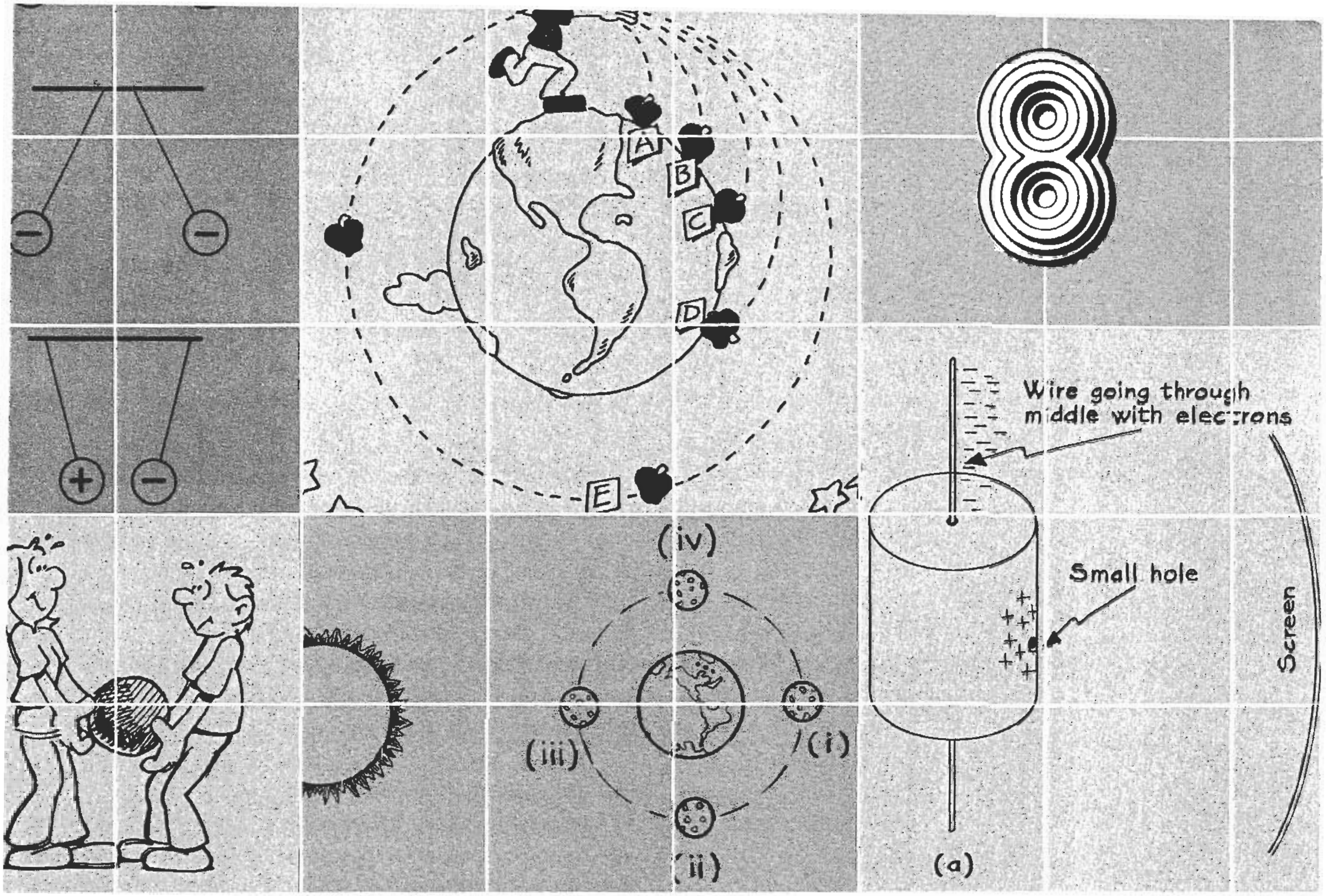


The Fundamental Interactions

To the North American Indians, the number four had magical properties, and they often classified things into groups of four. To Europeans, the magic number was three. The number seven, too, has been very significant in human legend and ritual. Psychologists suggest that seven is about the largest number of single bits of information we can process simultaneously. When we need to process more information, we lump seven bits into a larger bit and then process seven of those larger bits, and so forth.

The need to simplify seems almost instinctive. Faced with millions of life forms, biologists organize everything into five kingdoms: animal, plant, and three other kingdoms encompassing microscopic organisms. Faced with countless rocks, geologists organize the diversity they see into three groups: sedimentary, igneous, and metamorphic. Faced with the diversity of chemical elements, chemists organize the more than 100 elements into families and periods.

The drive to simplify has motivated physicists to look for just a few fundamental interactions that could embrace the enormous range of forces we experience daily. Physicists now identify just four mechanisms, called the *four fundamental interactions*, to explain all forces. These mechanisms are the *gravitational interaction*, the *electromagnetic interaction*, the *strong nuclear interaction*, and the *weak nuclear interaction*. In this chapter we examine each of these interactions, as well as current attempts to explain them in terms of a *unified theory of interaction*.

GRAVITATIONAL INTERACTIONS

In 1665, the Great Plague killed 10% of the population of London. By the fall of that year, fears that the disease would spread further caused officials to close the University of Cambridge, sending students and faculty home until the plague had run its course. One young student of mathematics, Isaac Newton, returned to his parents' home in rural Lincolnshire.

Legend relates that Newton's great inspiration came as he was resting under an apple tree on his parents' farm, contemplating the moon's motion. Why, he asked himself, does the moon revolve around the earth? How can its motion be explained? As Newton pondered, an apple fell beside him. Suddenly he realized the answer. Gravity! The moon revolves about the earth for the same reason that the apple falls to the ground. This realization, it is said, led Newton to propose the law of universal gravitation.

While an apple tree does grow near Newton's childhood home today, we do not know whether the story is true. Years later, when Newton described his work on universal gravitation to a friend, he used the falling apple to draw an analogy between the moon's motion and the motion of objects near the surface of the earth. So perhaps the apple really had been his inspiration. Regardless, the legend helps us understand how seemingly different motions can be linked by a single interaction—gravitation.

Satellites and Gravity

We can understand Newton's analogy between falling objects and the moon's orbit by considering Figure 8-1. Suppose you drop an apple. It accelerates downward along path A, landing directly beneath where you released it. Now suppose that instead of dropping the apple, you toss it away. The apple accelerates downward as before; but it also travels outward away from you, as shown by path B. Now throw the apple harder (path C). It lands even farther from you. The harder you throw the apple, the farther away from you it lands.

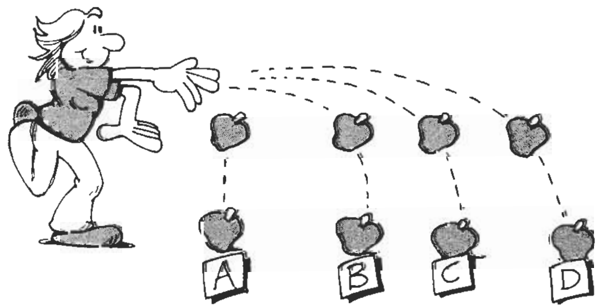


Figure 8-1
The harder you throw the apple, the farther away from you it lands.

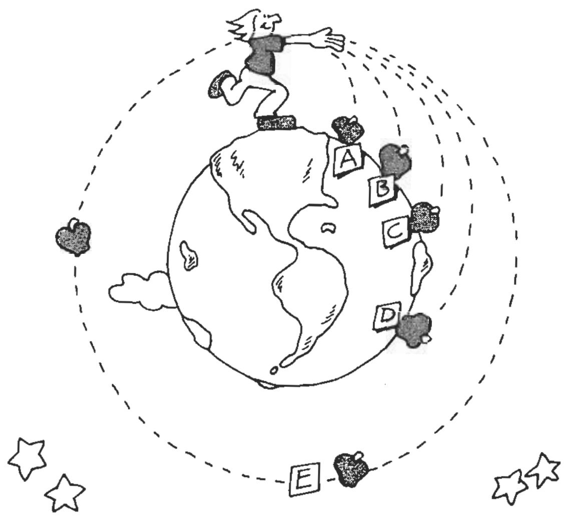


Figure 8-2
If we could actually throw the apple hard enough, it would miss the earth entirely. The apple would continue falling but would never quite catch up with the curvature of the earth.

If the surface of the earth were flat, there would be little more to say. The distance the apple travels outward before hitting the ground would simply depend on how hard you threw it. Since the earth is curved, however, the apple falls just a bit further each time it is thrown, as shown in Figure 8-2. The vertical distance it must travel increases because of the earth's curvature. If we could throw the apple hard enough so that it traveled from North America to, for instance, Africa (path D), it would have an enormous drop before hitting the ground. If we could throw it even harder still, it would eventually miss the earth entirely (path E). The apple now keeps falling and falling, but it never quite catches up with the earth's surface. Your apple behaves like the moon.

With this analogy, Newton conceived the artificial satellite 300 years before technology was advanced enough to launch one. He concluded that the same gravitational interaction that causes an apple to fall holds the moon in its orbit. With no horizontal velocity, the apple falls directly beneath its tree. With a horizontal velocity of over 1000 meters per second (m/s), the moon continues to fall toward the earth in an orbit 3.8×10^8 meters (m) above the earth's surface. The downward force of gravity becomes the centripetal force needed to hold the moon in its orbit about the earth. We can use the same concept to explain the motion of the earth around the sun. Just as the moon falls toward the earth, the earth falls toward the sun. Gravitational attraction holds our planet in orbit, just as it holds all the other planets, moons, and comets of the solar system.

Law of Universal Gravitation

Having realized that a single type of force, gravitation, is responsible for the acceleration of heavenly bodies as well as the downward acceleration of objects on earth, Newton developed a complete definition of the gravitational force. He found that the force increased as the mass of either object increased and as the objects came closer together. More precisely, the gravitational force is directly proportional to the masses of the two objects and inversely proportional to the square of the distance separating them. To calculate gravitational

Gravitational constant (6.67×10^{-11} N·m²/kg²)

Mass 1

Mass 2

$$F_{1\text{-}2} = G\,\frac{m_1 m_2}{r_{1\text{-}2}^2}$$

Gravitational force between mass 1 and mass 2

Distance separating mass 1 and mass 2

force, Newton used a constant, $G = 6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2$, to convert units of mass and distance into units of force. The **law of universal gravitation** states that the magnitude of the force is:

$$\begin{array}{c}\text{Force of gravity}\\ \text{exerted on 1 by 2}\end{array} = G\,\frac{(\text{mass}_1)(\text{mass}_2)}{(\text{distance between 1 and 2})^2}$$

The force acts along a line joining the centers of the two objects. When object 2 pulls object 1 toward it, object 1 pulls object 2 toward it.

We can gain some insight into this law by using it to determine the size of the gravitational force exerted on the apple by the earth. The earth's mass is 5.98×10^{24} kilograms (kg). A very large apple would have a mass of about 1 kg. The distance separating the apple and the earth is taken to be the distance between their centers—approximately the radius of the earth, 6.38×10^6 m. (The distance from the earth's surface to the apple is too small to make any detectable difference.) Substituting these values into the law of universal gravitation, we find that the force on the apple is $(6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2)(1\ \text{kg})(5.98 \times 10^{24}\ \text{kg})/(6.38 \times 10^6\ \text{m})^2 = 9.8$ N, toward the earth. The earth pulls the apple toward its center with a force of 9.8 N. If either the earth or the apple were twice as massive, the gravitational force exerted on the apple would be twice as great. If we moved the apple out into space, so that it was twice as far away from the center of the earth, the gravitational force exerted on it would be one-fourth as great. Three times as far away, the gravitational force exerted on the apple would be one-ninth as much (Figure 8-3).

Acceleration

Force

$$a = \frac{F}{m}$$

Mass

Newton's third law assures us that if the earth attracts the apple, then the apple attracts the earth with a force equal in magnitude but opposite in direction. The law of universal gravitation provides us with the magnitude of both forces. The earth exerts a force of 9.8 N on the 1 kg apple. The apple exerts a force of 9.8 N on the earth. The acceleration experienced by each object as a result of these forces, however, depends on the object's mass. With a mass of 1 kg, the acceleration experienced by the apple is (9.8 N, down)/(1 kg) = 9.8 (m/s)/s, down. With a mass of 5.98×10^{24} kg, the earth experiences an acceleration equal to (9.8 N, up)/(5.98×10^{24} kg) = 1.6×10^{-24} (m/s)/s, up. The apple experiences an acceleration of 9.8 (m/s)/s, down, while the earth experiences an acceleration of 1.6×10^{-24} (m/s)/s, up. The earth's acceleration is much too small to notice.

SELF-CHECK 8A

Use the law of universal gravitation to calculate the gravitational force you exert on a table. Assume that your mass is 70 kg, the table's mass is 5 kg, and that you and the table are separated by 2 m. The earth exerts a gravitational force of 49 N, down, on the table. How does the force you exert on the table compare to that of the earth?

A STEP FURTHER—MATH

WHAT IS IT LIKE ON MARS?

Newton's law of universal gravitation allows us to predict the acceleration due to gravity on planets other than Earth. Newton's second law tells us that the magnitude of the force due to gravity (F_g) acting on an object of mass (m) is

$$F_g = mg$$

where g is the acceleration due to gravity. Newton's law of universal gravitation describes the magnitude of the force due to gravity (F_g) in terms of the mass of the planet (M), the mass of the object (m), and the radius of the planet (r):

$$F_g = G\frac{Mm}{r^2}$$

If we set these two expressions for the force due to gravity equal to each other,

$$F_g = F_g$$

$$mg = G\frac{Mm}{r^2}$$

$$g = G\frac{M}{r^2}$$

we find that the acceleration due to gravity, g, depends on the mass of the planet (M) and the radius of the planet (r).

To check to see if this relationship really works, let's calculate the acceleration due to gravity on earth. The earth's mass is 5.98×10^{24} kg and its radius is 6.38×10^6 m. Substituting these values into the relationship derived above:

$$g = G\frac{M}{r^2} = 6.67 \times 10^{-11}\frac{\text{N} \cdot \text{m}^2}{\text{kg}^2}\frac{(5.98 \times 10^{24}\text{ kg})}{(6.38 \times 10^6\text{ m})^2}$$

$$= 9.8\ (\text{m/s})/\text{s}$$

Newton's law of universal gravitation predicts the same value for the acceleration due to gravity as the measured value!

Now let's head out to Mars. Mars has a mass of 6.34×10^{23} kg and a radius of 3.43×10^6 m. What is the acceleration due to gravity at the surface of Mars?

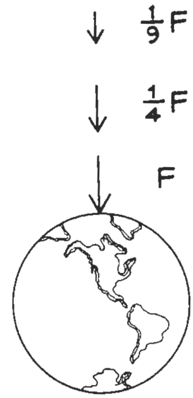


Figure 8-3
The gravitational force decreases quickly as we move away from the earth. Twice as far from the earth, the apple feels one-fourth the gravitational force. Three times as far away, the apple feels one-ninth the gravitational force.

The Future of the Universe

Gravity plays a major role in building models of the universe. The most widely accepted model of the universe is the **big bang model**. According to this model, all the matter in the universe was concentrated in an unimaginably small amount of space. Some 20 billion years ago an explosion, called the big bang, sent matter flying off in all directions. In some regions of space, the concentration of matter became high enough to allow gravitational forces to form planets, stars, and galaxies. These are the objects we see in the sky today. Other regions of space were very sparsely populated with matter, so bits of matter simply continued to move away from the point at which the big bang occurred. This matter makes up the interstellar dust and debris astronomers often mention.

The future of the universe depends on a struggle being waged daily between the outward motion that originated with the big bang and the inward forces due to gravitational attractions between masses. At present, all matter—the interstellar dust and the planets, stars, and galaxies—continues to move apart. If the gravitational forces that exist are large enough, this expansion will gradually come to a stop and the masses will once again be drawn back together. If the gravitational force is too weak, the universe will continue to expand forever.

Ultimately, the size of the gravitational force that exists depends on the amount of mass in the universe. Using Newton's law of universal gravitation, astronomers estimate that a minimum of 10^{-30} kg of mass per cubic meter of space is required to stop the present expansion. At present, the average known mass per cubic meter in the universe is less than this—about 10^{-31} kg/m^3. What is not known, however, is the amount of matter present in the interstellar dust and debris that we simply cannot see. This debris holds the key to our knowledge of the future of the universe.

ELECTROMAGNETIC INTERACTIONS

As humankind went about looking for problems to solve, it happened upon static cling. Clothes, particularly those made from synthetic fibers, stick together after being tumbled in a clothes dryer. Socks seem forever bound to shirts; pants wrap themselves tightly around your legs. An equally serious crisis is fly-away hair. Vigorous brushing, particularly during winter months, leads to hair that stands out on end. Rather than clinging to one another, the individual strands fly apart.

These experiences are modern examples of what the Greeks had noticed with amber, the hardened sap from some softwood trees. When the Greeks polished amber by rubbing it vigorously with a cloth, it attracted small bits of straw, paper, or seed. The amber exerts a force large enough to overcome the force due to gravity, pulling the bits of paper upward. To the Greeks, this effect seemed magical. Today we explain it in terms of electrical interactions which we have named from the Greek word *elektron*, meaning amber.

Experiments performed during the nineteenth century revealed that electrical interactions and magnetic interactions are related. Magnetism, also known to the Greeks, displays some of the same seemingly magical properties of acting across a distance. Our present model of forces unites electrical and magnetic phenomena under a single term—electromagnetic interactions. Here we will discuss only examples of electrical interactions; we consider electromagnetic phenomena further in later chapters.

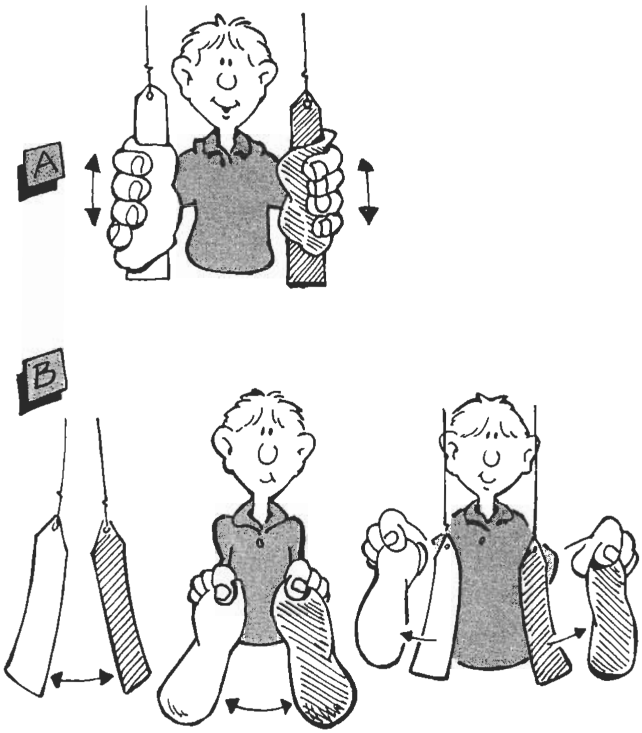


Figure 8-4

Each plastic strip has been rubbed with its cloth. The two plastic strips repel each other. The two cloths repel each other. Each plastic strip attracts a cloth.

Rubbing Leads to Electrical Interactions

The Greeks rubbed amber as they polished it. Clothes rub against one another in the dryer. Bristles rub against strands of your hair as you brush them. It seems that rubbing things can cause them either to stick together or fly apart. Let's examine this phenomenon in more detail.

We begin with a system consisting of a plastic strip and a piece of cloth. Before we do anything to them, no interaction occurs between them. If we now rub the plastic strip with the cloth, they attract one another. This attraction must have been produced by the rubbing. We conclude that the rubbing transferred something between the plastic strip and the cloth. This "something" leads to the attraction we observe.

Now consider two identical systems, each consisting of a plastic strip and a piece of cloth. Before the strips are rubbed with the cloth, no interaction occurs within either system or between the two systems. After each plastic strip is rubbed with its cloth, the two plastic strips repel each other, the two pieces of cloth repel each other, and either piece of cloth attracts either plastic strip (Figure 8-4). Whatever is exchanged between each plastic strip and its cloth during the rubbing process can cause an interaction not only between objects within a system but also between objects in systems that are initially isolated from one another.

We conclude that a force, which we call an electrical force, results from rubbing two objects together. In an isolated system, the initial interaction of the two objects (rubbing) results in a force of attraction between them. In a nonisolated system, the initial interactions can result both in forces of attraction and forces of repulsion.

Electrical Charge and Static Electricity

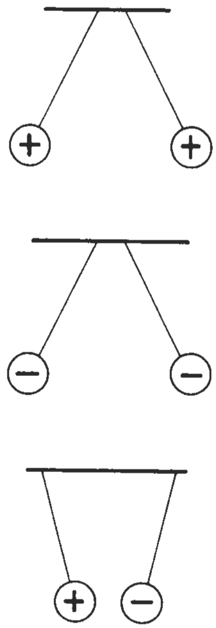


Figure 8-5
Like charges repel; unlike charges attract.

In some ways, electrical interactions are remarkably similar to gravitational interactions. Both involve interactions at a distance. Both involve attractive forces. Mass is associated with gravitational force; something else must be present in order for electrical interactions to occur. This thing is a property of matter called **electrical charge,** measured in units called **coulombs** (C). Because we see both attractive and repulsive forces, two types of electric charge must exist. By convention, these two types of charge are called **positive** (+) and **negative** (−).

Electrical interactions occur only when electrical charges are present. The rubbing process somehow results in electrical charges on the two rubbed objects. Two possibilities exist: (1) rubbing creates electrical charge from nothing, or (2) rubbing causes the objects to exchange electrical charge. Creating something from nothing violates our basic belief in conservation. So, we imagine that the rubbing process moves electrical charge from one object to another. When one of the objects becomes positively charged, the other becomes negatively charged to the same degree, so that the total charge of the system remains constant. In a closed system, electrical *charge is conserved.*

In its normal state, matter has an equal number of positive and negative charges. The sum of these charges, or the net charge of the object, is zero. Before rubbing, each object (the plastic strip and the cloth) has a zero net charge, and no electrical interaction occurs between them. During the rubbing process, electrical charge is moved from one object to another. In this case, negative charges are rubbed off the cloth and transferred to the plastic strip. The plastic strip then has more negative charge than positive charge, giving it a net negative charge. The cloth, having lost negative charges to the plastic strip, has an excess of positive charge—a net positive charge. The attraction between the cloth and the plastic strip arises from their net electrical charges. As shown in Figure 8-5, objects with opposite net charges (one positive and one negative) attract one another. Objects with the same net charge (both positive or both negative) repel one another. Like charges repel; unlike charges attract. All these attractions and repulsions are examples of static electricity—the interaction of localized regions of net positive and net negative charge.

SELF-CHECK 8B

When rubbed with silk, a glass rod becomes positively charged.

a. Does the silk cloth have a net charge? If so, is it positive or negative?

b. Will the glass rod attract or repel the plastic strip in Figure 8-4?

Coulomb's Law

The similarities between electrical interactions and gravitational interactions led Joseph Priestley (1733–1804) to hypothesize that the electrical force law was similar to Newton's law of universal gravitation. He expected the size of the electrical force to change with the size of the electrical charge on the two objects and with the distance between the centers of the two objects. We can examine the qualitative effect of both these variables, amount of charge and distance between centers, in a simple experiment with a comb and paper.

To observe the effect of charge, rub a comb through your hair a few times; then place your comb near some bits of paper and watch how strongly they are attracted. Now rub the comb through your hair a few more times. Increasing the rubbing should increase the net charge on the comb. Now when you place the comb near some bits of paper, watch the paper jump. The force of attraction is much greater. The electrical force increases as the net charge on the comb increases. (If you are wondering why a comb with a net electrical charge attracts paper with no net charge, work Problem C6.)

We can examine the way in which electrical force varies with distance by charging the comb again and holding it at various distances from the bits of paper. When the comb is relatively far from the paper, no interaction seems to occur. The electrical force is not large enough to overcome the gravitational force holding the paper to the table. As the comb is brought nearer to the paper, we see an interaction. The electrical force increases until it is large enough to overcome the gravitational force. The paper jumps to the comb. As the separation between the comb and the bits of paper decreases, the electrical force between them increases.

A careful study of these two variables, net charge and separation between the objects, was first completed by Benjamin Franklin. However, Franklin's interests turned to politics, and the equation defining the electrical force was discovered by Charles Coulomb in 1789. Called **Coulomb's law,** this equation states that the electrical force that one charged object exerts on a second charged object is directly proportional to the product of the two net charges and inversely proportional to the square of the distance between the two objects. To calculate the electrical force, Coulomb used a constant, $k = 9 \times 10^9 \ \mathrm{N \cdot m^2/C^2}$, to convert units of charge and distance into units of force. The relationship between the magnitude of the force and charge is

$$\begin{matrix}\text{Force exerted on} \\ \text{object 2 by object 1}\end{matrix} = k \frac{\text{(charge 1)(charge 2)}}{\text{(distance between 1 and 2)}^2}$$

Constant = 9×10^9 N·m²/C²

Charge of object 1

Charge of object 2

$$F_{1-2} = k \frac{q_1 q_2}{r_{1-2}^2}$$

Electrical force between objects 1 and 2

Distance between two objects

The direction of the force depends on the two charges. If charge 1 and charge 2 are the same (both positive or both negative), the force is positive and object 1 repels object 2. If charge 1 and charge 2 are different (one positive and the other negative), the electrical force is negative and object 1 attracts object 2. Newton's third law tells us that if object 1 attracts object 2, then object 2 will attract object 1 with a force of equal magnitude; likewise, forces of repulsion will be equal. The two charged objects exert mutual forces on one another.

Coulomb's law has exactly the same *form* as Newton's law of universal gravitation. Electrical charge has replaced mass. Two types of electrical charge result in two types of electrical force—attraction and repulsion. One type of mass results in one type of gravitational force—attraction. You can imagine the elation among physicists as they discovered a second interaction that behaved in almost exactly the same fashion as gravitation.

SELF-CHECK 8C

> **Each of the plastic strips in Figure 8-4 has a net charge of 10^{-7} C. What is the force that one strip exerts on the other if the two strips are separated by 10 m? By 1 m? By 0.01 m?**

Probing the Atom

Figure 8-6
Charges could be distributed in the atom in two ways: **(a)** evenly, or **(b)** in charge concentrations.

The properties of the electrical interaction provide us with a powerful tool for investigating the structure of matter. By the turn of the twentieth century, physicists knew that matter could be broken down into atoms and that atoms contained both positive and negative charges. What remained a mystery, however, was how these charges were distributed. The charges could be randomly distributed throughout the atom or they could be concentrated in densely positive and negative regions (Figure 8-6). Ernest Rutherford and his students resolved this question by shooting positively charged particles toward thin sections of gold.

The positively charged particles, called alpha particles, are given off spontaneously by certain atoms. They are small enough to penetrate thin sections of matter, and since they are electrically charged, their motion could reveal the distribution of electric charge in matter. Let's examine how the alpha particles would behave in each of the models proposed for the atom (Figure 8-7).

First, suppose that the electrical charges are randomly distributed throughout the atom. As the alpha particles move through the gold foil, they would constantly experience both attraction and repulsion. The two forces would generally balance out and there would be no net force on the alpha particles. They would move almost straight through the gold foil (Figure 8-7(a)).

Now suppose that the electrical charge in matter is concentrated in densely positive or densely negative regions. In this case, the motion of the alpha particles would depend on the relative mass of the charge concentration. If the charge concentrations have about the same mass as the alpha particles, then Newton's second and third laws require that they accelerate equally as a result of the electrical interaction between them. But if the concentrations of electrical charges are much more massive than the alpha particles, then only the alpha particles would change their motion measurably. Figure 8-7(b) shows the various paths predicted when the alpha particles approach fairly massive, positively charged regions. If the alpha particles approach head-on, the repulsive force would slow them to a stop and send them back along the same path. If slightly off center, the alpha particles would move on by but would be deflected from their original courses. At a large

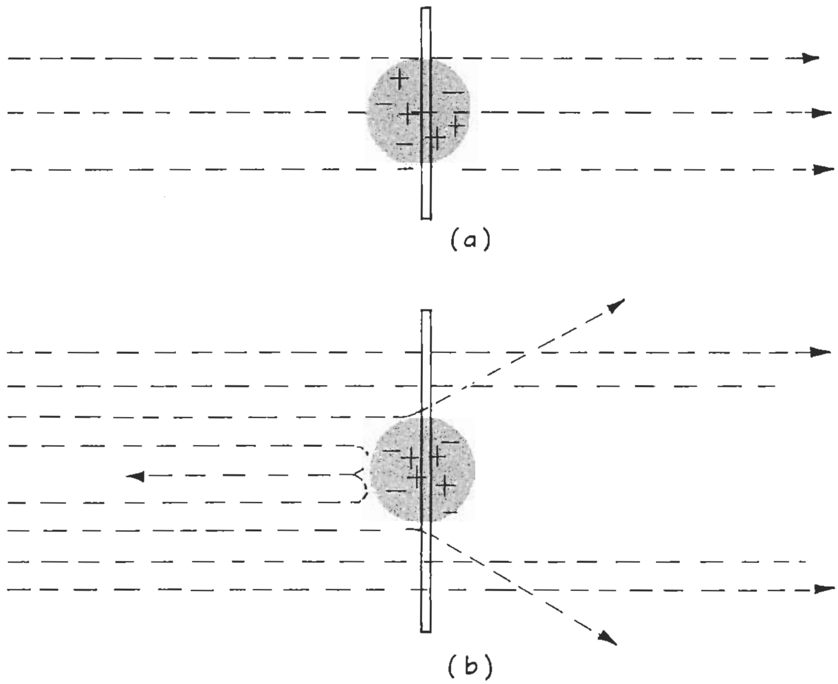


Figure 8-7
The paths followed by the alpha particles depend on the way in which electrical charge is distributed in the atom. **(a)** When the electrical charges are evenly distributed, the alpha particles continue along their original paths. **(b)** When the alpha particles encounter massive charge concentrations, some alpha particles will be deflected at large angles.

enough distance, the repulsive force would be too small to affect the alpha particles, which would continue moving along their original paths.

When he actually performed the experiment, Rutherford saw the patterns shown in Figure 8-7(b). Most of the alpha particles went through the gold foil undeflected, but a few were repelled at large angles. Still fewer were actually reflected—bounced back along their initial path. Only fairly massive concentrations of positive charge could explain these reflected alpha particles. Rutherford concluded that the gold foil contained massive regions of positive charge that were relatively far apart. The negative charges were probably scattered randomly through the foil. By applying his knowledge of Newton's laws and electrical interactions, Rutherford was able to construct a picture of the atom, an object far too small to see directly.

Rutherford's experiment and Coulomb's law provided the basis upon which the first workable model of the atom was built. As a result of Rutherford's discovery of massive concentrations of positive charge, Niels Bohr suggested that atoms are like miniature solar systems. A massive particle at the center, called the **nucleus,** is positively charged. Many small particles, called **electrons,** circle the nucleus much as planets circle the sun. The electrons are negatively charged; consequently they are held in orbit by the electrical force of attraction exerted by the nucleus. Atoms contain enough electrons to balance the positive charge of the nucleus, so each atom is left with zero net charge.

Bohr's model fit Rutherford's experimental results and prior experience with static electricity. The small, massive, positively charged nucleus causes alpha particles to rebound like tennis balls off a brick wall. The negatively charged electrons in orbit about the nucleus produce a fairly random distribution of negative charge in matter. Since the electrons have very small masses, they can be transferred from one object to another as a result of rubbing. This leaves one object positively charged and makes the other object negatively charged. Eventually Bohr's model gave way to a more sophisticated one, but the major features of negatively charged electrons with small masses and positively charged nuclei with large masses have remained unchanged.

NUCLEAR INTERACTIONS

Rutherford's experiment revealed the existence of the nucleus—a small, relatively massive, positively charged part of matter. Naturally enough, the next question asked was: What is inside the nucleus? Experiments with natural radioactivity provided part of the answer, and experiments similar in design to Rutherford's actually allowed physicists to penetrate the nucleus. By the 1930s, two additional particles—the **proton** and the **neutron**—had been found in matter. These two particles, collectively called **nucleons,** were found to exist in the nucleus. Table 8-1 summarizes the mass and electric charge of these two particles and the electron.

Subsequent research on the atomic nucleus has led physicists to believe that two more fundamental interactions, strong and weak nuclear interactions, exist in addition to gravitational and electromagnetic interactions. The strong nuclear interaction describes the mechanism that holds the nucleus together. The weak nuclear interaction describes a way in which the nucleus sometimes falls apart. Since research that probes the nucleus is a scant 50 or 60 years old, we still have much to learn.

Strong Nuclear Interactions Bind the Nucleus Together

Atoms have a diameter of about 10^{-8} to 10^{-10} m. The nucleus occupies a tiny fraction of this space—its diameter is estimated to be only about 10^{-14} m. Once physicists realized that the nucleus contains protons and neutrons, an interesting contradiction arose. Protons are positively charged; neutrons carry no electrical charge. Atoms consist of anywhere from 1 to over 100 protons and 0 to about 150 neutrons. We know that gravitational interactions exist among all these particles, but this interaction is very small (see Problem 8-B5).

Table 8-1 The Constituents of the Atom

Particle	Electrical Charge (C)	Mass (kg)
Electron	-1.6×10^{-19}	9.11×10^{-31}
Proton	$+1.6 \times 10^{-19}$	1.672×10^{-27}
Neutron	0	1.675×10^{-27}

Thanks to Electrical Charge . . .

The crackle and snap of static electricity is the most obvious example of electrical interactions in our everyday life. However, because all matter is composed of electrically charged particles, many other common interactions are electrical in nature. For example, electrical interactions within and between atoms are responsible for nearly all contact interactions—the forces you exert with your body, the force of friction offered by surfaces, the reaction forces provided by solid surfaces.

The electrical interactions that hold atoms and molecules together provide the resistance we have called a reaction force. When you push on a table, the molecules in your hand interact with the molecules of the table. Your hand is trying to push through the table. However, the only way for the table to give would be for these electrical interactions between atoms to break. They resist being pulled apart, so you feel a hard surface. Electrical forces form almost a miniature net—giving slightly but never enough to let you slip through.

For gases and liquids, the electrical interactions among molecules are not as strong as they are among the molecules of solids. An object can break the weak electrical forces holding a molecule to its neighbors. Thus, you can move through liquids and gases but not solids.

The frictional force that arises when one object moves along another also results from electrical interactions. When one object touches another, its molecules become distorted because of electrical forces from molecules of the neighboring object. These forces cause changes in the motions of the molecules in each object. Because the molecules move randomly in all directions, these forces do not cause motion of the whole object. Instead, these electrical forces are the force we call friction.

These electrical interactions can differ in strength. Anyone who has tried to move a heavy object knows that it takes more force to get the object moving than to keep it moving. We say that static friction is greater than moving friction. We can explain these observations in terms of electrical attraction between the object and the floor, for example. When an object sits in one place, even for a short time, some of its atoms "sink" into the floor. Because the atoms of the object and floor are now closer together, it takes more force to break their mutual electrical forces than when the atoms are moving past one another. Because of a decrease in distance, static frictional forces are greater than moving frictional forces.

Electrical forces sometimes cause atoms to be transferred from one object to another. Each time an automobile tire rotates, one layer of rubber molecules is actually "ripped" from the tire and left on the pavement. Take a step and you leave a bit of shoe leather behind. The electrical force required to transfer these atoms is the force we call friction.

Thanks to electrical charge, we can take that step forward, push that chair out of the way, or not fall through the floor. Electrical forces are, in fact, the glue that holds us all together.

Because of their electrical charge, however, protons should repel one another. Coulomb's law predicts a force of 2.3 N between two protons separated by the diameter of the nucleus. While this force does not seem very large, it will produce enormous accelerations (1.4×10^{27} (m/s)/s) on masses as small as protons. If gravitational forces are too small to hold the nucleus together and enormous electrical forces are driving the protons apart, just what is it that keeps the nucleus together?

Physicists believe that a third type of interaction, called the **strong nuclear interaction,** holds the nucleus together. Like electrical forces, the strong nuclear force can be either attractive or repulsive. Its range of effectiveness, however, is very limited. Beyond separations of 10^{-12} m, the strong nuclear force is, for all practical purposes, zero and electrical forces dominate all interactions. Within a distance of 10^{-12} m, however, the strong nuclear force produces an interaction between protons that is 100 times as great as the electrical force of repulsion at that same separation. At separations between 10^{-12} and 10^{-16} m, protons attract protons, neutrons attract neutrons, and protons attract neutrons. Within still shorter distances, 10^{-16} m or less, the strong nuclear force becomes repulsive and the nucleons all repel one another. Consequently, the nucleus does not collapse on itself.

Weak Nuclear Interactions

Even before Rutherford discovered the nucleus, Henri Becquerel and Marie and Pierre Curie had seen the results of nuclei falling apart. Some materials spontaneously emit electrically charged particles, collectively called radioactivity. Some radioactive emissions eventually were explained in terms of electrical interactions between protons. Too many protons packed into too small a space can result in an electrical repulsion large enough to cause the nucleus to fly apart, emitting some of its nucleons. Other emissions could not be explained so easily.

One emission that seemed particularly difficult to explain involves the neutron. A neutron left by itself will spontaneously turn into a proton, an electron, and a third particle called an antineutrino. These particles have electric charges of plus, minus, and zero, respectively. When this happens within the nucleus, the electron and antineutrino are ejected, while the proton remains inside. Neither electrical nor strong nuclear forces shed any light on why the neutron disintegrates.

The disintegration of the neutron and a variety of other nuclear interactions can be explained only if we introduce another interaction—the **weak nuclear interaction.** For many years this interaction has been the least understood of the four fundamental interactions. We will do little more here than simply list it among the fundamental interactions.

INTERACTION AT A DISTANCE

The introduction of the two types of nuclear interactions brings the number of fundamental interactions to four. All four are described as interactions at a distance. Objects exert forces on one another but do not actually touch. While

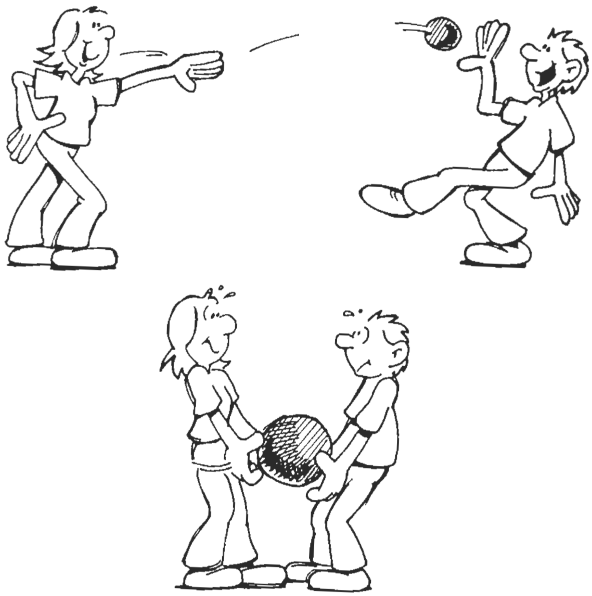


Figure 8-8
Seen from afar, a game of catch might look like interaction at a distance. The more massive the "ball," the stronger the force.

we are able to explain many observations in terms of interaction at a distance, we have not approached the question: How does an object *here* "communicate a force" to an object *there*? To address that question, we begin with an analogy.

Interaction at a Distance and a Game of Catch

Suppose you and a friend play a game of catch. The two of you stand several meters apart and throw a baseball back and forth. The distance between you and your friend will depend on your ability to throw, but it will never exceed some practical maximum. You and your friend will remain in some well-defined region of space.

Imagine how this game would look to observers who are close enough to see the two players but not the ball. The players would move about, sometimes moving closer together but never going farther apart than some maximum throwing distance (Figure 8-8). Being unable to see the ball, the observers might conclude that an attractive force holds the two players near one another. While the exact nature of the force would not be clear, it could explain both your friend's and your behavior.

Now imagine how the game would look if you played with balls of vastly different masses—for instance, a baseball and a bowling ball. In order to play catch with a bowling ball, you and your friend would have to stand rather close to one another. The observers would report a force with a very small range. By contrast, you and your friend could stand much farther apart if you played with a baseball. The observers would report a force with a much larger range. The range of the force seen by the observers is related to the mass of the ball you use to play catch. As the mass of the ball increases, the range of the force decreases.

Forces and the Exchange of Particles

The game of catch is analogous to an explanation, first suggested by H. Yukawa in the 1930s, of how the strong nuclear interaction works. Yukawa suggested that the strong nuclear force arises from the exchange of a particle between nucleons. From the known range of the strong nuclear force, Yukawa calculated the mass of this supposed particle, which he called the **pi-meson** or **pion,** to be about one-seventh the mass of the nucleon. Such a particle had never been seen when he offered this explanation, but shortly thereafter it was detected. Yukawa had been right.

The discovery of the pion led to a generalization of Yukawa's model to the other three fundamental interactions. In each case, an **exchange particle** can be used to explain the process by which objects exert forces on other objects across a distance. The mass of the exchange particle determines the range of the interaction.

Both gravitational and electrical interactions extend over all space. Newton's law of universal gravitation and Coulomb's law both predict that the forces become increasingly smaller as the separation between objects increases, but neither force actually reaches zero. For a force to extend over an infinite distance, the exchange particle must have zero mass. Such a particle, called the **photon,** has been discovered in electrical interactions. The photon has no mass, but it can move between electrically charged objects. The exchange particle for gravitational interactions, called the **graviton,** has yet to be detected. Like the photon, the graviton must have zero mass. In order to explain gravitational interactions, the graviton must be exchanged by all objects having mass.

The weak nuclear interaction presents a different situation. The range of the weak nuclear interaction is known to be quite short, on the order of 10^{-17} m. If our model of exchange particles is correct, then the exchange particle for these interactions, called the **W,** must have a mass considerably larger than the pion. In January 1983 experimenters announced that such a particle had been detected. A summary of the four interactions, their rela-

Table 8-2 The Fundamental Interactions

Interaction	Relative Strength	Approximate Range (m)	Exchange Particle	Mass of Exchange Particle (kg)
Strong nuclear	100	10^{-15}	Pion	2.5×10^{-28}
Electromagnetic	1	No limit	Photon	0
Weak nuclear	10^{-11}	$<10^{-17}$	W	$>1.5 \times 10^{-25}$
Gravitational	10^{-40}	No limit	Graviton*	0

*The graviton has not yet been observed.

tive strengths, their ranges, their exchange particles, and the mass of each particle is given in Table 8-2. The electromagnetic force is arbitrarily assigned a strength of 1. The strong nuclear force is 100 times greater, the weak nuclear force only 10^{-11} as large, and so forth.

A Unified Theory of Interactions

The four fundamental interactions and their properties have been known since the discovery of the pion in the 1930s. In recent years, new particles ranging in mass from zero to several times the mass of the nucleon have been discovered. In all cases the forces among these particles could be explained in terms of the four fundamental interactions.

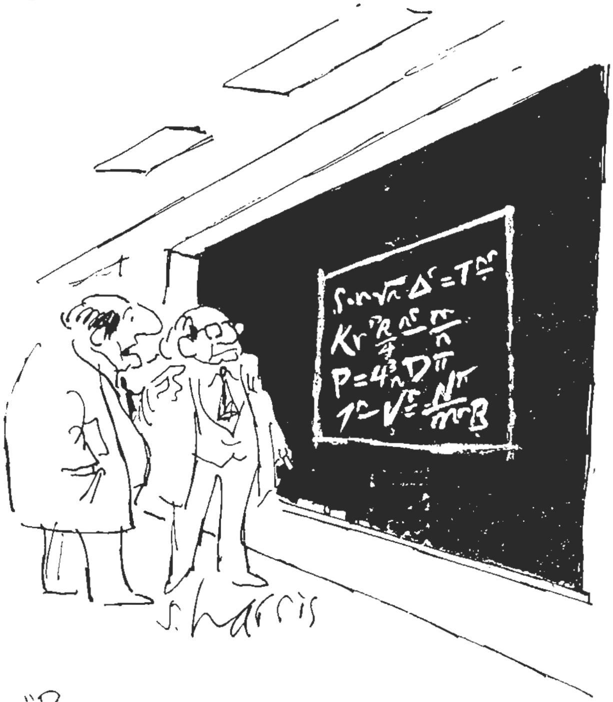
The reduction of a multitude of forces to four interactions provides a remarkably simple model of events. Yet, we might hope for an even simpler picture. The uncanny similarity between Newton's law of universal gravitation and Coulomb's law led to speculation that these two interactions are somehow variations of a single interaction. Albert Einstein spent a major portion of his life unsuccessfully trying to unify these two interactions. The discovery of the pion and a host of other particles smaller than either protons or neutrons has led to a new attack on the question of a unified theory of interactions.

Once considered a single unit, matter was eventually broken down into atoms. Atoms, in turn, were broken down into protons, neutrons, and electrons. Naturally, physicists wondered whether these particles could be broken down into still smaller particles. In the 1960s, a major theory proposed that nucleons (protons and neutrons) are composed of three smaller, charged particles called **quarks,** held together within each nucleon by the strong nuclear force. To date, no one has been able to "pull" a quark out from inside the nucleon. However, experiments similar in design to Rutherford's show three distinct locations of electric charge within each nucleon. Consequently, the quark model is regarded quite seriously.

In contrast to protons and neutrons, the electron seems to be a fundamental entity. Nothing suggests that it can be broken down into still smaller particles. However, a number of particles similar to electrons have been discovered. For example, the positron has the same mass as the electron, but it has a positive electric charge. Taus and muons behave like electrons but have larger masses. Together with still other similar particles, electrons, positrons, taus, and muons form a family of particles called **leptons.**

With quarks and leptons as the fundamental particles, physicists are now looking for a single interaction that unifies strong nuclear, weak nuclear, and electrical interactions. This single interaction is believed to act at distances less than 10^{-31} m. According to this unified theory of interaction, exchange particles, called X particles, move among quarks and leptons. At distances greater than 10^{-31} m, the X particle is replaced by pions, W particles, and photons; consequently, we see three separate interactions: strong nuclear, weak nuclear, and electrical interactions. (The gravitational interaction remains unreconcilable in this model.)

The success of a **unified theory of interaction** awaits the observation of events at distances less than 10^{-31} m. Today we are not yet able to ob-



"PUTTING A BOX AROUND IT, I'M AFRAID, DOES NOT MAKE IT A UNIFIED THEORY."

serve such events. Some indirect evidence in support of this theory comes from interactions at larger distances, and the model seems promising. Ultimately, however, our commitment to such a model is as much a reflection of our belief in simplicity as it is a reflection of reality. For physicists, the promise that three interactions can be replaced by one is indeed compelling.

Today we think that change occurs through four, and possibly only two, fundamental interactions. With them we can explain the fall of a pencil, the motion of the universe, the reason for static cling, and the mechanism by which atoms and nuclei are held together. Yet amid all this knowledge, fundamental questions still persist. What causes gravity? Why does an electric force exist? The concept of exchange particles provides a partial answer. Gravity and electrical forces are our way of describing the behavior of objects that exchange gravitons and photons. But then another question arises: Why do exchange particles go back and forth? Were we to answer that question, there would be another. Like the child who endlessly asks Why, we have an insatiable appetite for understanding.

CHAPTER SUMMARY

All forces in nature can be classified into four fundamental interactions: gravitational, electromagnetic, strong nuclear, and weak nuclear interactions.

The *gravitational interaction* explains the motion of falling objects on the surface of the earth, the motion of the moon about the earth, the motion of the planets about the sun, and the motion of galaxies. Every object attracts every other object with a force that is directly proportional to the product of the objects' masses and inversely proportional to the square of the distance between their centers. This is known as Newton's *law of universal gravitation.*

The description of the *electrical interaction* (one part of the electromagnetic interaction) is identical in form to the description of the gravitational interaction. The electrical force between two objects is directly proportional to the product of the objects' electrical charge and inversely proportional to the square of the distance between their centers. There are two kinds of *electrical charge,* called *positive* and *negative,* and the direction in which the force acts depends on the type of charge on each object. Like charges repel; unlike charges attract.

The two nuclear interactions describe forces that occur over the very short distances within the nucleus of the atom. The *strong nuclear interaction* is responsible for holding the nucleus together. The *weak nuclear interaction* is needed to explain why certain nuclei fall apart.

Each of the four fundamental interactions involves action at a distance. Action at a distance can be explained in terms of *exchange particles,* which move back and forth between two objects that are interacting. The range of the force depends on the mass of the exchange particle. *Pions,* the *W particle,* and *photons,* the exchange particles for strong nuclear, weak nuclear, and electrical interactions, respectively, have been detected. The *graviton,* yet to be observed, is postulated to be the exchange particle for the gravitational interaction.

The weak nuclear, electromagnetic, and strong nuclear interactions are now believed to be different manifestations of one interaction. This *unified interaction theory* will be tested when experiments can be performed to study interactions within distances of 10^{-31} m.

ANSWERS TO SELF-CHECKS

8A.
$$
\begin{aligned}
F_{\text{you on table}} &= G\frac{M_{\text{you}}M_{\text{table}}}{(r_{\text{you-table}})^2} \\
&= 6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\,\frac{(70\text{ kg})(5\text{ kg})}{(2\text{ m})^2} \\
&= 5.8 \times 10^{-9}\text{ N, toward you}
\end{aligned}
$$

The gravitational force we exert on the table is tiny compared to the gravitational force exerted by the earth. In a tug of war, the earth wins—hands down!

8B. a. The silk must have a net negative charge.
b. It attracts the plastic strip.

8C.
$$F = k\frac{\text{(charge 1)(charge 2)}}{\text{(distance)}^2}$$

At 10 m: $$F = 9 \times 10^9 \frac{\text{N} \cdot \text{m}^2}{\text{C}^2} \frac{(10^{-7}\text{ C})(10^{-7}\text{ C})}{(10\text{ m})^2} = 9 \times 10^{-7}\text{ N}$$

At 1 m: $$F = 9 \times 10^9 \frac{\text{N} \cdot \text{m}^2}{\text{C}^2} \frac{(10^{-7}\text{ C})(10^{-7}\text{ C})}{(1\text{ m})^2} = 9 \times 10^{-5}\text{ N}$$

At 0.01 m: $$F = 9 \times 10^9 \frac{\text{N} \cdot \text{m}^2}{\text{C}^2} \frac{(10^{-7}\text{ C})(10^{-7}\text{ C})}{(0.01\text{ m})^2} = 9 \times 10^{-1}\text{ N}$$

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Briefly describe each of the four fundamental interactions.

A2. How is the fall of an apple related to the motion of the moon about the earth?

A3. State how the gravitational force varies with mass and distance.

A4. What is the unknown quantity in determining if the universe will expand forever? How is this variable related to Newton's law of universal gravitation?

A5. How does the electric force vary with the type of electric charge, the size of the charge, and the distance between the charged objects?

A6. How are the electrical and gravitational interactions similar? How do they differ?

A7. Explain how Rutherford used the electrical interaction to learn about the structure of the atom.

A8. Explain why a strong nuclear interaction is necessary to explain the existence of the nucleus.

A9. What types of events are explained by the weak nuclear interaction?

A10. How do particle exchanges describe interaction at a distance?

B. Using the Chapter Material

B1. Two identical planets are orbiting a star. Planet A is 4000 km from the sun; planet B is 8000 km. On which planet does the sun exert a greater gravitational force of attraction? What is the ratio of the force felt by planet A to the force felt by planet B?

B2. Satellite C has twice the mass of satellite D. Both are orbiting the earth at the same altitude. On which satellite does the earth exert the greater gravitational force? What is the ratio of the gravitational force exerted on satellite C to the gravitational force exerted on satellite D?

B3. Skylab had a mass of 90,606 kg; the earth, 5.98×10^{24} kg. When it began orbiting, Skylab was 432 km above the earth's surface. The radius of the earth is 6380 km. What gravitational force did Skylab exert on the earth?

B4. The Apollo spacecraft felt gravitational attractions from both the earth and the moon. Was there any time during the flight when one of these forces was zero? Could a place exist where the net force from the two planets was zero?

B5. The mass of a proton is 1.672×10^{-27} kg. What is the force due to gravitational attraction for two protons separated by a distance of 10^{-15} m? Compare this to the electrical force between the same two protons.

B6. Which sets of charged objects have a larger electrical force acting on them?
   a. two objects with charges of +12 C each and 3 m apart or two objects with charges of +24 C each and 3 m apart
   b. two objects with charges of −14 C each and 6 m apart or two objects with charges of −14 C each and 20 m apart

B7. The electrical charge on the electron is -1.6×10^{-19} C. On the hydrogen nucleus the charge is $+1.6 \times 10^{-19}$ C. The distance between the nucleus and electron is 5.3×10^{-11} m. What is the electrical force on the electron? On the nucleus?

B8. A plastic comb begins with a zero net charge. After being used, it has a net charge of -3×10^{-6} C. What is the charge on the hair? Explain how you reached your answer.

B9. The net attractive force between two protons inside the nucleus is less than that between two neutrons. Why?

B10. We observe results of both electrical and gravitational interactions every day, but we do not notice direct evidence of nuclear interactions. Why?

B11. How would the mass of the pion need to change to decrease the range of the strong nuclear force?

C. Extensions to New Situations

C1. In Chapter 5 we noted that momentum was conserved for all interactions in a closed system. One such system involves an object falling near the surface of the earth. Suppose a 0.5 kg book is released from a height of 2 m and falls to the earth.

a. What objects form the closed system for this interaction?

b. Which of the fundamental interactions is involved in this interaction?

c. Why does the momentum of the earth change as the book falls?

d. Why is this momentum change not noticeable?

C2. When Newton introduced his law of universal gravitation, he successfully explained the ocean tides. The questions here will help you produce part of his explanation. Consider the earth-moon system shown in Figure 8-C2.

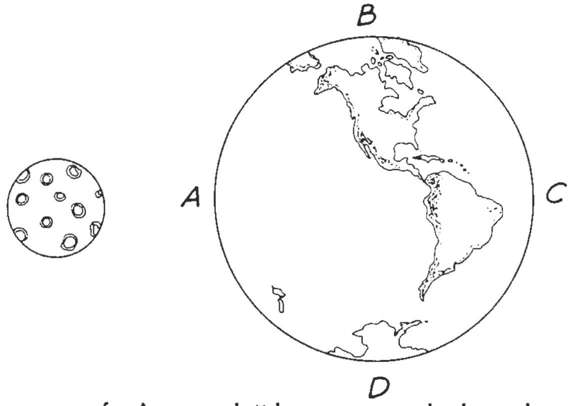
a. Why does the moon exert a force on the earth?

b. On which of the surface points—A, B, C, or D—is the force exerted by the moon the greatest? Why?

c. Suppose that an ocean is located at the point you chose in part (b). Draw an exaggerated picture of how the ocean would look at this point. Explain your drawing.

d. Now imagine that the earth is rotating while the moon stays fixed. Why will the ocean rise as each area reaches the point of maximum force?

e. Use the answers to (a)–(d) to explain why tides occur.



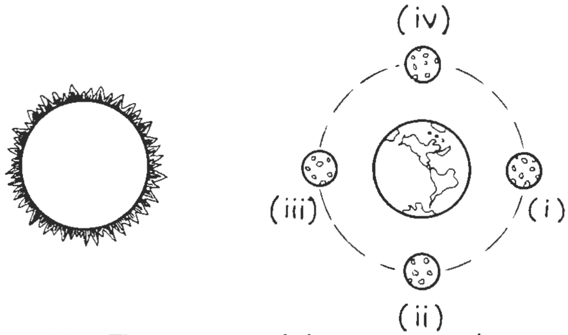
f. A second tide occurs each day when the location is opposite the first tide point. Can you explain this tide by comparing the force on the earth and the water farthest from the moon?

C3. Tides arise from gravitational interactions between the earth and moon. Because the moon rotates about the earth once every 28 days, the high tides do not occur at the same time each day. Also, the magnitude of the high tide will vary from day to day. To understand why, consider various positions of the moon relative to the sun and earth as illustrated in Figure 8-C3.

a. For which of these configurations will the high tide be the greatest? Explain your answer.

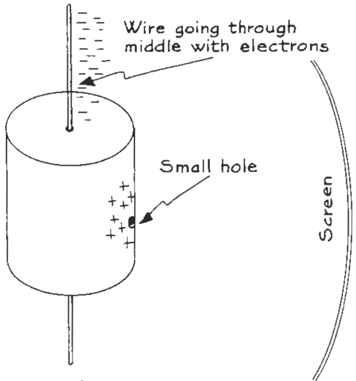
b. For which of these configurations will the high tide be the least? Explain your answer.

c. Describe the sun's role in determining the magnitude of the high tides.

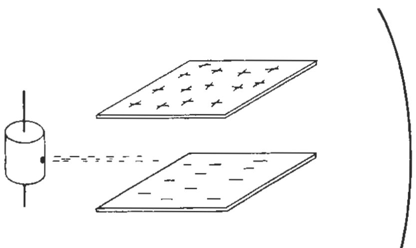


C4. The presence of the outermost planets in the solar system was detected by noticing small irregularities in the orbits of the known planets. Their orbits deviated slightly from those predicted by the known gravitational forces. Explain why such irregularities would be considered evidence for another planet.

C5. Oscilloscopes and old-fashioned televisions use a series of electrical forces to create a picture. Electrons hit a screen and create light. The color of the light depends on the type of atom struck by the electron. Electrical forces are used to get the electron to the place it is needed.



(a)



(b)

a. The first step is to get electrons moving. The basic setup is shown in Figure 8-C5(a). Why does this arrangement result in a bright spot on the screen as shown? (This arrangement is called an electron gun.)

b. Looking at bright spots on screens is not very exciting, so we must move the electrons. How does the arrangement in Figure 8-C5(b) change the motion of the electrons? Draw the path of the electron from the electron gun to the screen.

c. In television the charge on the deflecting plates changes from positive on the top and negative on the bottom to positive on the bottom and negative on the top in $\frac{1}{60}$ s. The change is gradual, not sudden. What will be the motion of the electrons?

C6. When a plastic comb with a net charge on it is placed near paper with zero net charge, the paper will still accelerate toward the comb. A net charge on one object is sufficient for electrical attraction to occur. To see why, consider a piece of paper in which no net charge exists but in which the electrons can move. A comb with a net positive charge is brought near the piece of paper.

a. How will the electrons in the paper move when the comb is brought near to but does not touch the paper? Explain your answer.

b. Draw the comb and the paper showing the positions of positive and negative charges in each. Explain why your drawing is correct.

c. What are the directions of the electrical forces on the paper's positive and negative charges?

d. On which set of charges, positive or negative, will the magnitude of the force be greater? Why?

e. Suppose that the comb had a net negative charge. Work through steps (a)–(d) and show that the paper will still be attracted to the comb.

f. Describe why an object with a positive or negative net charge can attract an object with no net charge.

C7. Nuclei come with a variety of different numbers of protons, ranging from 1 to about 110. The number of neutrons extends over a wider range, 0 to more than 150. However, nuclei which consist only of protons do not exist, except for hydrogen. Very massive nuclei exist only in forms for which the neutrons outnumber the protons.

a. What are the forces acting between two protons? Between a proton and a neutron? Between two neutrons?

b. How does the net force between a proton and a neutron differ from that between two protons?

c. Could an "all-proton nucleus" ever result in a net force that is repulsive for the protons? How might that occur?

d. Use the answers for (a)–(c) to explain why neutrons must be present in the nucleus.