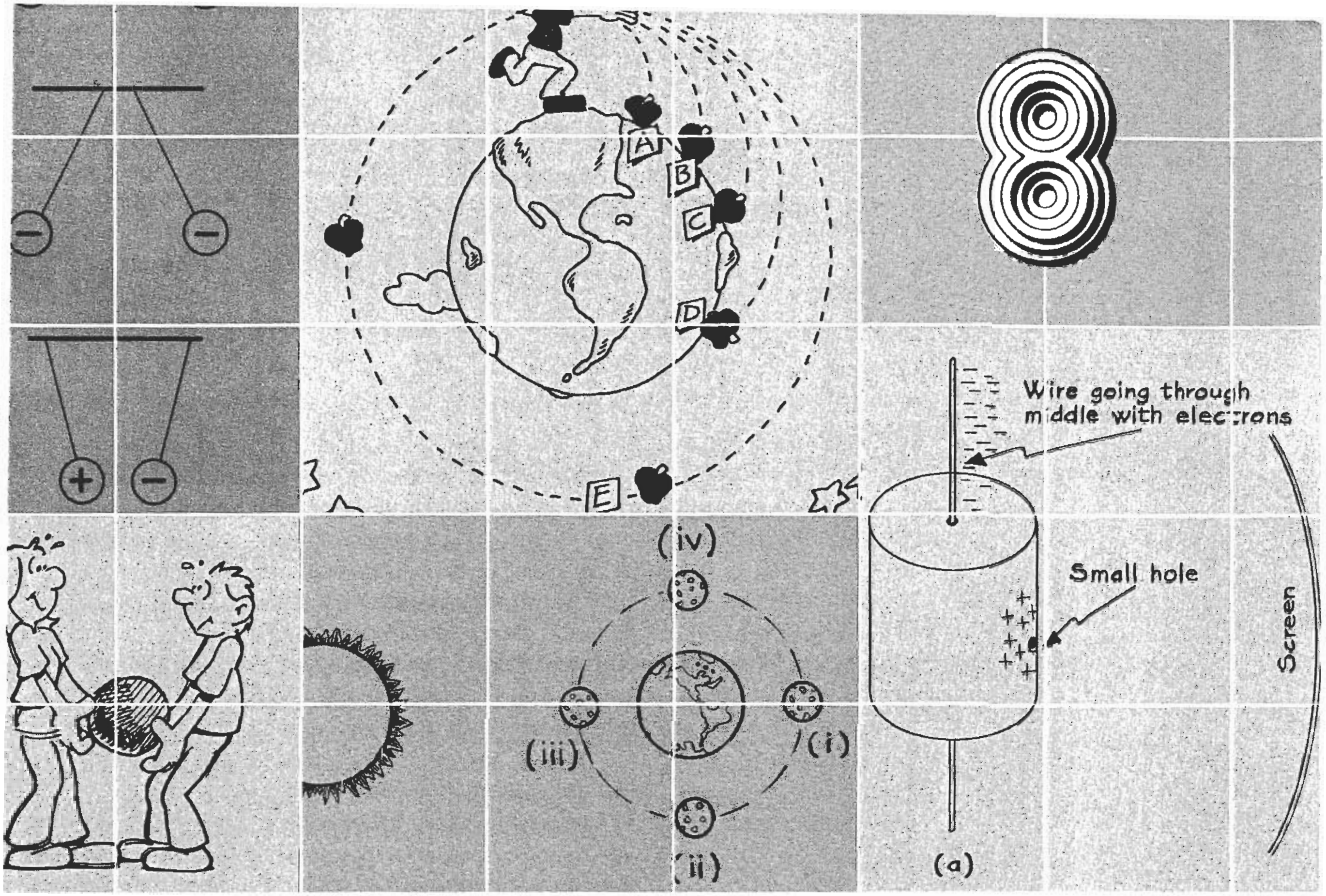
Cornell University
Prison Education Program

Conceptual Physics
Readings

This packet contains the following two readings:

1. **Four Fundamental Interactions:** Reading for section on forces, March 2nd.
2. **Conservation of Mass and Energy:** Reading for section on energy, March 16th.



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.

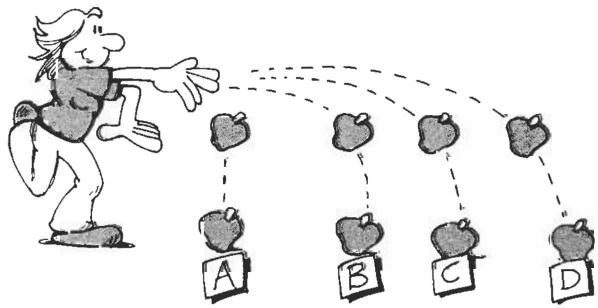


Figure 8-1
The harder you throw the apple, the farther away from you it lands.

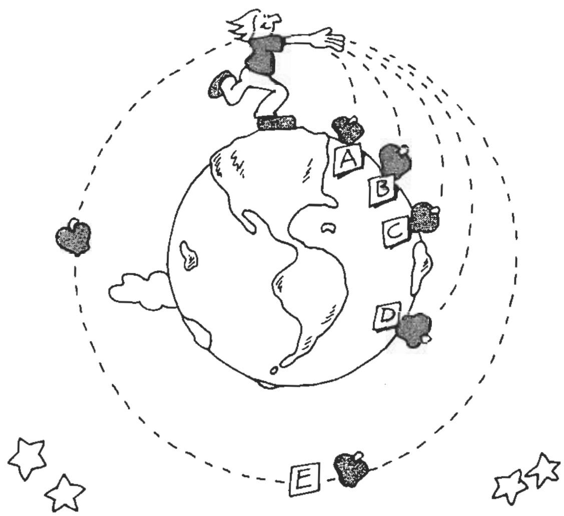


Figure 8-2
If we could actually throw the apple hard enough, it would miss the earth entirely. The apple would continue falling but would never quite catch up with the curvature of the earth.

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

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

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:

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

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:

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

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

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?

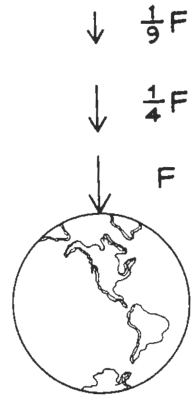


Figure 8-3
The gravitational force decreases quickly as we move away from the earth. Twice as far from the earth, the apple feels one-fourth the gravitational force. Three times as far away, the apple feels one-ninth the gravitational force.

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.

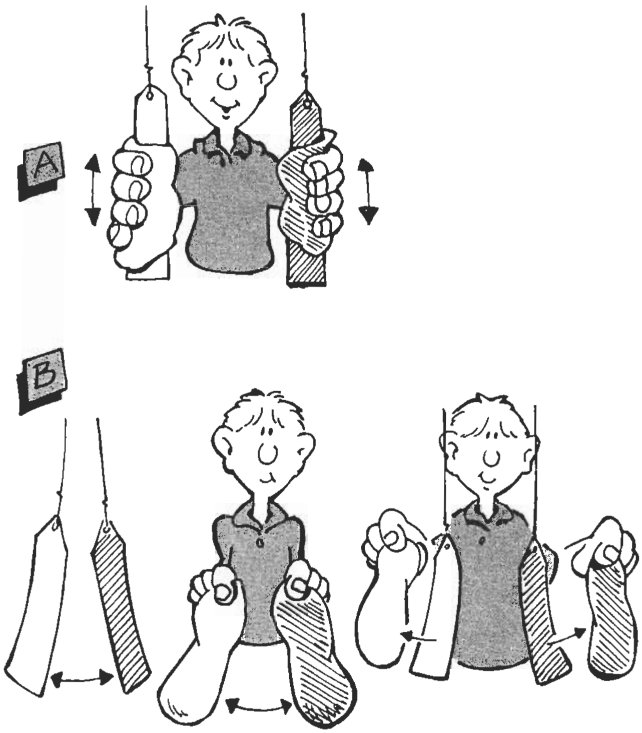


Figure 8-4

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

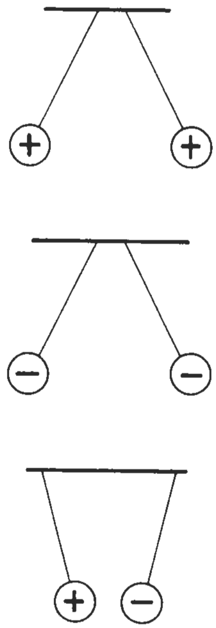


Figure 8-5
Like charges repel; unlike charges attract.

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

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

Constant = $9 \times 10^9\ \mathrm{N \cdot m^2/C^2}$

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

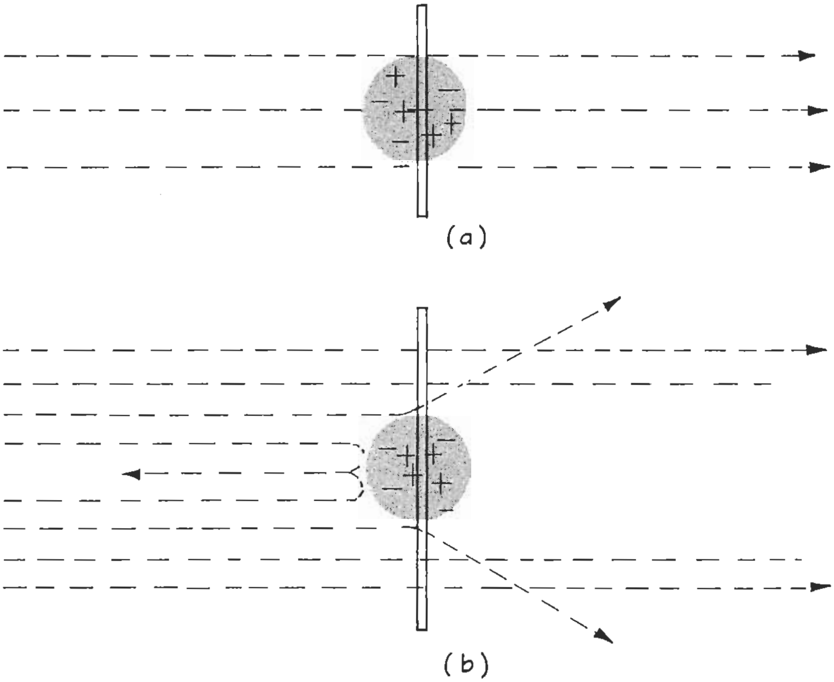


Figure 8-7
The paths followed by the alpha particles depend on the way in which electrical charge is distributed in the atom. **(a)** When the electrical charges are evenly distributed, the alpha particles continue along their original paths. **(b)** When the alpha particles encounter massive charge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

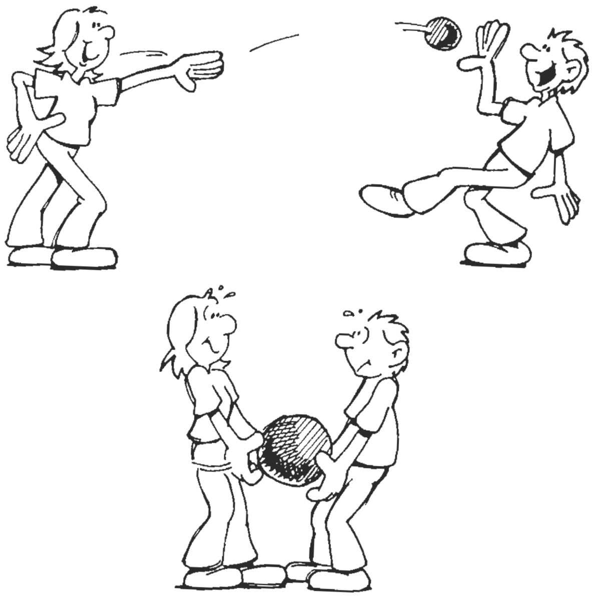


Figure 8-8
Seen from afar, a game of catch might look like interaction at a distance. The more massive the "ball," the stronger the force.

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. $$F_{\text{you on table}} = G\frac{M_{\text{you}}M_{\text{table}}}{(r_{\text{you-table}})^2}$$

$$= 6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\,\frac{(70\text{ kg})(5\text{ kg})}{(2\text{ m})^2}$$

$$= 5.8 \times 10^{-9}\text{ N, toward you}$$

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.

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

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

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

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

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?

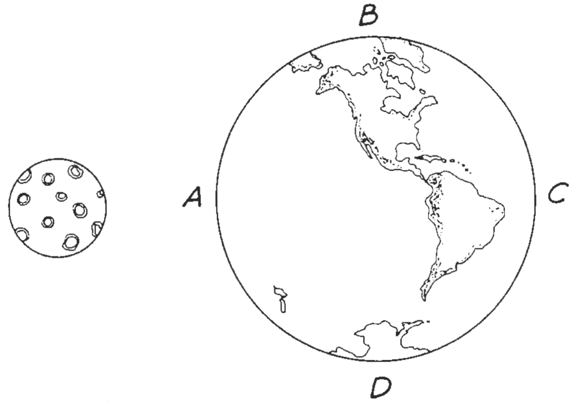
B10. We observe results of both electrical and gravitational interactions every day, but we do not notice direct evidence of nuclear interactions. Why?

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

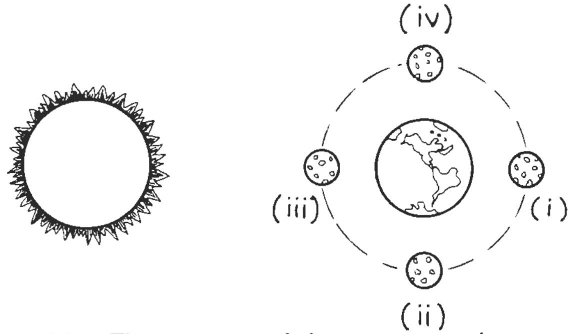
C1. In Chapter 5 we noted that momentum was conserved for all interactions in a closed system. One such system involves an object falling near the surface of the earth. Suppose a 0.5 kg book is released from a height of 2 m and falls to the earth.
   a. What objects form the closed system for this interaction?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



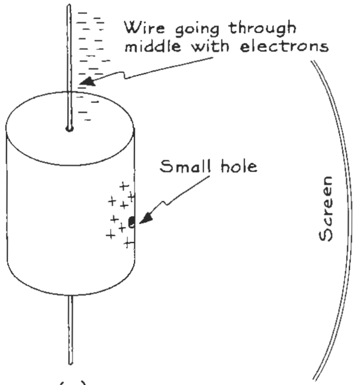
   f. A second tide occurs each day when the location is opposite the first tide point. Can you explain this tide by comparing the force on the earth and the water farthest from the moon?

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.

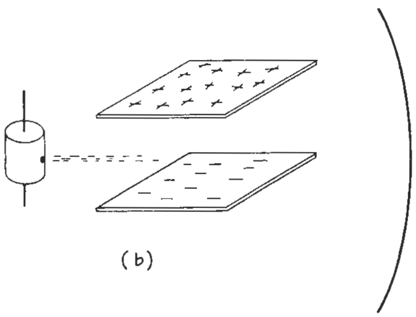


C4. The presence of the outermost planets in the solar system was detected by noticing small irregularities in the orbits of the known planets. Their orbits deviated slightly from those predicted by the known gravitational forces. Explain why such irregularities would be considered evidence for another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

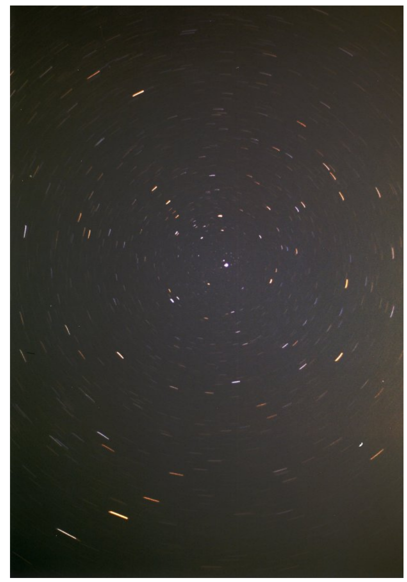
C7. Nuclei come with a variety of different numbers of protons, ranging from 1 to about 110. The number of neutrons extends over a wider range, 0 to more than 150. However, nuclei which consist only of protons do not exist, except for hydrogen. Very massive nuclei exist only in forms for which the neutrons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

Chapter 1

Conservation of Mass and Energy

1.1 Symmetry and Conservation Laws

Even before history began, people must already have noticed certain facts about the sky. The sun and moon both rise in the east and set in the west. Another fact that can be settled to a fair degree of accuracy using the naked eye is that the apparent sizes of the sun and moon don't change noticeably. (There is an optical illusion that makes the moon appear bigger when it's near the horizon, but you can easily verify that it's nothing more than an illusion by checking its angular size against some standard, such as your pinkie held at arm's length.) If the sun and moon were varying their distances from us, they would appear to get bigger and smaller, and since they don't appear to change in size, it appears, at least approximately, that they always stay at the same distance from us.



a / Due to the rotation of the earth, everything in the sky appears to spin in circles. In this time-exposure photograph, each star appears as a streak.

From observations like these, the ancients constructed a scientific *model*, in which the sun and moon traveled around the earth in perfect circles. Of course, we now know that the earth isn't the center of the universe, but that doesn't mean the model wasn't useful. That's the way science always works. Science never aims to reveal the ultimate reality. Science only tries to make models of reality that have predictive power.

Our modern approach to understanding physics revolves around the concepts of *symmetry* and *conservation laws*, both of which are demonstrated by this example.

The sun and moon were believed to move in circles, and a circle is a very symmetric shape. If you rotate a circle about its center, like a spinning wheel, it doesn't change. Therefore, we say that the circle is *symmetric* with respect to rotation about its center. The ancients thought it was beautiful that the universe seemed to have this type of symmetry built in, and they became very attached to the idea.

A *conservation law* is a statement that some number stays the same with the passage of time. In our example, the distance between the sun and the earth is conserved, and so is the distance between the moon and the earth. (The ancient Greeks were even able to determine that earth-moon distance.)

b / Emmy Noether (1882-1935). The daughter of a prominent German mathematician, she did not show any early precocity at mathematics — as a teenager she was more interested in music and dancing. She received her doctorate in 1907 and rapidly built a world-wide reputation, but the University of Göttingen refused to let her teach, and her colleague Hilbert had to advertise her courses in the university's catalog under his own name. A long controversy ensued, with her opponents asking what the country's soldiers would think when they returned home and were expected to learn at the feet of a woman. Allowing her on the faculty would also mean letting her vote in the academic senate. Said Hilbert, "I do not see that the sex of the candidate is against her admission as a privatdozent [instructor]. After all, the university senate is not a bathhouse." She was finally admitted to the faculty in 1919. A Jew, Noether fled Germany in 1933 and joined the faculty at Bryn Mawr in the U.S.

In our example, the symmetry and the conservation law both give the same information. Either statement can be satisfied only by a circular orbit. That isn't a coincidence. Physicist Emmy Noether showed on very general mathematical grounds that for physical theories of a certain type, every symmetry leads to a corresponding conservation law. Although the precise formulation of Noether's theorem, and its proof, are too mathematical for this book, we'll see many examples like this one, in which the physical content of the theorem is fairly straightforward.

c / In this scene from Swan Lake, the choreography has a symmetry with respect to left and right.

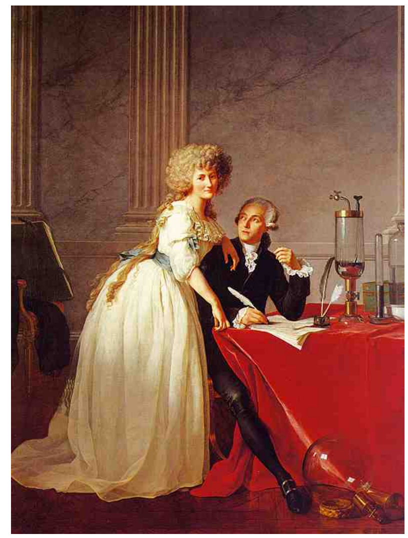
The idea of perfect circular orbits seems very beautiful and intuitively appealing. It came as a great disappointment, therefore, when the astronomer Johannes Kepler discovered, by the painstaking analysis of precise observations, that orbits such as the moon's were actually ellipses, not circles. This is the sort of thing that led the biologist Huxley to say, "The great tragedy of science is the slaying of a beautiful theory by an ugly fact." The lesson of the story, then, is that symmetries are important and beautiful, but we can't decide which symmetries are right based only on common sense or aesthetics; their validity has to be determined based on observations and experiments.

d / C.S. Wu at Columbia University in 1963.

As a more modern example, consider the symmetry between right and left. For example, we observe that a top spinning clockwise has exactly the same behavior as a top spinning counterclockwise. This kind of observation led physicists to believe, for hundreds of years, that the laws of physics were perfectly symmetric with respect to right and left. This mirror symmetry appealed to physicists' common sense. However, experiments by Chien-Shiung Wu et al. in 1957 showed that right-left symmetry was violated in certain types of nuclear reactions. Physicists were thus forced to change their opinions about what constituted common sense.

1.2 Conservation of Mass

We intuitively feel that matter shouldn't appear or disappear out of nowhere: that the amount of matter should be a conserved quantity. If that was to happen, then it seems as though atoms would have to be created or destroyed, which doesn't happen in any physical processes that are familiar from everyday life, such as chemical reactions. On the other hand, I've already cautioned you against believing that a law of physics must be true just because it seems appealing. The laws of physics have to be found by experiment, and there seem to be experiments that are exceptions to the conservation of matter. A log weighs more than its ashes. Did some matter simply disappear when the log was burned?



e / Portrait of Monsieur Lavoisier and His Wife, by Jacques-Louis David, 1788. Lavoisier invented the concept of conservation of mass. The husband is depicted with his scientific apparatus, while in the background on the left is the portfolio belonging to Madame Lavoisier, who is thought to have been a student of David's.

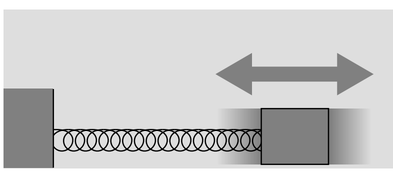
The French chemist Antoine-Laurent Lavoisier was the first scientist to realize that there were no such exceptions. Lavoisier hypothesized that when wood burns, for example, the supposed loss of weight is actually accounted for by the escaping hot gases that the flames are made of. Before Lavoisier, chemists had almost never weighed their chemicals to quantify the amount of each substance that was undergoing reactions. They also didn't completely understand that gases were just another state of matter, and hadn't tried performing reactions in sealed chambers to determine whether gases were being consumed from or released into the air. For this they had at least one practical excuse, which is that if you perform a gas-releasing reaction in a sealed chamber with no room for expansion, you get an explosion! Lavoisier invented a balance that was capable of measuring milligram masses, and figured out how to do reactions in an upside-down bowl in a basin of water, so that the gases could expand by pushing out some of the water. In one crucial experiment, Lavoisier heated a red mercury compound, which we would now describe as mercury oxide (HgO), in such a sealed chamber. A gas was produced (Lavoisier later named it "oxygen"), driving out some of the water, and the red compound was transformed into silvery liquid mercury metal. The crucial point was that the total mass of the entire apparatus was exactly the same before and after the reaction. Based on many observations of this type, Lavoisier proposed a general law of nature, that matter is always conserved.

self-check A

In ordinary speech, we say that you should "conserve" something, because if you don't, pretty soon it will all be gone. How is this different from the meaning of the term "conservation" in physics? ▷ Answer, p. 179

Although Lavoisier was an honest and energetic public official, he was caught up in the Terror and sentenced to death in 1794. He requested a fifteen-day delay of his execution so that he could complete some experiments that he thought might be of value to the Republic. The judge, Coffinhal, infamously replied that "the state

f / Example 1.



g / The time for one cycle of vibration is related to the object's mass.

h / Astronaut Tamara Jernigan measures her mass aboard the Space Shuttle. She is strapped into a chair attached to a spring, like the mass in figure g. (*NASA*)

has no need of scientists." As a scientific experiment, Lavoisier decided to try to determine how long his consciousness would continue after he was guillotined, by blinking his eyes for as long as possible. He blinked twelve times after his head was chopped off. Ironically, Judge Coffinhal was himself executed only three months later, falling victim to the same chaos.

A stream of water *example 1*

The stream of water is fatter near the mouth of the faucet, and skinnier lower down. This can be understood using conservation of mass. Since water is being neither created nor destroyed, the mass of the water that leaves the faucet in one second must be the same as the amount that flows past a lower point in the same time interval. The water speeds up as it falls, so the two quantities of water can only be equal if the stream is narrower at the bottom.

Physicists are no different than plumbers or ballerinas in that they have a technical vocabulary that allows them to make precise distinctions. A pipe isn't just a pipe, it's a PVC pipe. A jump isn't just a jump, it's a grand jeté. We need to be more precise now about what we really mean by "the amount of matter," which is what we're saying is conserved. Since physics is a mathematical science, definitions in physics are usually definitions of numbers, and we define these numbers *operationally*. An operational definition is one that spells out the steps required in order to *measure* that quantity. For example, one way that an electrician knows that current and voltage are two different things is that she knows she has to do completely different things in order to measure them with a meter.

If you ask a room full of ordinary people to define what is meant by mass, they'll probably propose a bunch of different, fuzzy ideas, and speak as if they all pretty much meant the same thing: "how much space it takes up," "how much it weighs," "how much matter is in it." Of these, the first two can be disposed of easily. If we were to define mass as a measure of how much space an object occupied, then mass wouldn't be conserved when we squished a piece of foam rubber. Although Lavoisier did use weight in his experiments, weight also won't quite work as the ultimate, rigorous definition, because weight is a measure of how hard gravity pulls on an object, and gravity varies in strength from place to place. Gravity is measurably weaker on the top of a mountain that at sea level, and much weaker on the moon. The reason this didn't matter to Lavoisier was that he was doing all his experiments in one location. The third proposal is better, but how exactly should we define "how much matter?" To make it into an operational definition, we could do something like figure g. A larger mass is harder to whip back and forth — it's harder to set into motion, and harder to stop once it's started. For this reason, the vibration of the mass on the spring will take a longer time if the mass is greater. If we put two different masses on the spring, and they both take the same time to complete one oscillation, we can define them as having the same mass.

Since I started this chapter by highlighting the relationship between conservation laws and symmetries, you're probably wondering what symmetry is related to conservation of mass. I'll come back to that at the end of the chapter.

When you learn about a new physical quantity, such as mass, you need to know what units are used to measure it. This will lead us to a brief digression on the metric system, after which we'll come back to physics.

1.3 Review of the Metric System and Conversions

The metric system

Every country in the world besides the U.S. has adopted a system of units known colloquially as the "metric system." Even in the U.S., the system is used universally by scientists, and also by many engineers. This system is entirely decimal, thanks to the same eminently logical people who brought about the French Revolution. In deference to France, the system's official name is the Système International, or SI, meaning International System. (The phrase "SI system" is therefore redundant.)

The metric system works with a single, consistent set of prefixes (derived from Greek) that modify the basic units. Each prefix stands for a power of ten, and has an abbreviation that can be combined with the symbol for the unit. For instance, the meter is a unit of distance. The prefix kilo- stands for 1000, so a kilometer, 1 km, is a thousand meters.

In this book, we'll be using a flavor of the metric system, the SI, in which there are three basic units, measuring distance, time, and mass. The basic unit of distance is the meter (m), the one for time is the second (s), and for mass the kilogram (kg). Based on these units, we can define others, e.g., m/s (meters per second) for the speed of a car, or kg/s for the rate at which water flows through a pipe. It might seem odd that we consider the basic unit of mass to be the kilogram, rather than the gram. The reason for doing this is that when we start defining other units starting from the basic three, some of them come out to be a more convenient size for use in everyday life. For example, there is a metric unit of force, the newton (N), which is defined as the push or pull that would be able to change a 1-kg object's velocity by 1 m/s, if it acted on it for 1 s. A newton turns out to be about the amount of force you'd use to pick up your keys. If the system had been based on the gram instead of the kilogram, then the newton would have been a thousand times smaller, something like the amount of force required in order to pick up a breadcrumb.

The following are the most common metric prefixes. You should memorize them.

prefix		meaning	example	
kilo-	k	1000	60 kg	= a person's mass
centi-	c	1/100	28 cm	= height of a piece of paper
milli-	m	1/1000	1 ms	= time for one vibration of a guitar string playing the note D

The prefix centi-, meaning 1/100, is only used in the centimeter; a hundredth of a gram would not be written as 1 cg but as 10 mg. The centi- prefix can be easily remembered because a cent is 1/100 of a dollar. The official SI abbreviation for seconds is "s" (not "sec") and grams are "g" (not "gm").

You may also encounter the prefixes mega- (a million) and micro- (one millionth).

Scientific notation

Most of the interesting phenomena in our universe are not on the human scale. It would take about 1,000,000,000,000,000,000,000 bacteria to equal the mass of a human body. When the physicist Thomas Young discovered that light was a wave, scientific notation hadn't been invented, and he was obliged to write that the time required for one vibration of the wave was 1/500 of a millionth of a millionth of a second. Scientific notation is a less awkward way to write very large and very small numbers such as these. Here's a quick review.

Scientific notation means writing a number in terms of a product of something from 1 to 10 and something else that is a power of ten. For instance,

$$32 = 3.2 \times 10^1$$
$$320 = 3.2 \times 10^2$$
$$3200 = 3.2 \times 10^3 \quad \ldots$$

Each number is ten times bigger than the last.

Since 10^1 is ten times smaller than 10^2 , it makes sense to use the notation 10^0 to stand for one, the number that is in turn ten times smaller than 10^1 . Continuing on, we can write 10^{-1} to stand for 0.1, the number ten times smaller than 10^0 . Negative exponents are used for small numbers:

$$3.2 = 3.2 \times 10^0$$
$$0.32 = 3.2 \times 10^{-1}$$
$$0.032 = 3.2 \times 10^{-2} \quad \ldots$$

A common source of confusion is the notation used on the displays of many calculators. Examples:

3.2×10^6	(written notation)
3.2E+6	(notation on some calculators)
3.2^6	(notation on some other calculators)

The last example is particularly unfortunate, because 3.2^6 really stands for the number $3.2 \times 3.2 \times 3.2 \times 3.2 \times 3.2 \times 3.2 = 1074$, a totally different number from $3.2 \times 10^6 = 3200000$. The calculator notation should never be used in writing. It's just a way for the manufacturer to save money by making a simpler display.

self-check B

A student learns that 10^4 bacteria, standing in line to register for classes at Paramecium Community College, would form a queue of this size:

The student concludes that 10^2 bacteria would form a line of this length:

Why is the student incorrect? ▷ Answer, p. 179

Conversions

I suggest you avoid memorizing lots of conversion factors between SI units and U.S. units. Suppose the United Nations sends its black helicopters to invade California (after all who wouldn't rather live here than in New York City?), and institutes water fluoridation and the SI, making the use of inches and pounds into a crime punishable by death. I think you could get by with only two mental conversion factors:

> 1 inch = 2.54 cm
>
> An object with a weight on Earth of 2.2 pounds-force has a mass of 1 kg.

The first one is the present definition of the inch, so it's exact. The second one is not exact, but is good enough for most purposes. (U.S. units of force and mass are confusing, so it's a good thing they're not used in science. In U.S. units, the unit of force is the pound-force, and the best unit to use for mass is the slug, which is about 14.6 kg.)

More important than memorizing conversion factors is understanding the right method for doing conversions. Even within the SI, you may need to convert, say, from grams to kilograms. Different people have different ways of thinking about conversions, but the method I'll describe here is systematic and easy to understand. The idea is that if 1 kg and 1000 g represent the same mass, then we can consider a fraction like

$$\frac{10^3\ \text{g}}{1\ \text{kg}}$$

to be a way of expressing the number one. This may bother you. For instance, if you type 1000/1 into your calculator, you will get 1000, not one. Again, different people have different ways of thinking about it, but the justification is that it helps us to do conversions, and it works! Now if we want to convert 0.7 kg to units of grams, we can multiply kg by the number one:

$$0.7\ \text{kg} \times \frac{10^3\ \text{g}}{1\ \text{kg}}$$

If you're willing to treat symbols such as "kg" as if they were variables as used in algebra (which they're really not), you can then cancel the kg on top with the kg on the bottom, resulting in

$$0.7\ \cancel{\text{kg}} \times \frac{10^3\ \text{g}}{1\ \cancel{\text{kg}}} = 700\ \text{g}.$$

To convert grams to kilograms, you would simply flip the fraction upside down.

One advantage of this method is that it can easily be applied to a series of conversions. For instance, to convert one year to units of seconds,

$$1\ \cancel{\text{year}} \times \frac{365\ \cancel{\text{days}}}{1\ \cancel{\text{year}}} \times \frac{24\ \cancel{\text{hours}}}{1\ \cancel{\text{day}}} \times \frac{60\ \cancel{\text{min}}}{1\ \cancel{\text{hour}}} \times \frac{60\ \text{s}}{1\ \cancel{\text{min}}} = \\ = 3.15 \times 10^7\ \text{s}.$$

Should that exponent be positive or negative?

A common mistake is to write the conversion fraction incorrectly. For instance the fraction

$$\frac{10^3\ \text{kg}}{1\ \text{g}} \qquad \text{(incorrect)}$$

does not equal one, because 10^3 kg is the mass of a car, and 1 g is the mass of a raisin. One correct way of setting up the conversion factor would be

$$\frac{10^{-3}\ \text{kg}}{1\ \text{g}} \qquad \text{(correct)}.$$

You can usually detect such a mistake if you take the time to check your answer and see if it is reasonable.

If common sense doesn't rule out either a positive or a negative exponent, here's another way to make sure you get it right. There are big prefixes, like kilo-, and small ones, like milli-. In the example above, we want the top of the fraction to be the same as the bottom. Since k is a big prefix, we need to *compensate* by putting a small number like 10^{-3} in front of it, not a big number like 10^3.

Discussion question

A Each of the following conversions contains an error. In each case, explain what the error is.

(a) 1000 kg $\times \frac{1 \text{ kg}}{1000 \text{ g}}$ = 1 g

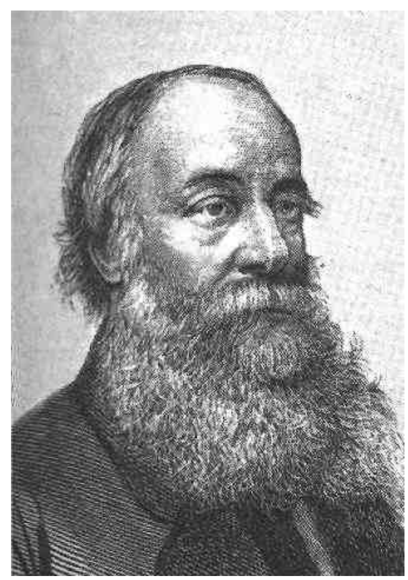
(b) 50 m $\times \frac{1 \text{ cm}}{100 \text{ m}}$ = 0.5 cm

1.4 Conservation of Energy

Energy

Consider the hockey puck in figure i. If we release it at rest, we expect it to remain at rest. If it did start moving all by itself, that would be strange: it would have to pick some direction in which to move, and why would it pick that direction rather than some other one? If we observed such a phenomenon, we would have to conclude that that direction in space was somehow special. It would be the favored direction in which hockey pucks (and presumably other objects as well) preferred to move. That would violate our intuition about the symmetry of space, and this is a case where our intuition is right: a vast number of experiments have all shown that that symmetry is a correct one. In other words, if you secretly pick up the physics laboratory with a crane, and spin it around gently with all the physicists inside, all their experiments will still come out the same, regardless of the lab's new orientation. If they don't have windows they can look out of, or any other external cues (like the Earth's magnetic field), then they won't notice anything until they hang up their lab coats for the evening and walk out into the parking lot.

i / A hockey puck is released at rest. If it spontaneously scooted off in some direction, that would violate the symmetry of all directions in space.


j / James Joule (1818-1889) discovered the law of conservation of energy.

Another way of thinking about it is that a moving hockey puck would have some *energy*, whereas a stationary one has none. I haven't given you an operational definition of energy yet, but we'll gradually start to build one up, and it will end up fitting in pretty well with your general idea of what energy means from everyday life. Regardless of the mathematical details of how you would actually calculate the energy of a moving hockey puck, it makes sense that a puck at rest has zero energy. It starts to look like energy is conserved. A puck that initially has zero energy must continue to have zero energy, so it can't start moving all by itself.

You might conclude from this discussion that we have a new example of Noether's theorem: that the symmetry of space with respect to different directions must be equivalent, in some mysterious way, to conservation of energy. Actually that's not quite right, and the possible confusion is related to the fact that we're not going to deal with the full, precise mathematical statement of Noether's theorem. In fact, we'll see soon that conservation of energy is really more closely related to a different symmetry, which is symmetry with respect to the passage of time.

The principle of inertia

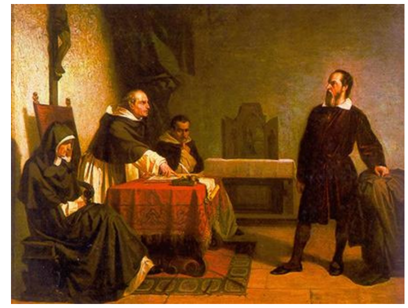
Now there's one very subtle thing about the example of the hockey puck, which wouldn't occur to most people. If we stand on the ice and watch the puck, and we don't see it moving, does that mean that it really is at rest in some absolute sense? Remember, the planet earth spins once on its axis every 24 hours. At the latitude where I live, this results in a speed of about 800 miles per hour, or something like 400 meters per second. We could say, then that the puck wasn't really staying at rest. We could say that it was really in motion at a speed of 400 m/s, and remained in motion at that same speed. This may be inconsistent with our earlier description, but it is still consistent with the same description of the laws of physics. Again, we don't need to know the relevant formula for energy in order to believe that if the puck keeps the same speed (and its mass also stays the same), it's maintaining the same energy.

k / Why does Aristotle look so sad? Is it because he's realized that his entire system of physics is wrong?

l / The jets are at rest. The Empire State Building is moving.

In other words, we have two different *frames of reference*, both equally valid. The person standing on the ice measures all velocities relative to the ice, finds that the puck maintained a velocity of zero, and says that energy was conserved. The astronaut watching the scene from deep space might measure the velocities relative to her own space station; in her frame of reference, the puck is moving at 400 m/s, but energy is still conserved.

This probably seems like common sense, but it wasn't common sense to one of the smartest people ever to live, the ancient Greek philosopher Aristotle. He came up with an entire system of physics based on the premise that there is one frame of reference that is special: the frame of reference defined by the dirt under our feet. He believed that all motion had a tendency to slow down unless a force was present to maintain it. Today, we know that Aristotle was wrong. One thing he was missing was that he didn't understand the concept of friction as a force. If you kick a soccer ball, the reason it eventually comes to rest on the grass isn't that it "naturally" wants to stop moving. The reason is that there's a frictional force from the grass that is slowing it down. (The energy of the ball's motion is transformed into other forms, such as heat and sound.) Modern people may also have an easier time seeing his mistake, because we have experience with smooth motion at high speeds. For instance, consider a passenger on a jet plane who stands up in the aisle and inadvertently drops his bag of peanuts. According to Aristotle, the bag would naturally slow to a stop, so it would become a life-threatening projectile in the cabin! From the modern point of view, the cabin can just as well be considered to be at rest.



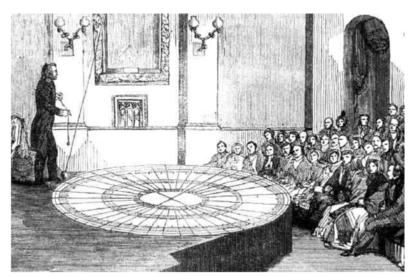
m / Galileo Galilei was the first physicist to state the principle of inertia (in a somewhat different formulation than the one given here). His contradiction of Aristotle had serious consequences. He was interrogated by the Church authorities and convicted of teaching that the earth went around the sun as a matter of fact and not, as he had promised previously, as a mere mathematical hypothesis. He was placed under permanent house arrest, and forbidden to write about or teach his theories. Immediately after being forced to recant his claim that the earth revolved around the sun, the old man is said to have muttered defiantly "and yet it does move."

The *principle of inertia* says, roughly, that all frames of reference are equally valid:

The principle of inertia
The results of experiments don't depend on the straight-line, constant-speed motion of the apparatus.

Speaking slightly more precisely, the principle of inertia says that if frame B moves at constant speed, in a straight line, relative to frame A, then frame B is just as valid as frame A, and in fact an observer in frame B will consider B to be at rest, and A to be moving. The laws of physics will be valid in both frames. The necessity for the more precise formulation becomes evident if you think about examples in which the motion changes its speed or direction. For instance, if you're in a car that's accelerating from rest, you feel yourself being pressed back into your seat. That's very different from the experience of being in a car cruising at constant speed, which produces no physical sensation at all. A more extreme example of this is shown in figure n on page 18.

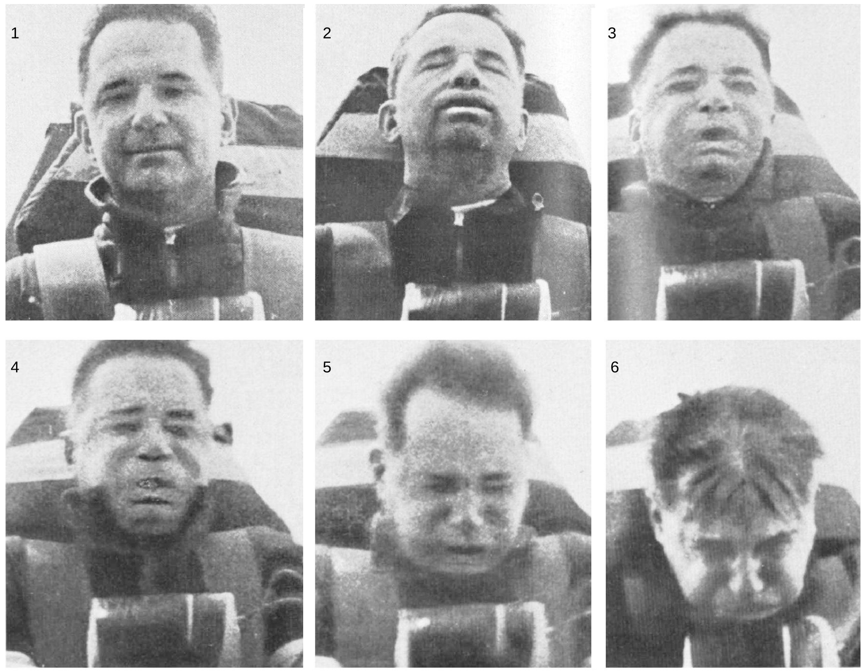
A frame of reference moving at constant speed in a straight line is known as an inertial frame of reference. A frame that changes its speed or direction of motion is called noninertial. The principle of inertia applies only to inertial frames. The frame of reference defined by an accelerating car is noninertial, but the one defined by a car cruising at constant speed in a straight line is inertial.



o / Foucault demonstrates his pendulum to an audience at a lecture in 1851.

Foucault's pendulum — *example 2*

Earlier, I spoke as if a frame of reference attached to the surface of the rotating earth was just as good as any other frame of reference. Now, with the more exact formulation of the principle of inertia, we can see that that isn't quite true. A point on the earth's surface moves in a circle, whereas the principle of inertia refers only to motion in a straight line. However, the curve of the motion is so gentle that under ordinary conditions we don't notice that the local dirt's frame of reference isn't quite inertial. The first demonstration of the noninertial nature of the earth-fixed frame of reference was by Léon Foucault using a very massive pendulum



n / This Air Force doctor volunteered to ride a rocket sled as a medical experiment. The obvious effects on his head and face are not because of the sled's speed but because of its rapid changes in speed: increasing in 2 and 3, and decreasing in 5 and 6. In 4 his speed is greatest, but because his speed is not increasing or decreasing very much at this moment, there is little effect on him.

(figure o) whose oscillations would persist for many hours without becoming imperceptible. Although Foucault did his demonstration in Paris, it's easier to imagine what would happen at the north pole: the pendulum would keep swinging in the same plane, but the earth would spin underneath it once every 24 hours. To someone standing in the snow, it would appear that the pendulum's plane of motion was twisting. The effect at latitudes less than 90 degrees turns out to be slower, but otherwise similar. The Foucault pendulum was the first definitive experimental proof that the earth really did spin on its axis, although scientists had been convinced of its rotation for a century based on more indirect evidence about the structure of the solar system.

People have a strong intuitive belief that there is a state of absolute rest, and that the earth's surface defines it. But Copernicus proposed as a mathematical assumption, and Galileo argued as a matter of physical reality, that the earth spins on its axis, and also circles the sun. Galileo's opponents objected that this was impossible, because we would observe the effects of the motion. They said, for example, that if the earth was moving, then you would never be able to jump up in the air and land in the same place again — the earth would have moved out from under you. Galileo realized that this wasn't really an argument about the earth's motion but about physics. In one of his books, which were written in the form of dialogues, he has the three characters debate what would happen if a ship was cruising smoothly across a calm harbor and a sailor climbed up to the top of its mast and dropped a rock. Would it hit the deck at the base of the mast, or behind it because the ship had moved out from under it? This is the kind of experiment referred to in the principle of inertia, and Galileo knew that it would come out the same regardless of the ship's motion. His opponents' reasoning, as represented by the dialog's stupid character Simplicio, was based on the assumption that once the rock lost contact with the sailor's hand, it would naturally start to lose its forward motion. In other words, they didn't even believe in the idea that motion naturally continues unless a force acts to stop it.

But the principle of inertia says more than that. It says that motion isn't even real: to a sailor standing on the deck of the ship, the deck and the masts and the rigging are not even moving. People on the shore can tell him that the ship and his own body are moving in a straight line at constant speed. He can reply, "No, that's an illusion. I'm at rest. The only reason you think I'm moving is because you and the sand and the water are moving in the opposite direction." The principle of inertia says that straight-line, constant-speed motion is a matter of opinion. Thus things can't "naturally" slow down and stop moving, because we can't even agree on which things are moving and which are at rest.

If observers in different frames of reference disagree on velocities, it's natural to want to be able to convert back and forth. For motion in one dimension, this can be done by simple addition.

A sailor running on the deck *example 3*

▷ A sailor is running toward the front of a ship, and the other sailors say that in their frame of reference, fixed to the deck, his velocity is 7.0 m/s. The ship is moving at 1.3 m/s relative to the shore. How fast does an observer on the beach say the sailor is moving?

▷ They see the ship moving at 7.0 m/s, and the sailor moving even faster than that because he's running from the stern to the bow. In one second, the ship moves 1.3 meters, but he moves $1.3+7.0$ m, so his velocity relative to the beach is 8.3 m/s.

The only way to make this rule give consistent results is if we define velocities in one direction as positive, and velocities in the opposite direction as negative.

Running back toward the stern *example 4*

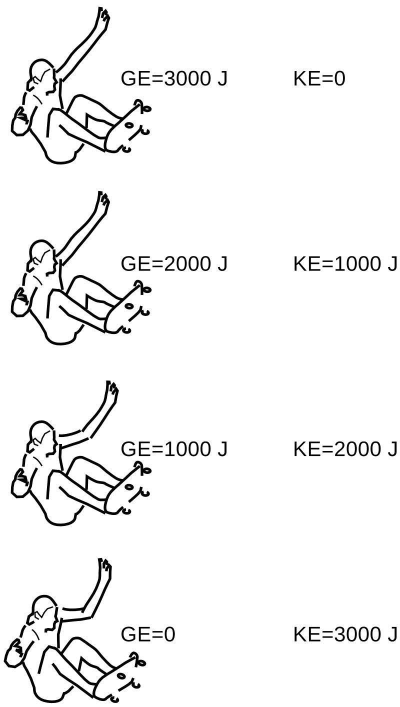
▷ The sailor of example 3 turns around and runs back toward the stern at the same speed relative to the deck. How do the other sailors describe this velocity mathematically, and what do observers on the beach say?

▷ Since the other sailors described his original velocity as positive, they have to call this negative. They say his velocity is now -7.0 m/s. A person on the shore says his velocity is $1.3+(-7.0) = -5.7$ m/s.

p / The skater has converted all his kinetic energy into gravitational energy on the way up the side of the pool. Photo by J.D. Rogge, www.sonic.net/∼shawn.

Kinetic and gravitational energy

Now suppose we drop a rock. The rock is initially at rest, but then begins moving. This seems to be a violation of conservation of energy, because a moving rock would have more energy. But actually this is a little like the example of the burning log that seems to violate conservation of mass. Lavoisier realized that there was a second form of mass, the mass of the smoke, that wasn't being accounted for, and proved by experiments that mass *was*, after all, conserved once the second form had been taken into account. In the case of the falling rock, we have two forms of energy. The first is the energy it has because it's moving, known as *kinetic energy*. The second form is a kind of energy that it has because it's interacting with the planet earth via gravity. This is known as *gravitational energy*.[1] The earth and the rock attract each other gravitationally, and the greater the distance between them, the greater the gravitational energy — it's a little like stretching a spring.



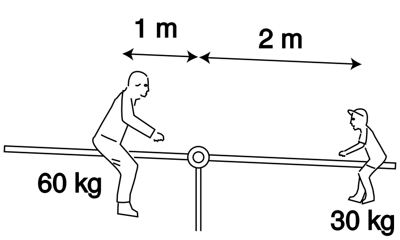
q / As the skater free-falls, his gravitational energy is converted into kinetic energy.

The SI unit of energy is the joule (J), and in those units, we find that lifting a 1-kg mass through a height of 1 m requires 9.8 J of energy. This number, 9.8 joules per meter per kilogram, is a measure of the strength of the earth's gravity near its surface. We notate this number, known as the gravitational field, as g, and often round it off to 10 for convenience in rough calculations. If you lift a 1-kg rock to a height of 1 m above the ground, you're giving up 9.8 J of the energy you got from eating food, and changing it into gravitational energy stored in the rock. If you then release the rock, it starts transforming the energy into kinetic energy, until finally when the rock is just about to hit the ground, all of that energy is in the form of kinetic energy. That kinetic energy is then transformed into heat and sound when the rock hits the ground.

Stated in the language of algebra, the formula for gravitational energy is

$$GE = mgh,$$

where m is the mass of an object, g is the gravitational field, and h is the object's height.



r / Example 5.

A lever *example 5*

Figure r shows two sisters on a seesaw. The one on the left has twice as much mass, but she's at half the distance from the center. No energy input is needed in order to tip the seesaw. If

[1] You may also see this referred to in some books as gravitational potential energy.

the girl on the left goes up a certain distance, her gravitational energy will increase. At the same time, her sister on the right will drop twice the distance, which results in an equal decrease in energy, since her mass is half as much. In symbols, we have

$$(2m)gh$$

for the gravitational energy gained by the girl on the left, and

$$mg(2h)$$

for the energy lost by the one on the right. Both of these equal $2mgh$, so the amounts gained and lost are the same, and energy is conserved.

Looking at it another way, this can be thought of as an example of the kind of experiment that you'd have to do in order to arrive at the equation $GE = mgh$ in the first place. If we didn't already know the equation, this experiment would make us suspect that it involved the product mh, since that's what's the same for both girls.

Once we have an equation for one form of energy, we can establish equations for other forms of energy. For example, if we drop a rock and measure its final velocity, v, when it hits the ground, we know how much GE it lost, so we know that's how much KE it must have had when it was at that final speed. Here are some imaginary results from such an experiment.

m (kg)	**v** (m/s)	**energy** (J)
1.00	1.00	0.50
1.00	2.00	2.00
2.00	1.00	1.00

Comparing the first line with the second, we see that doubling the object's velocity doesn't just double its energy, it quadruples it. If we compare the first and third lines, however, we find that doubling the mass only doubles the energy. This suggests that kinetic energy is proportional to mass times the square of velocity, mv^2, and further experiments of this type would indeed establish such a general rule. The proportionality factor equals 0.5 because of the design of the metric system, so the kinetic energy of a moving object is given by

$$KE = \frac{1}{2}mv^2.$$

t / The spinning coin slows down. It looks like conservation of energy is violated, but it isn't.

Energy in general

By this point, I've casually mentioned several forms of energy: kinetic, gravitational, heat, and sound. This might be disconcerting, since we can get thoroughly messed up if we don't realize that a

s / A vivid demonstration that heat is a form of motion. A small amount of boiling water is poured into the empty can, which rapidly fills up with hot steam. The can is then sealed tightly, and soon crumples. This can be explained as follows. The high temperature of the steam is interpreted as a high average speed of random motions of its molecules. Before the lid was put on the can, the rapidly moving steam molecules pushed their way out of the can, forcing the slower air molecules out of the way. As the steam inside the can thinned out, a stable situation was soon achieved, in which the force from the less dense steam molecules moving at high speed balanced against the force from the more dense but slower air molecules outside. The cap was put on, and after a while the steam inside the can reached the same temperature as the air outside. The force from the cool, thin steam no longer matched the force from the cool, dense air outside, and the imbalance of forces crushed the can.

certain form of energy is important in a particular situation. For instance, the spinning coin in figure t gradually loses its kinetic energy, and we might think that conservation of energy was therefore being violated. However, whenever two surfaces rub together, friction acts to create heat. The correct analysis is that the coin's kinetic energy is gradually converted into heat.

One way of making the proliferation of forms of energy seem less scary is to realize that many forms of energy that seem different on the surface are in fact the same. One important example is that heat is actually the kinetic energy of molecules in random motion, so where we thought we had two forms of energy, in fact there is only one. Sound is also a form of kinetic energy: it's the vibration of air molecules.

This kind of unification of different types of energy has been a process that has been going on in physics for a long time, and at this point we've gotten it down the point where there really only appear to be four forms of energy:

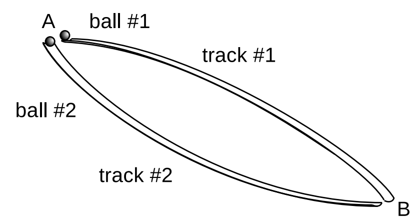
1. kinetic energy
2. gravitational energy
3. electrical energy
4. nuclear energy

We don't even encounter nuclear energy in everyday life (except in the sense that sunlight originates as nuclear energy), so really for most purposes the list only has three items on it. Of these three, electrical energy is the only form that we haven't talked about yet. The interactions between atoms are all electrical, so this form of energy is what's responsible for all of chemistry. The energy in the food you eat, or in a tank of gasoline, are forms of electrical energy.

You take the high road and I'll take the low road. *example 6*

▷ Figure u shows two ramps which two balls will roll down. Compare their final speeds, when they reach point B. Assume friction is negligible.

▷ Each ball loses some gravitational energy because of its decreasing height above the earth, and conservation of energy says that it must gain an equal amount of kinetic energy (minus a little heat created by friction). The balls lose the same amount of height, so their final speeds must be equal.



u / Example 6.

The birth of stars *example 7*

Orion is the easiest constellation to find. You can see it in the winter, even if you live under the light-polluted skies of a big city. Figure v shows an interesting feature of this part of the sky that you can easily pick out with an ordinary camera (that's how I took the picture) or a pair of binoculars. The three stars at the top are Orion's belt, and the stuff near the lower left corner of the picture is known as his sword — to the naked eye, it just looks like three more stars that aren't as bright as the stars in the belt. The middle "star" of the sword, however, isn't a star at all. It's a cloud of gas, known as the Orion Nebula, that's in the process of collapsing due to gravity. Like the pool skater on his way down, the gas is losing gravitational energy. The results are very different, however. The skateboard is designed to be a low-friction device, so nearly all of the lost gravitational energy is converted to kinetic energy, and very little to heat. The gases in the nebula flow and rub against each other, however, so most of the gravitational energy is converted to heat. This is the process by which stars are born: eventually the core of the gas cloud gets hot enough to ignite nuclear reactions.

v / Example 7.

Lifting a weight *example 8*

▷ At the gym, you lift a mass of 40 kg through a height of 0.5 m. How much gravitational energy is required? Where does this energy come from?

▷ The strength of the gravitational field is 10 joules per kilogram per meter, so after you lift the weight, its gravitational energy will be greater by $10 \times 40 \times 0.5 = 200$ joules.

Energy is conserved, so if the weight gains gravitational energy, something else somewhere in the universe must have lost some. The energy that was used up was the energy in your body, which came from the food you'd eaten. This is what we refer to as "burning calories," since calories are the units normally used to describe the energy in food, rather than metric units of joules.

In fact, your body uses up even more than 200 J of food energy, because it's not very efficient. The rest of the energy goes into heat, which is why you'll need a shower after you work out. We can summarize this as

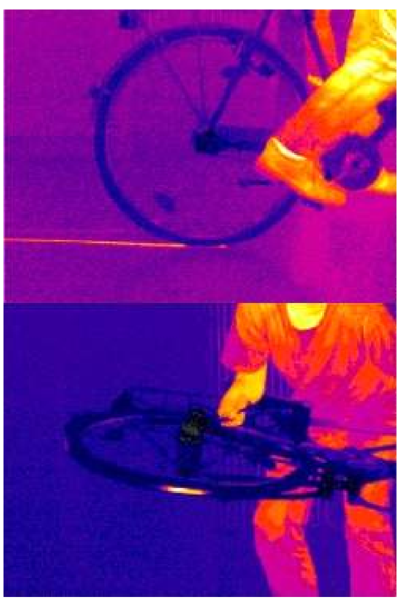
$$\text{food energy} \rightarrow \text{gravitational energy} + \text{heat}.$$

w / Example 10.

Lowering a weight *example 9*

▷ After lifting the weight, you need to lower it again. What's happening in terms of energy?

▷ Your body isn't capable of accepting the energy and putting it back into storage. The gravitational energy all goes into heat. (There's nothing fundamental in the laws of physics that forbids this. Electric cars can do it — when you stop at a stop sign, the car's kinetic energy is absorbed back into the battery, through a generator.)



x / Example 10.

Absorption and emission of light *example 10*

Light has energy. Light can be absorbed by matter and transformed into heat, but the reverse is also possible: an object can glow, transforming some of its heat energy into light. Very hot objects, like a candle flame or a welding torch, will glow in the visible part of the spectrum, as in figure w.

Objects at lower temperatures will also emit light, but in the infrared part of the spectrum, i.e., the part of the rainbow lying beyond the red end, which humans can't see. The photos in figure x were taken using a camera that is sensitive to infrared light. The cyclist locked his rear brakes suddenly, and skidded to a stop. The kinetic energy of the bike and his body are rapidly transformed into heat by the friction between the tire and the floor. In the first panel, you can see the glow of the heated strip on the floor, and in the second panel, the heated part of the tire.

Heavy objects don't fall faster — *example 11*

Stand up now, take off your shoe, and drop it alongside a much less massive object such as a coin or the cap from your pen.

Did that surprise you? You found that they both hit the ground at the same time. Aristotle wrote that heavier objects fall faster than lighter ones. He was wrong, but Europeans believed him for thousands of years, partly because experiments weren't an accepted way of learning the truth, and partly because the Catholic Church gave him its posthumous seal of approval as its official philosopher.

Heavy objects and light objects have to fall the same way, because conservation laws are additive — we find the total energy of an object by adding up the energies of all its atoms. If a single atom falls through a height of one meter, it loses a certain amount of gravitational energy and gains a corresponding amount of kinetic energy. Kinetic energy relates to speed, so that determines how fast it's moving at the end of its one-meter drop. (The same reasoning could be applied to any point along the way between zero meters and one.)

Now what if we stick two atoms together? The pair has double the mass, so the amount of gravitational energy transformed into kinetic energy is twice as much. But twice as much kinetic energy is exactly what we need if the pair of atoms is to have the same speed as the single atom did. Continuing this train of thought, it doesn't matter how many atoms an object contains; it will have the same speed as any other object after dropping through the same height.

1.5 Newton's Law of Gravity

Why does the gravitational field on our planet have the particular value it does? For insight, let's compare with the strength of gravity elsewhere in the universe:

location	g (joules per kg per m)
asteroid Vesta (surface)	0.3
earth's moon (surface)	1.6
Mars (surface)	3.7
earth (surface)	9.8
Jupiter (cloud-tops)	26
sun (visible surface)	270
typical neutron star (surface)	10^{12}
black hole (center)	infinite according to some theories, on the order of 10^{52} according to others

A good comparison is Vesta versus a neutron star. They're roughly the same size, but they have vastly different masses — a teaspoonful of neutron star matter would weigh a million tons! The different mass must be the reason for the vastly different gravitational fields. (The notation 10^{12} means 1 followed by 12 zeroes.) This makes sense, because gravity is an attraction between things that have mass.

The mass of an object, however, isn't the only thing that determines the strength of its gravitational field, as demonstrated by the difference between the fields of the sun and a neutron star, despite their similar masses. The other variable that matters is distance. Because a neutron star's mass is compressed into such a small space (comparable to the size of a city), a point on its surface is within a fairly short distance from every part of the star. If you visited the surface of the sun, however, you'd be millions of miles away from most of its atoms.

As a less exotic example, if you travel from the seaport of Guayaquil, Ecuador, to the top of nearby Mt. Cotopaxi, you'll experience a slight reduction in gravity, from 9.7806 to 9.7624 J/kg/m. This is because you've gotten a little farther from the planet's mass. Such differences in the strength of gravity between one location and another on the earth's surface were first discovered because pendulum clocks that were correctly calibrated in one country were found to run too fast or too slow when they were shipped to another location.

The general equation for an object's gravitational field was discovered by Isaac Newton, by working backwards from the observed motion of the planets:[2]

$$g = \frac{GM}{d^2},$$

where M is the mass of the object, d is the distance from the object, and G is a constant that is the same everywhere in the universe. This is known as Newton's law of gravity.[3] This type of relationship, in which an effect is inversely proportional to the square of the distance from the object creating the effect, is known as an inverse square law. For example, the intensity of the light from a candle obeys an inverse square law, as discussed in subsection 7.2.1 on page 140.

y / Isaac Newton (1642-1727)

self-check C

Mars is about twice as far from the sun as Venus. Compare the strength of the sun's gravitational field as experienced by Mars with the strength of the field felt by Venus. ▷ Answer, p. 179

Newton's law of gravity really gives the field of an individual atom, and the field of a many-atom object is the sum of the fields of the atoms. Newton was able to prove mathematically that this scary sum has an unexpectedly simple result in the case of a spherical object such as a planet: the result is the same as if all the object's

[2]Example 12 on page 50 shows the type of reasoning that Newton had to go through.

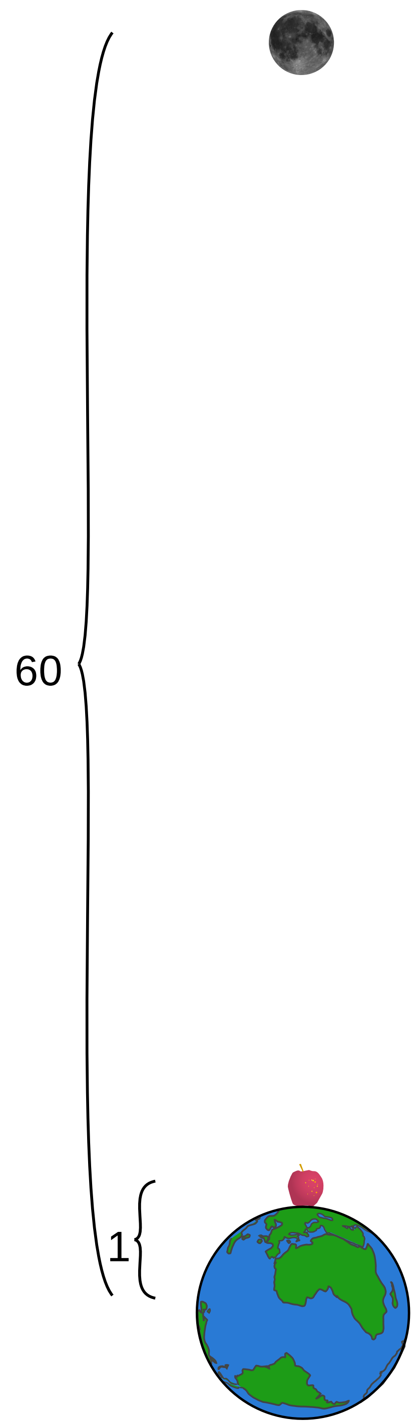
[3]This is not the form in which Newton originally wrote the equation.

mass had been concentrated at its center.

Newton showed that his theory of gravity could explain the orbits of the planets, and also finished the project begun by Galileo of driving a stake through the heart of Aristotelian physics. His book on the motion of material objects, the *Mathematical Principles of Natural Philosophy*, was uncontradicted by experiment for 200 years, but his other main work, *Optics*, was on the wrong track due to his conviction that light was composed of particles rather than waves. He was an avid alchemist, an embarrassing fact that modern scientists would like to forget. Newton was on the winning side of the revolution that replaced King James II with William and Mary of Orange, which led to a lucrative post running the English royal mint; he worked hard at what could have been a sinecure, and took great satisfaction from catching and executing counterfeiters. Newton's personal life was less happy, as we'll see in chapter 5.

Newton's apple — *example 12*

A charming legend attested to by Newton's niece is that he first conceived of gravity as a universal attraction after seeing an apple fall from a tree. He wondered whether the force that made the apple fall was the same one that made the moon circle the earth rather than flying off straight. Newton had astronomical data that allowed him to calculate that the gravitational field the moon experienced from the earth was 1/3600 as strong as the field on the surface of the earth.[4] (The moon has its own gravitational field, but that's not what we're talking about.) The moon's distance from the earth is 60 times greater than the earth's radius, so this fit perfectly with an inverse-square law: $60 \times 60 = 3600$.



z / Example 12.

1.6 Noether's Theorem for Energy

Now we're ready for our first full-fledged example of Noether's theorem. Conservation of energy is a law of physics, and Noether's theorem says that the laws of physics come from symmetry. Specifically, Noether's theorem says that every symmetry implies a conservation law. Conservation of energy comes from a symmetry that we haven't even discussed yet, but one that is simple and intuitively appealing: as time goes by, the universe doesn't change the way it works. We'll call this time symmetry.

We have strong evidence for time symmetry, because when we see a distant galaxy through a telescope, we're seeing light that has taken billions of years to get here. A telescope, then, is like a time machine. For all we know, alien astronomers with advanced technology may be observing our planet right now,[5] but if so, they're

[4] See example 12 on page 50.

[5] Our present technology isn't good enough to let us pick the planets of other solar systems out from the glare of their suns, except in a few exceptional cases.

seeing it not as it is now but as it was in the distant past, perhaps in the age of the dinosaurs, or before life even evolved here. As we observe a particularly distant, and therefore ancient, supernova, we see that its explosion plays out in exactly the same way as those that are closer, and therefore more recent.

Now suppose physics really does change from year to year, like politics, pop music, and hemlines. Imagine, for example, that the "constant" G in Newton's law of gravity isn't quite so constant. One day you might wake up and find that you've lost a lot of weight without dieting or exercise, simply because gravity has gotten weaker since the day before.

If you know about such changes in G over time, it's the ultimate insider information. You can use it to get as rich as Croesus, or even Bill Gates. On a day when G is low, you pay for the energy needed to lift a large mass up high. Then, on a day when gravity is stronger, you lower the mass back down, extracting its gravitational energy. The key is that the energy you get back out is greater than what you originally had to put in. You can run the cycle over and over again, always raising the weight when gravity is weak, and lowering it when gravity is strong. Each time, you make a profit in energy. Everyone else thinks energy is conserved, but your secret technique allows you to keep on increasing and increasing the amount of energy in the universe (and the amount of money in your bank account).

The scheme can be made to work if anything about physics changes over time, not just gravity. For instance, suppose that the mass of an electron had one value today, and a slightly different value tomorrow. Electrons are one of the basic particles from which atoms are built, so on a day when the mass of electrons is low, every physical object has a slightly lower mass. In problem 14 on page 35, you'll work out a way that this could be used to manufacture energy out of nowhere.

Sorry, but it won't work. Experiments show that G doesn't change measurably over time, nor does there seem to be any time variation in any of the other rules by which the universe works.[6] If archaeologists find a copy of this book thousands of years from now, they'll be able to reproduce all the experiments you're doing in this course.

I've probably convinced you that if time symmetry was violated, then conservation of energy wouldn't hold. But does it work the

[6] In 2002, there have been some reports that the properties of atoms as observed in distant galaxies are slightly different than those of atoms here and now. If so, then time symmetry is weakly violated, and so is conservation of energy. However, this is a revolutionary claim, and it needs to be examined carefully. The change being claimed is large enough that, if it's real, it should be detectable from one year to the next in ultra-high-precision laboratory experiments here on earth.

other way around? If time symmetry is valid, must there be a law of conservation of energy? Logically, that's a different question. We may be able to prove that if A is false, then B must be false, but that doesn't mean that if A is true, B must be true as well. For instance, if you're not a criminal, then you're presumably not in jail, but just because someone is a criminal, that doesn't mean he is in jail — some criminals never get caught.

Noether's theorem does work the other way around as well: if physics has a certain symmetry, then there must be a certain corresponding conservation law. This is a stronger statement. The full-strength version of Noether's theorem can't be proved without a model of light and matter more detailed than the one currently at our disposal.

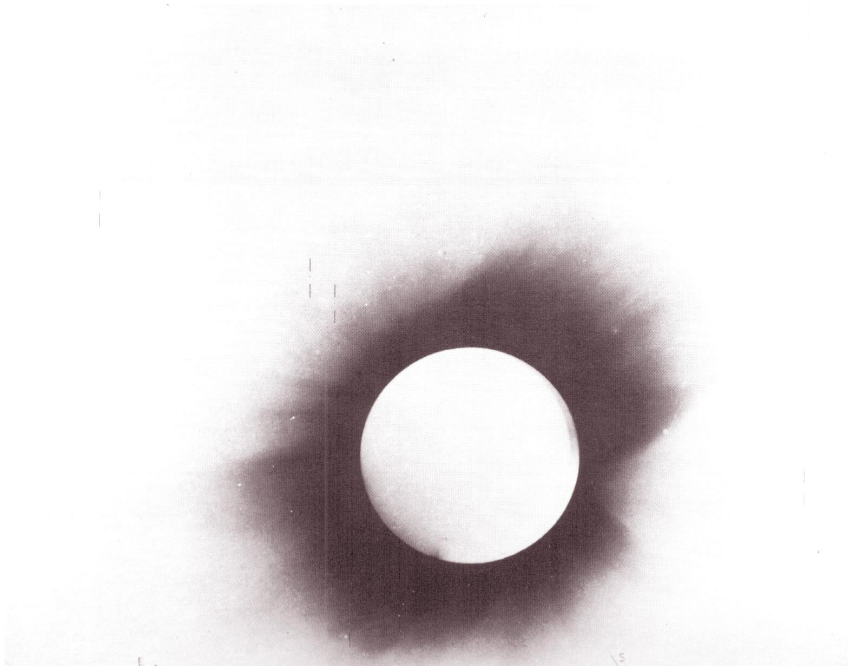
1.7 Equivalence of Mass and Energy

Mass-energy

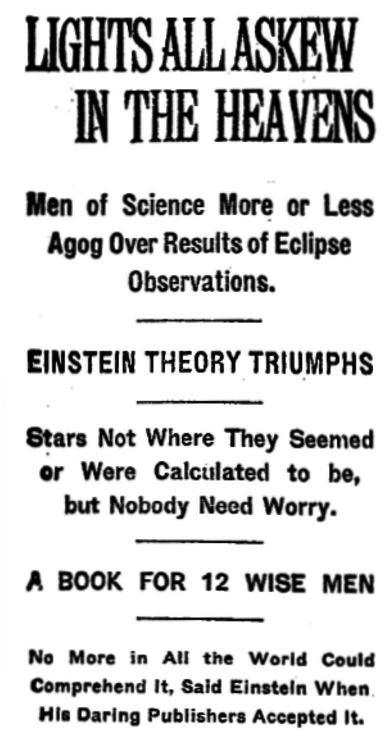
You've encountered two conservation laws so far: conservation of mass and conservation of energy. If conservation of energy is a consequence of symmetry, is there a deeper reason for conservation of mass?

Actually they're not even separate conservation laws. Albert Einstein found, as a consequence of his theory of relativity, that mass and energy are equivalent, and are not separately conserved — one can be converted into the other. Imagine that a magician waves his wand, and changes a bowl of dirt into a bowl of lettuce. You'd be impressed, because you were expecting that both dirt and lettuce would be conserved quantities. Neither one can be made to vanish, or to appear out of thin air. However, there are processes that can change one into the other. A farmer changes dirt into lettuce, and a compost heap changes lettuce into dirt. At the most fundamental level, lettuce and dirt aren't really different things at all; they're just collections of the same kinds of atoms — carbon, hydrogen, and so on.

We won't examine relativity in detail in this book, but mass-energy equivalence is an inevitable implication of the theory, and it's the only part of the theory that most people have heard of, via the famous equation $E = mc^2$. This equation tells us how much energy is equivalent to how much mass: the conversion factor is the square of the speed of light, c. Since c is a big number, you get a really really big number when you multiply it by itself to get c^2. This means that even a small amount of mass is equivalent to a very large amount of energy.



aa / Example 13.



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

ab / A New York Times headline from November 10, 1919, describing the observations discussed in example 13.

Gravity bending light — *example 13*

Gravity is a universal attraction between things that have mass, and since the energy in a beam of light is equivalent to some very small amount of mass, we expect that light will be affected by gravity, although the effect should be very small. The first experimental confirmation of relativity came in 1919 when stars next to the sun during a solar eclipse were observed to have shifted a little from their ordinary position. (If there was no eclipse, the glare of the sun would prevent the stars from being observed.) Starlight had been deflected by the sun's gravity. Figure aa is a photographic negative, so the circle that appears bright is actually the dark face of the moon, and the dark area is really the bright corona of the sun. The stars, marked by lines above and below them, appeared at positions slightly different than their normal ones.

Black holes — *example 14*

A star with sufficiently strong gravity can prevent light from leaving. Quite a few black holes have been detected via their gravitational forces on neighboring stars or clouds of gas and dust.

Because mass and energy are like two different sides of the same coin, we may speak of mass-energy, a single conserved quantity, found by adding up all the mass and energy, with the appropriate conversion factor: $E + mc^2$.

A rusting nail *example 15*

▷ An iron nail is left in a cup of water until it turns entirely to rust. The energy released is about 500,000 joules. In theory, would a sufficiently precise scale register a change in mass? If so, how much?

▷ The energy will appear as heat, which will be lost to the environment. The total mass-energy of the cup, water, and iron will indeed be lessened by 500,000 joules. (If it had been perfectly insulated, there would have been no change, since the heat energy would have been trapped in the cup.) The speed of light in metric units is $c = 3 \times 10^8$ meters per second (scientific notation for 3 followed by 8 zeroes), so converting to mass units, we have

$$\begin{aligned} m &= \frac{E}{c^2} \\ &= \frac{500,000}{\left(3 \times 10^8\right)^2} \\ &= 0.000000000006 \text{ kilograms.} \end{aligned}$$

(The design of the metric system is based on the meter, the kilogram, and the second. The joule is designed to fit into this system, so the result comes out in units of kilograms.) The change in mass is too small to measure with any practical technique. This is because the square of the speed of light is such a large number in metric units.

The correspondence principle

The realization that mass and energy are not separately conserved is our first example of a general idea called the correspondence principle. When Einstein came up with relativity, conservation of energy had been accepted by physicists for decades, and conservation of mass for over a hundred years.

Does an example like this mean that physicists don't know what they're talking about? There is a recent tendency among social scientists to deny that the scientific method even exists, claiming that science is no more than a social system that determines what ideas to accept based on an in-group's criteria. If science is an arbitrary social ritual, it would seem difficult to explain its effectiveness in building such useful items as airplanes, CD players and sewers. If voodoo and astrology were no less scientific in their methods than chemistry and physics, what was it that kept them from producing anything useful? This silly attitude was effectively skewered in a famous hoax carried out in 1996 by New York University physicist Alan Sokal. Sokal wrote an article titled "Transgressing the Boundaries: Toward a Transformative Hermeneutics of Quantum Gravity," and got it accepted by a cultural studies journal called *Social Text*.[7]

[7] The paper appeared in *Social Text* #46/47 (1996) pp. 217-

The scientific content of the paper is a carefully constructed soup of mumbo jumbo, using technical terms to create maximum confusion; I can't make heads or tails of it, and I assume the editors and peer reviewers at *Social Text* understood even less. The physics, however, is mixed in with cultural relativist statements designed to appeal to them — "...the truth claims of science are inherently theory-laden and self-referential" — and footnoted references to academic articles such as "Irigaray's and Hayles' exegeses of gender encoding in fluid mechanics ... and ... Harding's comprehensive critique of the gender ideology underlying the natural sciences in general and physics in particular..." On the day the article came out, Sokal published a letter explaining that the whole thing had been a parody — one that apparently went over the heads of the editors of *Social Text*.

What keeps physics from being merely a matter of fashion is that it has to agree with experiments and observations. If a theory such as conservation of mass or conservation of energy became accepted in physics, it was because it was supported by a vast number of experiments. It's just that experiments never have perfect accuracy, so a discrepancy such as the tiny change in the mass of the rusting nail in example 15 was undetectable. The old experiments weren't all wrong. They were right, within their limitations. If someone comes along with a new theory he claims is better, it must still be consistent with all the same experiments. In computer jargon, it must be backward-compatible. This is called the correspondence principle: new theories must be compatible with old ones in situations where they are both applicable. The correspondence principle tells us that we can still use an old theory within the realm where it works, so for instance I'll typically refer to conservation of mass and conservation of energy in this book rather than conservation of mass-energy, except in cases where the new theory is actually necessary.

Ironically, the extreme cultural relativists want to attack what they see as physical scientists' arrogant claims to absolute truth, but what they fail to understand is that science only claims to be able to find partial, provisional truth. The correspondence principle tells us that each of today's scientific truths can be superseded tomorrow by another truth that is more accurate and more broadly applicable. It also tells us that today's truth will not lose any value when that happens.

---

252. The full text is available on Professor Sokal's web page at www.physics.nyu.edu/faculty/sokal/.