't be divided into amounts smaller than the charge of one electron or proton. (The quark charges, $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$ of the electron charge, are probably not observable as isolated charges.) Thus the charge on any macroscopic body is always either zero or an integer multiple (negative or positive) of the electron charge.

22–4 CONDUCTORS, INSULATORS, AND INDUCED CHARGES

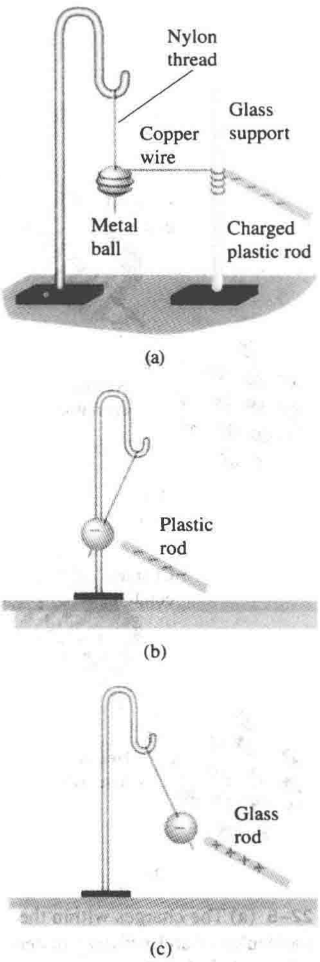
Some materials permit electric charge to move easily from one region of the material to another, while others do not. For example, Fig. 22–3a shows a copper wire supported by a glass rod. Suppose you touch one end of the wire to a charged plastic rod and attach the other end to a metal ball that is initially uncharged; you then remove the charged rod and the wire. When you bring another charged body up close to the ball (Figs. 22–3b and 22–3c), the ball is attracted or repelled, showing that the ball has become electrically charged. Electric charge has been transferred through the copper wire between the ball and the surface of the plastic rod.

The wire is called a **conductor** of electricity. If you repeat the experiment using a rubber band or nylon thread in place of the wire, you find that *no* charge is transferred to the ball. These materials are called **insulators.** Conductors permit the easy movement of charge through them, while insulators do not. As an example, carpet fibers on a dry day are good insulators. As you walk across a carpet, the rubbing of your shoes against the fibers causes charge to build up on you, and this charge will remain on you because it can't flow through the insulating fibers. If you then touch a conducting object such as a doorknob, a rapid charge transfer takes place between your finger and the doorknob, and you feel a shock. One way to prevent this is to wind some of the carpet fibers around conducting cores so that any charge that builds up on you can be transferred harmlessly to the carpet. Another solution is to coat the carpet fibers with an antistatic layer that does not easily transfer electrons to or from your shoes; this prevents any charge from building up on you in the first place.

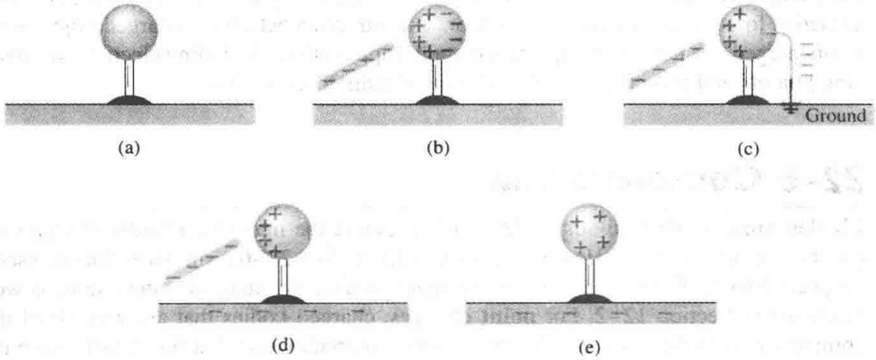
Most metals are good conductors, while most nonmetals are insulators. Within a solid metal such as copper, one or more outer electrons in each atom become detached and can move freely throughout the material, just as the molecules of a gas can move through the spaces between the grains in a bucket of sand. The motion of these negatively charged electrons carries charge through the metal. The other electrons remain bound to the positively charged nuclei, which themselves are bound in nearly fixed positions within the material. In an insulator there are no, or very few, free electrons, and electric charge cannot move freely through the material. Some materials called *semiconductors* are intermediate in their properties between good conductors and good insulators.

We can charge a metal ball by touching it with an electrically charged plastic rod, as in Fig. 22–3a. In this process, some of the excess electrons on the rod are transferred from it to the ball, leaving the rod with a smaller negative charge. There is a different technique in which the plastic rod can give another body a charge of *opposite* sign without losing any of its own charge. This process is called charging by **induction.**

Figure 22–4a shows an example of charging by induction. A metal sphere is supported on an insulating stand. When you bring a negatively charged rod near it, without actually touching it (Fig. 22–4b), the free electrons in the metal sphere are repelled by the excess electrons on the rod, and they shift toward the right, away from the rod. They cannot escape from the sphere because the supporting stand and the surrounding air are insulators. So we get excess negative charge at the right surface of the sphere and a deficiency of negative charge (that is, a net positive charge) at the left surface. These excess charges are called **induced charges.**



22–3 Copper is a good conductor of electricity; glass and nylon are good insulators. (a) The wire conducts charge between the metal ball and charged plastic rod to charge the ball negatively. (b) Afterward, the metal ball is repelled by a negatively charged plastic rod and (c) attracted to a positively charged glass rod.



22–4 Charging a metal sphere by induction.

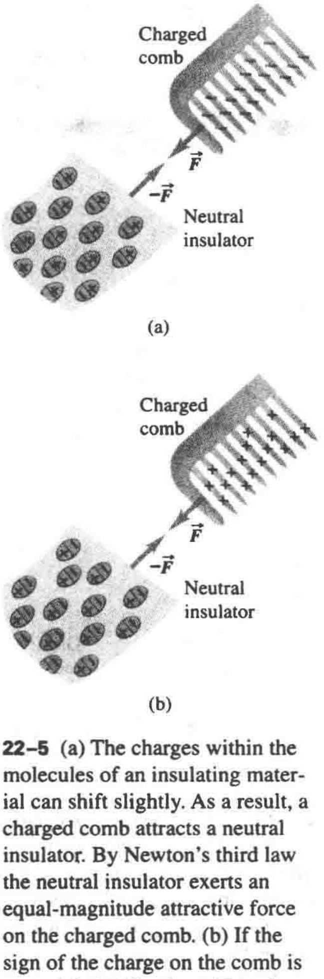
Not all of the free electrons move to the right surface of the sphere. As soon as any induced charge develops, it exerts forces toward the *left* on the other free electrons. These electrons are repelled by the negative induced charge on the right and attracted toward the positive induced charge on the left. The system reaches an equilibrium state in which the force toward the right on an electron, due to the charged rod, is just balanced by the force toward the left due to the induced charge. If we remove the charged rod, the free electrons shift back to the left, and the original neutral condition is restored.

What happens if, while the plastic rod is nearby, you touch one end of a conducting wire to the right surface of the sphere and the other end to the earth (Fig. 22–4c)? The earth is a conductor, and it is so large that it can act as a practically infinite source of extra electrons or sink of unwanted electrons. Some of the negative charge flows through the wire to the earth. Now suppose you disconnect the wire (Fig. 22–4d) and then remove the rod (Fig. 22–4e); a net positive charge is left on the sphere. The charge on the negatively charged rod has not changed during this process. The earth acquires a negative charge that is equal in magnitude to the induced positive charge remaining on the sphere.

Charging by induction would work just as well if the mobile charges in the spheres were positive charges instead of negatively charged electrons, or even if both positive and negative mobile charges were present. In a metallic conductor the mobile charges are always negative electrons, but it is often convenient to describe a process *as though* the moving charges were positive. In ionic solutions and ionized gases, both positive and negative charges are mobile.

Finally, we note that a charged body can exert forces even on objects that are *not* charged themselves. If you rub a balloon on the rug and then hold the balloon against the ceiling, it sticks, even though the ceiling has no net electric charge. After you electrify a comb by running it through your hair, you can pick up uncharged bits of paper with the comb. How is this possible?

This interaction is an induced-charge effect. In Fig. 22–4b the plastic rod exerts a net attractive force on the conducting sphere even though the total charge on the sphere is zero, because the positive charges are closer to the rod than the negative charges. Even in an insulator, electric charges can shift back and forth a little when there is charge nearby. This is shown in Fig. 22–5a; the negatively charged plastic comb causes a slight shifting of charge within the molecules of the neutral insulator, an effect called *polarization*. The positive and negative charges in the material are present in equal amounts, but the positive charges are closer to the plastic comb and so feel an attraction that is stronger than the repulsion felt by the negative charges, giving a net attractive force. (In Section 22–5 we will study how electric forces depend on distance.) Note that a neutral insulator is also attracted to a *positively* charged comb (Fig. 22–5b). Now the charges in the insulator shift in the opposite direction; the negative charges in the insulator are closer to the comb and feel an attractive force that is stronger than the repulsion felt by the positive charges in the insulator. Hence a charged object of *either* sign exerts an attractive force on an uncharged insulator. The attraction between a charged object and an uncharged one has many important practical applications, including electrostatic dust precipitators and attracting droplets of sprayed paint to a car body.



(a)

(b)

22–5 (a) The charges within the molecules of an insulating material can shift slightly. As a result, a charged comb attracts a neutral insulator. By Newton's third law the neutral insulator exerts an equal-magnitude attractive force on the charged comb. (b) If the sign of the charge on the comb is reversed, the charges within the insulator shift in the opposite direction, and the insulator is again attracted to the comb.

22–5 COULOMB'S LAW

Charles Augustin de Coulomb (1736–1806) studied the interaction forces of charged particles in detail in 1784. He used a torsion balance (Fig. 22–6a) similar to the one used 13 years later by Cavendish to study the much weaker gravitational interaction, as we discussed in Section 12–2. For **point charges,** charged bodies that are very small in comparison with the distance r between them, Coulomb found that the electric force is proportional to $1/r^2$. That is, when the distance r doubles, the force decreases to $\frac{1}{4}$ of its initial value; when the distance is halved, the force increases to four times its initial value.

The electric force between two point charges also depends on the quantity of charge on each body, which we will denote by q or Q. To explore this dependence, Coulomb divided a charge into two equal parts by placing a small charged spherical conductor into contact with an identical but uncharged sphere; by symmetry, the charge is shared equally between the two spheres. (Note the essential role of the principle of conservation of charge in this procedure.) Thus he could obtain one half, one quarter, and so on, of any initial charge. He found that the forces that two point charges q_1 and q_2 exert on each other are proportional to each charge and therefore are proportional to the *product* q_1q_2 of the two charges.

Thus Coulomb established what we now call **Coulomb's law:**

> **The magnitude of the electric force between two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.**

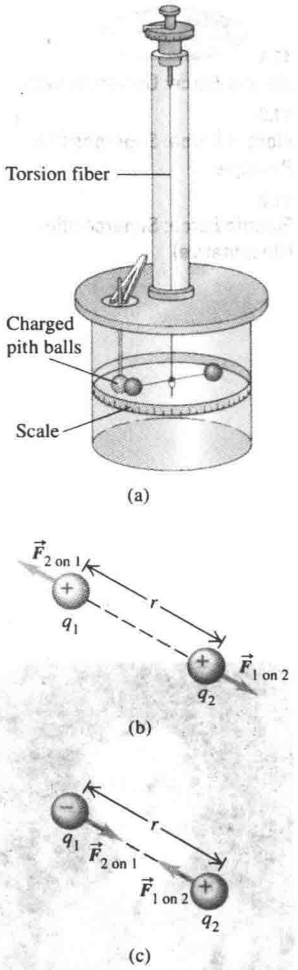
In mathematical terms, the magnitude F of the force that each of two point charges q_1 and q_2 a distance r apart exerts on the other can be expressed as

$$F = k\frac{|q_1q_2|}{r^2}, \tag{22-1}$$

where k is a proportionality constant whose numerical value depends on the system of units used. The absolute value bars are used in Eq. (22–1) because the charges q_1 and q_2 can be either positive or negative, while the force magnitude F is always positive.

The directions of the forces the two charges exert on each other are always along the line joining them. When the charges q_1 and q_2 have the same sign, either both positive or both negative, the forces are repulsive (Fig. 22–6b); when the charges have opposite signs, the forces are attractive (Fig. 22–6c). The two forces obey Newton's third law; they are always equal in magnitude and opposite in direction, even when the charges are not equal.

The proportionality of the electric force to $1/r^2$ has been verified with great precision. There is no reason to suspect that the exponent is anything different from precisely 2. Thus the form of Eq. (22–1) is the same as that of the law of gravitation. But electric and gravitational interactions are two distinct classes of phenomena. Electric interactions depend on electric charges and can be either attractive or repulsive, while gravitational interactions depend on mass and are always attractive (because there is no such thing as negative mass).



22–6 (a) A torsion balance of the type used by Coulomb to measure the electric force. (b) Electric charges of the same sign repel each other. (c) Electric charges of opposite sign attract each other. In each case the magnitude of the force on each point charge is proportional to the product of the charges and is inversely proportional to the square of the distance between them. The forces obey Newton's third law: $\vec{F}_{1\text{ on }2} = -\vec{F}_{2\text{ on }1}$.

The value of the proportionality constant k in Coulomb's law depends on the system of units used. In our study of electricity and magnetism we will use SI units exclusively. The SI electric units include most of the familiar units such as the volt, the ampere, the ohm, and the watt. (There is *no* British system of electric units.) The SI unit of electric charge is called one **coulomb** (1 C). In SI units the constant k in Eq. (22–1) is

$$k = 8.987551787 \times 10^9\ \mathrm{N \cdot m^2/C^2} \cong 8.988 \times 10^9\ \mathrm{N \cdot m^2/C^2}.$$

The value of k is known to such a large number of significant digits because this value is closely related to the speed of light in vacuum. (We will show this in Chapter 33 when we study electromagnetic radiation.) As we discussed in Section 1–4, this speed is *defined* to be exactly $c = 2.99792458 \times 10^8$ m/s. The numerical value of k is defined in terms of c to be precisely

$$k = (10^{-7}\ \mathrm{N \cdot s^2/C^2})c^2.$$

You may want to check this expression to confirm that k has the right units.