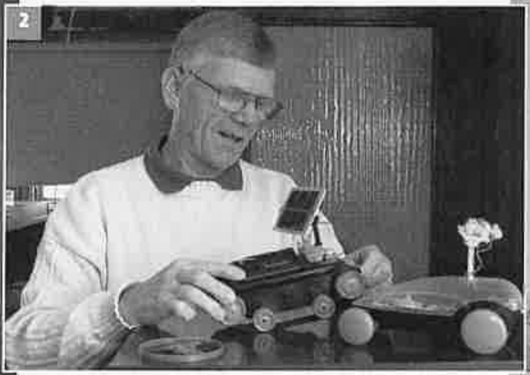
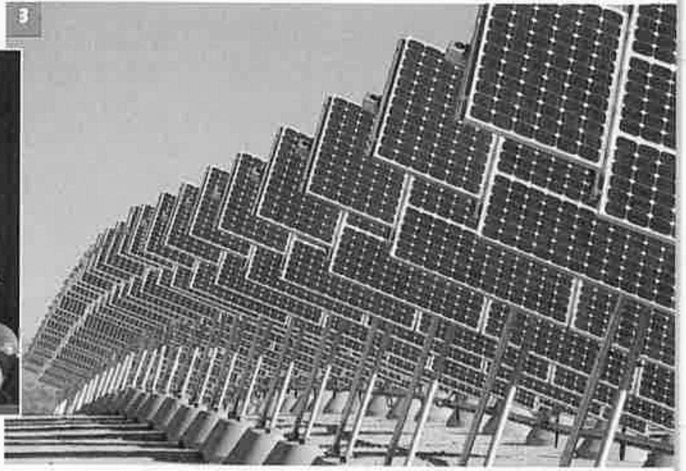
7 Energy





1 Electrical energy is created by wind turbines; we call them windmills when they are used to mill grain or pump water. 2 Roy Unruh converts light energy to electrical energy with small photovoltaic cells mounted on model solar-powered vehicles. 3 On a grander scale, this photovoltaic farm at Nellis Air Force Base in Nevada leads America's way in harvesting clean solar energy.

One of France's greatest scientists was Emilie du Chatelet, who lived during the 1700s when all of Europe was celebrating the achievements of Isaac Newton. She was accomplished not only in science but also in philosophy and even Biblical studies. She was the first to translate Newton's *Principia* into French, and she annotated her translation with new results in mechanics.

Of du Chatelet's several lovers, Voltaire was the most intense. For 15 years they lived together, collecting a library of more than 20,000 volumes, each encouraging and critiquing the work of the other. Theirs was one of the most exciting and passionate European love stories.

At the time there was a great debate in physics about the nature of the "oomph" possessed by moving objects. Scientists in England claimed oomph (what we would now call kinetic energy) was mass × velocity, whereas scientists such as Leibniz in Germany claimed it was mass × velocity squared. The debate was finally settled by observations and a paper published by du Chatelet that cited another scientist's simple experiment to distinguish between the two hypotheses. When a small solid brass sphere is dropped into clay, it makes a dent. If the ball hits with twice the speed, and if its oomph is mass × velocity, the dent in the clay should be twice as deep. But experiment showed it was 4 times as deep (2 squared). Dropping the ball higher so it hit with 3 times the speed produced a dent that was not 3 times as deep, but 9 times as deep (3 squared). Since Emilie du Chatelet was so highly respected by the scientific community, she ended the controversy by supporting the argument that the oomph of moving things is proportional to mass × velocity squared.

Emilie became pregnant at the age of 42, which was dangerous at the time. Doctors then had no awareness that they should wash their hands or instruments. There were no antibiotics to control infections, which were common. She died a week after the birth. Voltaire was beside himself: "I have lost the half of myself—a soul for which mine was made." Although Voltaire's collected publications had exceeded 10,000 printed pages, after her death he published no other scientific commentaries, even into a ripe old age.

As we learned in the previous chapter, mass × velocity is what we call *momentum*. In this chapter, we see that mass × velocity squared (together with a factor of 1/2) is what we call *kinetic energy*. We will now learn about forms of energy, including kinetic energy.

We begin by considering a related concept: *work*.

Work

In the previous chapter, we saw that changes in an object's motion depend both on force and on how long the force acts. "How long" meant time. We called the quantity "force × time" *impulse*. But "how long" does not always mean time. It can mean distance also. When we consider the concept of force × *distance*, we are talking about an entirely different concept—**work.** Work is the effort exerted on something that will change its energy.

When we lift a load of gravel against Earth's gravity, work is done. The heavier the load or the higher we lift the load, the more work is done. Two things enter the picture whenever work is done: (1) application of a force and (2) the movement of something by that force. For the simplest case, where the force is constant and the motion is in a straight line in the direction of the force,[1] we define the work done on an object by an applied force as the product of the force and the distance through which the object is moved. In shorter form:

$$\text{Work} = \text{force} \times \text{distance}$$

$$W = Fd$$

The word *work*, in common usage, means physical or mental exertion. Don't confuse the physics definition of work with the everyday notion of work. Work is a transfer of energy.

If we lift two loads of gravel one story up, we do twice as much work as in lifting one load the same distance, because the *force* needed to lift twice the weight is twice as much. Similarly, if we lift a load two stories instead of one story, we do twice as much work because the *distance* is twice as great.

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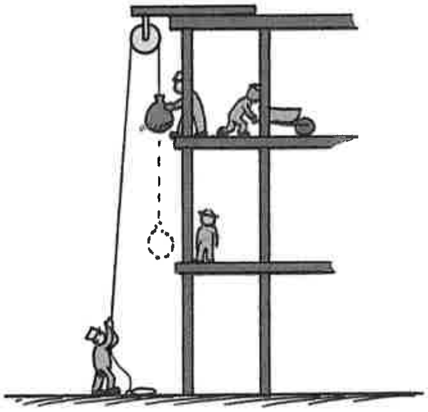

FIGURE 7.1
Compared with the work done in lifting a load of gravel one story high, twice as much work is done in lifting the same load two stories high. Twice the work is done because the distance is twice as much.

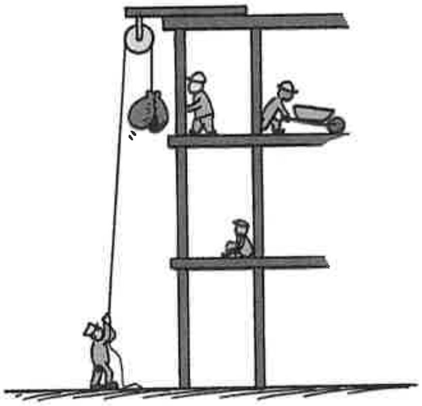

FIGURE 7.2
When twice the load of gravel is lifted to the same height, twice as much work is done because the force needed to lift it is twice as much.

We see that the definition of work involves both a force and a distance. A weightlifter who holds a barbell weighing 1000 newtons overhead does no work on the barbell. He may get really tired holding the barbell, but, if it is not moved by

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[1] More generally, work is the product of only the component of force that acts in the direction of motion and the distance moved. For example, if a force acts at an angle to the motion, the component of force parallel to motion is multiplied by the distance moved. When a force acts at right angles to the direction of motion, with no force component in the direction of motion, no work is done. A common example is a satellite in a circular orbit; the force of gravity is at right angles to its circular path and no work is done on the satellite. Hence, it orbits with no change in speed.

the force he exerts, he does no work *on the barbell.* Work may be done on the muscles by stretching and contracting, which is force times distance on a biological scale, but this work is not done on the barbell. Lifting the barbell, however, is a different story. When the weightlifter raises the barbell from the floor, he does work on it.

Work generally falls into two categories. One of these is the work done against another force. When an archer stretches her bowstring, she is doing work against the elastic forces of the bow. Similarly, when the ram of a pile driver is raised, work is required to raise the ram against the force of gravity. When you do push-ups, you do work against your own weight. You do work on something when you force it to move against the influence of an opposing force—often friction.

The other category of work is work done to change the speed of an object. This kind of work is done in bringing an automobile up to speed or in slowing it down. Another example of this kind of work occurs when a club hits a stationary golf ball and gets it moving. In both categories (working against a force or changing speed), work involves a transfer of energy.

The unit of measurement for work combines a unit of force (N) with a unit of distance (m); the unit of work is the newton-meter (N·m), also called the *joule* (J), which rhymes with *cool.* One joule of work is done when a force of 1 newton is exerted over a distance of 1 meter, as in lifting an apple over your head. For larger values, we speak of kilojoules (kJ, thousands of joules), or megajoules (MJ, millions of joules). The weightlifter in Figure 7.3 does work in kilojoules. To stop a loaded truck going at 100 km/h takes megajoules of work.

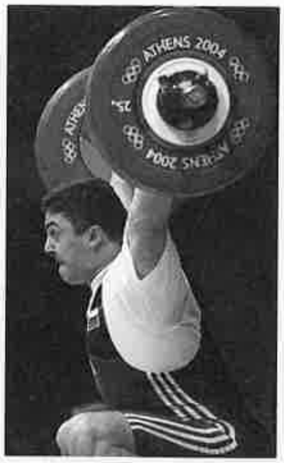
FIGURE 7.3
Work is done in lifting the barbell.


FIGURE 7.4
He may expend energy when he pushes on the wall, but, if the wall doesn't move, no work is done on the wall.

CHECK POINT

1. How much work is needed to lift a bag of groceries that weighs 200 N to a height of 3 m?
2. How much work is needed to lift it twice as high?

Check Your Answers

1. $W = F \times d = 200\ \text{N} \times 3\ \text{m} = 600\ \text{J}$.
2. Lifting the bag twice as high requires twice the work ($200\ \text{N} \times 6\ \text{m} = 1200\ \text{J}$).

Power

The definition of work says nothing about how long it takes to do the work. The same amount of work is done when carrying a load of groceries up a flight of stairs, whether we walk up or run up. So why are we more tired after running upstairs in a few seconds than after walking upstairs in a few minutes? To understand this difference, we need to talk about a measure of how fast the work is done—*power.* **Power** is equal to the amount of work done per time it takes to do it:

$$\text{Power} = \frac{\text{work done}}{\text{time interval}}$$

A high-power engine does work rapidly. An automobile engine that delivers twice the power of another automobile engine does not necessarily produce twice as much work or make a car go twice as fast as the less powerful engine. Twice the power means the engine can do twice the work in the same time or do the same amount of work in half the time. A more powerful engine can get an automobile up to a given speed in less time than a less powerful engine can.

fyi

- Your heart uses slightly more than 1 W of power in pumping blood through your body.

Here's another way to look at power: A liter (L) of fuel can do a certain amount of work, but the power produced when we burn it can be any amount, depending on how *fast* it is burned. It can operate a lawnmower for a half hour or a jet engine for a half second.

The unit of power is the joule per second (J/s), also known as the watt (in honor of James Watt, the 18th-century developer of the steam engine). One watt (W) of power is expended when 1 joule of work is done in 1 second. One kilowatt (kW) equals 1000 watts. One megawatt (MW) equals 1 million watts. In the United States, we customarily rate engines in units of horsepower and electricity in kilowatts, but either may be used. In the metric system of units, automobiles are rated in kilowatts. (One horsepower is the same as three-fourths of a kilowatt, so an engine rated at 134 horsepower is a 100-kW engine.)

FIGURE 7.5

The three main engines of a space shuttle can develop 33,000 MW of power when fuel is burned at the enormous rate of 3400 kg/s. This is like emptying an average-size swimming pool in 20 s.

CHECK POINT

If a forklift is replaced with a new forklift that has twice the power, how much more dirt can it lift in the same amount of time? If it lifts the same dirt, how much faster can it operate?

Check Your Answer

The forklift that delivers twice the power will lift twice the load of dirt in the same time or the same load in half the time. Either way, the owner of the new forklift is happy.

Mechanical Energy

When work is done by an archer in drawing a bowstring, the bent bow acquires the ability to do work on the arrow. When work is done to raise the heavy ram of a pile driver, the ram acquires the ability to do work on the object it hits when it falls. When work is done to wind a spring mechanism, the spring acquires the ability to do work on various gears to run a clock, ring a bell, or sound an alarm.

fyi

- The concept of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Although familiar, energy is difficult to define because it is both a "thing" and a process—similar to both a noun and a verb. We observe the energy in things only when it is being transferred or being transformed.

In each case, something has been acquired that enables the object to do work. It may be in the form of a compression of atoms in the material of an object, a physical separation of attracting bodies, or a rearrangement of electric charges in the molecules of a substance. This "something" that enables an object to do work is **energy.**[2] Like work, energy is measured in joules. It appears in many forms that will be discussed in the following chapters. For now, we will focus on the two most common forms of **mechanical energy**—the energy due to the position of something or the movement of something. Mechanical energy can be in the form of potential energy, kinetic energy, or the sum of the two.

POTENTIAL ENERGY

An object may store energy by virtue of its position. The energy that is stored and held in readiness is called **potential energy** (PE) because in the stored state it has the potential for doing work. A stretched or compressed spring, for example, has the potential for doing work. When a bow is drawn, energy is stored in the bow. The bow can do work on the arrow. A stretched rubber band has potential energy because of the relative position of its parts. If the rubber band is part of a slingshot, it is capable of doing work.

The chemical energy in fuels is also potential energy. It is actually energy of position at the submicroscopic level. This energy is available when the positions of

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[2] Strictly speaking, that which enables an object to do work is its *available energy*, for not all the energy in an object can be transformed to work.

electric charges within and between molecules are altered—that is, when a chemical change occurs. Any substance that can do work through chemical action possesses potential energy. Potential energy is found in fossil fuels, electric batteries, and the foods we consume.

Work is required to elevate objects against Earth's gravity. The potential energy due to elevated positions is called *gravitational potential energy.* Water in an elevated reservoir and the raised ram of a pile driver both have gravitational potential energy. Whenever work is done, energy is exchanged.

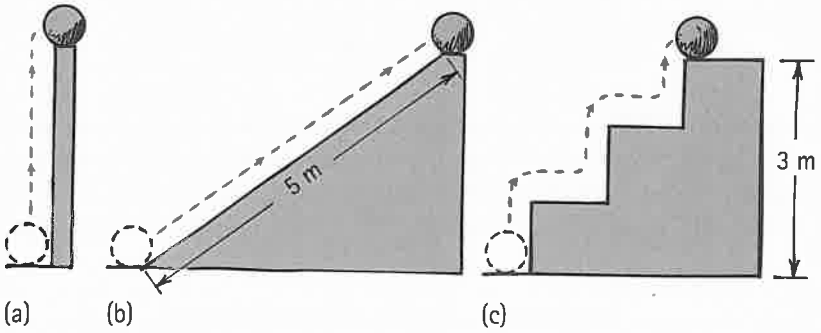

FIGURE 7.6

The potential energy of the 10-N ball is the same (30 J) in all three cases because the work done in elevating it 3 m is the same whether it is (a) lifted with 10 N of force, (b) pushed with 6 N of force up the 5-m incline, or (c) lifted with 10 N up each 1-m stair. No work is done in moving it horizontally (neglecting friction).

The amount of gravitational potential energy possessed by an elevated object is equal to the work done against gravity in lifting it. The work done equals the force required to move it upward times the vertical distance it is moved (remember $W = Fd$). The upward force required while moving at constant velocity is equal to the weight, mg, of the object, so the work done in lifting it through a height h is the product mgh.

$$\text{Gravitational potential energy} = \text{weight} \times \text{height}$$

$$\text{PE} = mgh$$

Note that the height is the distance above some chosen reference level, such as the ground or the floor of a building. The gravitational potential energy, mgh, is relative to that level and depends only on mg and h. We can see, in Figure 7.6, that the potential energy of the elevated ball does not depend on the path taken to get it there.

Potential energy, gravitational or otherwise, has significance only when it *changes*—when it does work or transforms to energy of some other form. For example, if the ball in Figure 7.6 falls from its elevated position and does 20 joules of work when it lands, then it has lost 20 joules of potential energy. The potential energy of the ball or any object is relative to some reference level. Only *changes* in potential energy are meaningful. One of the kinds of energy into which potential energy can change is energy of motion, or *kinetic energy.*

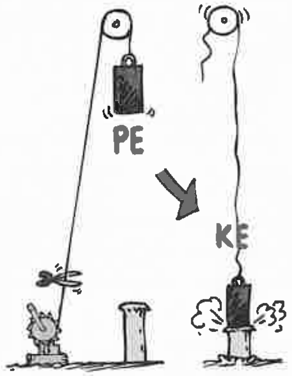

FIGURE 7.7

The potential energy of the elevated ram of the pile driver is converted to kinetic energy when it is released.

CHECK POINT

1. How much work is done in lifting the 100-N block of ice a vertical distance of 2 m, as shown in Figure 7.8?
2. How much work is done in pushing the same block of ice up the 4-m-long ramp? (The force needed is only 50 N, which is the reason ramps are used).
3. What is the increase in the block's gravitational potential energy in each case?

Check your Answers

1. $W = Fd = 100\text{ N} \times 2\text{ m} = 200\text{ J}$.
2. $W = Fd = 50\text{ N} \times 4\text{ m} = 200\text{ J}$.
3. Either way increases the block's potential energy by 200 J. The ramp simply makes this work easier to perform.

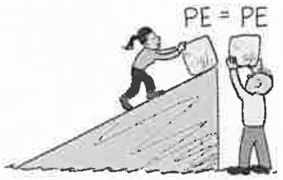

FIGURE 7.8

Both do the same work in elevating the block.

FIGURE 7.9

The potential energy of Tenny's drawn bow equals the work (average force × distance) that she did in drawing the arrow into position. When the arrow is released, most of the potential energy of the drawn bow will become the kinetic energy of the arrow.

KINETIC ENERGY

If you push on an object, you can set it in motion. If an object is moving, then it is capable of doing work. It has energy of motion. We say it has *kinetic energy* (KE). The **kinetic energy** of an object depends on the mass of the object as well as its speed. It is equal to the mass multiplied by the square of the speed, multiplied by the constant $\frac{1}{2}$.

$$\text{Kinetic energy} = \frac{1}{2}\,\text{mass} \times \text{speed}^2$$

$$\text{KE} = \frac{1}{2}\,mv^2$$

When you throw a ball, you do work on it to give it speed as it leaves your hand. The moving ball can then hit something and push it, doing work on what it hits. The kinetic energy of a moving object is equal to the work required to bring it from rest to that speed, or the work the object can do while being brought to rest:

$$\text{Net force} \times \text{distance} = \text{kinetic energy}$$

or, in equation notation,

$$Fd = \frac{1}{2}\,mv^2$$

Note that the speed is squared, so if the speed of an object is doubled, its kinetic energy is quadrupled ($2^2 = 4$). Consequently, it takes 4 times the work to double the speed. Whenever work is done, energy changes.

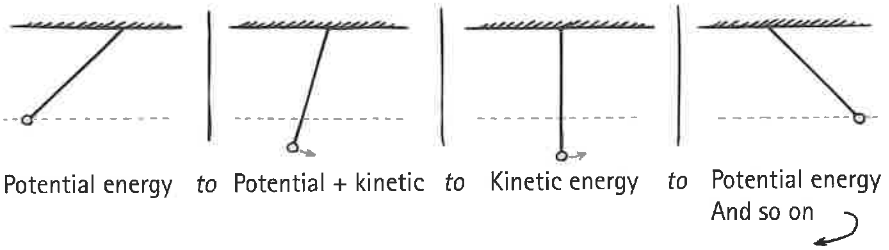

FIGURE 7.10

Energy transitions in a pendulum. PE is relative to the lowest point of the pendulum, when it is vertical.

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Bowling Ball and Conservation of Energy

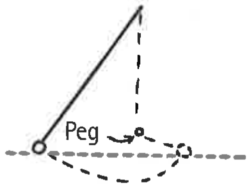

FIGURE 7.11

INTERACTIVE FIGURE

The pendulum bob will swing to its original height whether or not the peg is present.

FIGURE 7.12

The downhill "fall" of the roller coaster results in its roaring speed in the dip, and this kinetic energy sends it up the steep track to the next summit.

WORK-ENERGY THEOREM

When a car speeds up, its gain in kinetic energy comes from the work done on it. Or, when a moving car slows, work is done to reduce its kinetic energy. We can say[3]

$$\text{Work} = \Delta\text{KE}$$

Energy is nature's way of keeping score. Scams that sell energy-making machines rely on funding from deep pockets and shallow brains!

Work equals *change* in kinetic energy. This is the **work-energy theorem.** The work in this equation is the *net* work—that is, the work based on the net force. If, for instance, you push on an object and friction also acts on the object, the change of kinetic energy is equal to the work done by the net force, which is your push minus friction. In this case, only part of the total work that you do changes the object's kinetic energy. The rest is soaked up by friction, which goes into heat. If the force of friction is equal and opposite to your push, the net force on the object is zero and no net work is done. Then there is zero change in the object's kinetic energy. The work-energy theorem applies to decreasing speed as well. When you slam on the brakes of an old car, causing it to skid, the road does work on the car. This work is the friction force multiplied by the distance over which the friction force acts.

Interestingly, the maximum friction that the road can supply to a skidding tire is nearly the same whether the car moves slowly or quickly. A car moving at twice the speed of another takes 4 times ($2^2 = 4$) as much work to stop. Since the frictional force is nearly the same for both cars, the faster one skids 4 times as far before it stops. So, as accident investigators are well aware, an automobile going 100 km/h, with 4 times the kinetic energy that it would have at 50 km/h, skids 4 times as far with its wheels locked as it would from a speed of 50 km/h. Kinetic energy depends on speed *squared.* The same reasoning applies for antilock brakes (which keep wheels from skidding). For the not-quite-skidding tire, the maximum road friction is also nearly independent of speed, so even with antilock brakes, it takes 4 times as far to stop at twice the speed.

When an automobile is braked, the drums and tires convert kinetic energy to heat. Some drivers are familiar with another way to slow a vehicle—shift to low gear and allow the engine to do the braking. Today's hybrid cars do something similar; they use an electric generator to convert the kinetic energy of the slowing car to electric energy that can be stored in batteries, where it is used to complement the energy produced by gasoline combustion. (Chapter 25 treats how they do this.) Hooray for hybrid cars!

The work-energy theorem applies to more than changes in kinetic energy. Work can change the potential energy of a mechanical device, the heat energy in a thermal system, or the electrical energy in an electrical device. Work is not a form of energy, but a way of transferring energy from one place to another or one form to another.

Kinetic energy and potential energy are two among many forms of energy, and they underlie other forms of energy, such as chemical energy, nuclear energy, and the energy carried by sound and light. Kinetic energy of random molecular motion is related to temperature; potential energies of electric charges account for voltage; and kinetic and potential energies of vibrating air define sound intensity. Even light energy originates from the motion of electrons within atoms. Every form of energy can be transformed into every other form.

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[3] This can be derived as follows: If we multiply both sides of $F = ma$ (Newton's second law) by d, we get $Fd = mad$. Recall from Chapter 3 that for constant acceleration from rest, $d = \frac{1}{2}at^2$, so we can say $Fd = ma(\frac{1}{2}at^2) = (\frac{1}{2})maat^2 = \frac{1}{2}m(at)^2$; and substituting $v = at$, we get $Fd = \frac{1}{2}mv^2$. That is, Work = KE gained.

FIGURE 7.13

Due to friction, energy is transferred both into the floor and into the tire when the bicycle skids to a stop. An infrared camera reveals the heated tire track (the red streak on the floor, left) and the warmth of the tire (right). (Courtesy of Michael Vollmer.)

CHECK POINT

1. When you are driving at 90 km/h, how much more distance do you need to stop compared with driving at 30 km/h?
2. Can an object have energy?
3. Can an object have work?

Check Your Answers

1. Nine times farther. The car has 9 times as much kinetic energy when it travels 3 times as fast: $\frac{1}{2}m(3v)^2 = \frac{1}{2}m9v^2 = 9(\frac{1}{2}mv^2)$. The friction force will ordinarily be the same in either case; therefore, 9 times as much work requires 9 times as much distance.
2. Yes, but in a relative sense. For example, an elevated object may possess PE relative to the ground below, but none relative to a point at the same elevation. Similarly, the KE that an object has is relative to a frame of reference, usually Earth's surface. (We will see that material objects have *energy of being*, $E = mc^2$, the congealed energy that makes up their mass. Read on!)
3. No, unlike momentum or energy, work is not something that an object *has*. Work is something that an object *does* to some other object. An object does work when it exchanges energy.

Conservation of Energy

More important than knowing *what energy is* is understanding how it behaves—*how it transforms.* We can better understand the processes and changes that occur in nature if we analyze them in terms of energy *changes*—transformations from one form into another, or of transfers from one location to another. Energy is nature's way of keeping score.

Consider the changes in energy in the operation of the pile driver back in Figure 7.7. Work done to raise the ram, giving it potential energy, becomes kinetic energy when the ram is released. This energy transfers to the piling below. The distance the piling penetrates into the ground multiplied by the average force of impact is almost equal to the initial potential energy of the ram. We say *almost* because some energy goes into heating the ground and ram during penetration. Taking heat energy into account, we find energy transforms without net loss or net gain. Quite remarkable!

Inventors take heed: When introducing a new idea, first be sure it is in context with what is presently known. For example, it should be consistent with the conservation of energy.

The study of various forms of energy and their transformations from one form into another has led to one of the greatest generalizations in physics—the law of **conservation of energy:**

> **Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.**

When we consider any system in its entirety, whether it be as simple as a swinging pendulum or as complex as an exploding supernova, there is one quantity that isn't created or destroyed: energy. It may change form or it may simply be transferred from one place to another, but, as scientists have learned, the total energy score stays the same. This energy score takes into account the fact that the atoms that make up matter are themselves concentrated bundles of energy. When the nuclei (cores) of atoms rearrange themselves, enormous amounts of energy can be released. The Sun shines because some of this nuclear energy is transformed into radiant energy.

Enormous compression due to gravity and extremely high temperatures in the deep interior of the Sun fuse the nuclei of hydrogen atoms together to form helium nuclei. This is *thermonuclear fusion,* a process that releases radiant energy, a small part of which reaches Earth. Part of the energy reaching Earth falls on plants (and on other photosynthetic organisms), and part of this, in turn, is later stored in the form of coal. Another part supports life in the food chain that begins with plants (and other photosynthesizers), and part of this energy later is stored in oil. Part of the energy from the Sun goes into the evaporation of water from the ocean, and part of this returns to Earth in rain that may be trapped behind a dam. By virtue of its elevated position, the water behind a dam has energy that may be used to power a generating plant below, where it will be transformed to electric energy. The energy travels through wires to homes, where it is used for lighting, heating, cooking, and operating electrical gadgets. How wonderful that energy transforms from one form to another!

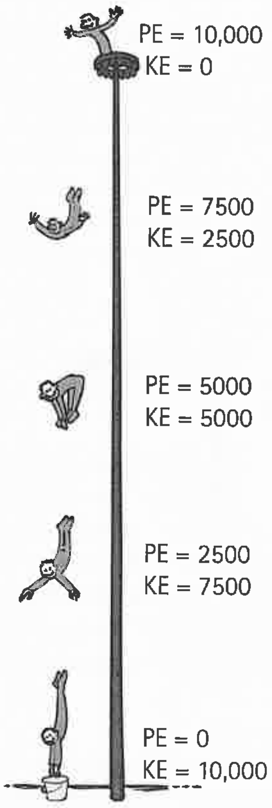


FIGURE 7.14

INTERACTIVE FIGURE

A circus diver at the top of a pole has a PE of 10,000 J. As he dives, his PE converts to KE. Note that, at successive positions one-fourth, one-half, three-fourths, and all the way down, the total energy is constant.

Energy and Technology

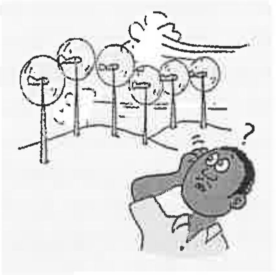
Try to imagine life before energy was something that humans controlled. Imagine home life without electric lights, refrigerators, heating and cooling systems, the telephone, and radio and TV—not to mention the family automobile. We may romanticize a better life without these, but only if we overlook the hours of daily toil devoted to doing laundry, cooking, and heating our homes. We'd also have to overlook how difficult it was getting a doctor in times of emergency before the advent of the telephone—when a doctor had little more in his bag than laxatives, aspirins, and sugar pills—and when infant death rates were staggering.

We have become so accustomed to the benefits of technology that we are only faintly aware of our dependence on dams, power plants, mass transportation, electrification, modern medicine, and modern agricultural science for our very existence. When we dig into a good meal, we give little thought to the technology that went into growing, harvesting, and delivering the food on our table. When we turn on a light, we give little thought to the centrally controlled power grid that links the widely separated power stations by long-distance transmission lines. These lines serve as the productive arteries of industry, transportation, and the electrification of our society. Anyone who thinks of science and technology as "inhuman" fails to grasp the ways in which they make our lives more human.

CHECK POINT

1. Does an automobile consume more fuel when its air conditioner is turned on? When its lights are on? When its radio is on while it is sitting in the parking lot?
2. Rows of wind-powered generators are used in various windy locations to generate electric power. Does the power that is generated affect the speed of the wind? That is, would locations behind the wind generators be windier if the generators weren't there?

Check Your Answers



1. The answer to all three questions is *yes*, for energy consumed ultimately comes from the fuel. Even the energy taken from the battery must be given back to the battery by the alternator, which is turned by the engine, which runs from the energy of the fuel. There's no free lunch!
2. Wind-powered generators take KE from the wind, so the wind is slowed by interaction with the blades. So, yes, it would be windier behind the wind generators if they weren't there.

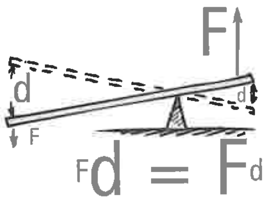


FIGURE 7.15

The lever.

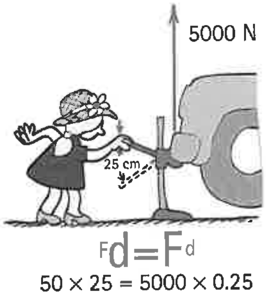


FIGURE 7.16

Applied force × applied distance = output force × output distance.

Machines

A **machine** is a device for multiplying force or simply changing the direction of force. The principle underlying every machine is the **conservation of energy** concept. Consider one of the simplest machines, the **lever** (Figure 7.15). At the same time that we do work on one end of the lever, the other end does work on the load. We see that the direction of force is changed: If we push down, the load is lifted up. If the work done by friction forces is small enough to neglect, the work input will be equal to the work output.

$$\text{Work input} = \text{work output}$$

Since work equals force times distance, input force × input distance = output force × output distance:

$$(\text{Force} \times \text{distance})_{\text{input}} = (\text{force} \times \text{distance})_{\text{output}}$$

The point of support on which a lever rotates is called a *fulcrum.* When the fulcrum of a lever is relatively close to the load, then a small input force will produce a large output force. This is because the input force is exerted through a large distance

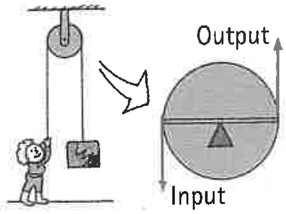


FIGURE 7.17

INTERACTIVE FIGURE

This pulley acts like a lever with equal lever arms. It changes only the direction of the input force.

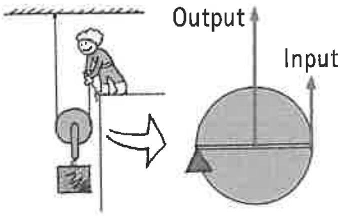


FIGURE 7.18

INTERACTIVE FIGURE

In this arrangement, a load can be lifted with half the input force. Note the "fulcrum" is at the left end rather than at the center.

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Video

Machines: Pulleys

and the load is moved through a correspondingly short distance. So a lever can be a force multiplier. But no machine can multiply work or multiply energy. That's a conservation-of-energy no-no!

The principle of the lever was understood by Archimedes, a famous Greek scientist in the third century BC. He said, "Give me a place to stand, and I will move the world."

Today, a child can use the principle of the lever to jack up the front end of an automobile. By exerting a small force through a large distance, she can provide a large force that acts through a small distance. Consider the ideal example illustrated in Figure 7.16. Every time she pushes the jack handle down 25 centimeters, the car rises only a hundredth as far but with 100 times the force.

Another simple machine is a pulley. Can you see that it is a lever "in disguise"? When used as in Figure 7.17, it changes only the direction of the force; but, when used as in Figure 7.18, the output force is doubled. Force is increased and distance moved is decreased. As with any machine, forces can change while work input and work output are unchanged.

A block and tackle is a system of pulleys that multiplies force more than a single pulley can do. With the ideal pulley system shown in Figure 7.19, the man pulls 7 m of rope with a force of 50 N and lifts a load of 500 N through a vertical distance of 0.7 m. The energy the man expends in pulling the rope is numerically equal to the increased potential energy of the 500-N block. Energy is transferred from the man to the load.

FIGURE 7.19

INTERACTIVE FIGURE

Applied force × applied distance = output force × output distance.

Any machine that multiplies force does so at the expense of distance. Likewise, any machine that multiplies distance, such as your forearm and elbow, does so at the expense of force. No machine or device can put out more energy than is put into it. No machine can create energy; it can only transfer energy or transform it from one form to another.

Efficiency

The three previous examples were of *ideal machines;* 100% of the work input appeared as work output. An ideal machine would operate at 100% efficiency. In practice, this doesn't happen, and we can never expect it to happen. In any transformation, some energy is dissipated to molecular kinetic energy—thermal energy. This makes the machine and its surroundings warmer.

A machine can multiply force, but never *energy*—no way!

Even a lever rocks about its fulcrum and converts a small fraction of the input energy into thermal energy. We may do 100 J of work and get out 98 J of work. The lever is then 98% efficient, and we degrade only 2 J of work input into thermal energy. If the girl back in Figure 7.16 puts in 100 J of work and increases the potential energy of the car by 60 J, the jack is 60% efficient; 40 J of her input work has been applied against friction, making its appearance as thermal energy.

In a pulley system, a considerable fraction of input energy typically goes into thermal energy. If we do 100 J of work, the forces of friction acting through the distances through which the pulleys turn and rub about their axles may dissipate 60 J of energy as thermal energy. In that case, the work output is only 40 J and the pulley system has an efficiency of 40%. The lower the efficiency of a machine, the greater the percentage of energy that is degraded to thermal energy.

Inefficiency exists whenever energy in the world around us is transformed from one form to another. **Efficiency** can be expressed by the ratio

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

An automobile engine is a machine that transforms chemical energy stored in fuel into mechanical energy. The bonds between the molecules in the petroleum fuel break

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- A perpetual-motion machine (a device that can do work without energy input) is a no-no. But perpetual motion itself, is a yes-yes. Atoms and their electrons, and stars and their planets, for example, are in a state of perpetual motion. Perpetual motion is the natural order of things.

when the fuel burns. Carbon atoms in the fuel combine with oxygen in the air to form carbon dioxide, hydrogen atoms in the fuel combine with oxygen to form water, and energy is released. How nice if all this energy could be converted into useful mechanical energy—that is to say, how nice it would be if we could have an engine that is 100% efficient. This is impossible, however, because much of the energy is transformed into thermal energy, a little of which may be used to warm passengers in the winter but most of which is wasted. Some goes out in the hot exhaust gases, and some is dissipated to the air through the cooling system or directly from hot engine parts.[5]

Look at the inefficiency that accompanies transformations of energy in this way: In any transformation, there is a dilution of available *useful energy.* The amount of usable energy decreases with each transformation until there is nothing left but thermal energy at ordinary temperature. When we study thermodynamics, we'll see that thermal energy is useless for doing work unless it can be transformed to a lower temperature. Once it reaches the lowest practical temperature, that of our environment, it cannot be used. The environment around us is the graveyard of useful energy.

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- Comparing transportation efficiencies, the most efficient is the human on a bicycle—far more efficient than train and car travel, and even that of fish and animals. Hooray for bicycles and those who use them!

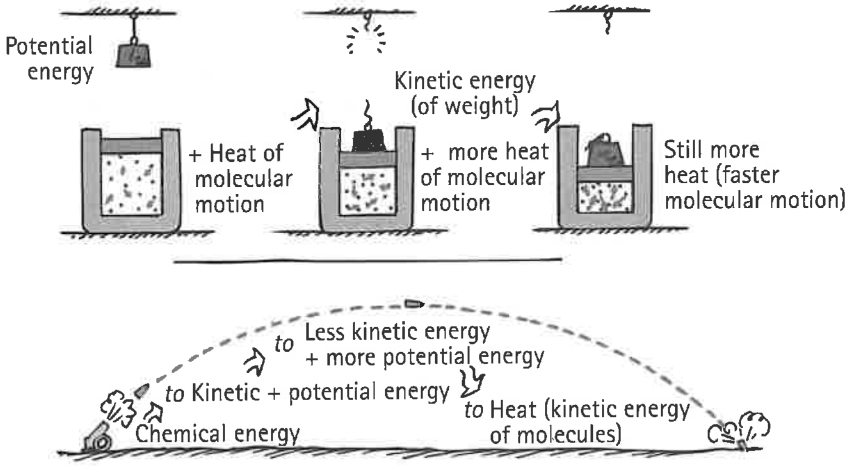

FIGURE 7.20

Energy transitions. The graveyard of mechanical energy is thermal energy.

Recycled Energy

Recycled energy is the reemployment of energy that otherwise would be wasted. A typical fossil-fuel-fired power plant discards about two-thirds of the energy present in fuel as wasted thermal energy. Only about one-third of the energy input is converted to useful electricity. What other business throws away two-thirds of its input? This was not always so. Thomas Edison's early power plants in the late 1880s, for example, converted much more input energy to useful purposes than today's electric-only power plants. Edison used the castoff heat from his generators to warm nearby homes and factories. The company he founded still delivers heat to thousands of Manhattan buildings via the largest commercial steam system in the world. New York is not alone: Most homes in the region around Copenhagen, Denmark, are warmed by heat from power plants. More than 50% of energy used in Denmark is recycled energy. In contrast, recycled energy in the United States amounts to less than 10% of all energy used. A principal reason is that power plants are now typically built far from buildings that would benefit from recycled energy. Nevertheless, we can't continue to throw heat energy to the sky in one place and then burn more fossil fuel to supply heat somewhere else. Watch for more energy recycling.

Watch for the production of biofuels made from edible corn, soybeans, and sugar cane to take a back seat to cellulose biofuels—liquid fuels made from inedible fast-growing grasses and agricultural leftovers such as cornstalks and wood waste.

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[5] When you study thermodynamics in Chapter 18, you'll learn that an internal combustion engine *must* transform some of its fuel energy into thermal energy. A fuel cell that powers vehicles, on the other hand, doesn't have this limitation.

CHECK POINT

Consider an imaginary miracle car that has a 100% efficient engine and burns fuel that has an energy content of 40 MJ per liter. If the air drag and overall frictional forces on the car traveling at highway speed is 500 N, how far could the car travel per liter of fuel at this speed?

Check Your Answer

From the definition work = force × distance, simple rearrangement gives distance = work/force. If all 40 million J of energy in 1 L were used to do the work of overcoming the air drag and frictional forces, the distance would be

$$\text{Distance} = \frac{\text{work}}{\text{force}} = \frac{40{,}000{,}000\ \text{J/L}}{500\ \text{N}} = 80{,}000\ \text{m/L} = 80\ \text{km/L}$$

(This is about 190 mpg.) The important point here is that, even with a hypothetically perfect engine, there is an upper limit of fuel economy dictated by the conservation of energy.

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Conservation of Energy: Numerical Example

Energy for Life

Your body is a machine—an extraordinarily wonderful machine. It is made up of smaller machines—living cells. Like any machine, a living cell needs a source of energy. In animals—including you—cells feed on various hydrocarbon compounds that release energy when they react with oxygen. Like gasoline burned in an automobile engine, there is more potential energy in the food molecules than there is in the reaction products after food metabolism. The energy difference is what sustains life.

We see inefficiency at work in the food chain. Larger creatures feed on smaller creatures, which, in turn, eat smaller creatures, and so on down the line to land plants and ocean plankton that are nourished by the Sun. Advancing each step up the food chain involves inefficiency. In the African bush, 10 kg of grass may produce 1 kg of gazelle. However, it will require 10 kg of gazelle to sustain 1 kg of lion. We see that each energy transformation along the food chain contributes to overall inefficiency. Interestingly enough, some of the largest creatures on the planet, the elephant and the blue whale, consume lower down on the food chain. Humans also are considering such tiny organisms as krill and yeast as efficient sources of nourishment.

Sources of Energy

Sunlight evaporates water, which later falls as rain; rainwater flows into rivers and into reservoirs behind dams where it is directed to generator turbines. Then it returns to the sea, where the cycle continues. The Sun is the source of practically all our energy (except that from nuclear power). Even the energy we obtain from petroleum, coal, natural gas, and wood originally came from the Sun. That's because these fuels are created by photosynthesis—the process by which plants trap solar energy and store it as plant tissue. A square mile of sunlight at midday can provide a gigawatt of electric power, the same output as a large coal or nuclear plant. Solar power is a growing green industry.

Photovoltaic solar cells transform sunlight to electricity, as is impressively shown on the cover of this book. They are more familiar in solar-powered calculators and iPods. Photovoltaic cells are already established as building materials, roofing, tiles, and soon windows. Photovoltaic cells have normally been crystal wafers produced the same way

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- Imagine you're in a completely dark room with no windows. Suppose you cut a 1-ft^2 round hole in the roof. When the Sun is high in the sky, about 100 W of solar power enters the hole. On the floor where the light hits, place a beachball covered with aluminum foil, the shiny side out. Guess what? Your room is illuminated with just as much light as a 100-W lamp produces!

FIGURE 7.21
In Bermuda, where fresh water is scarce, rooftops are designed to catch water, which is stored in containers for household use.

FIGURE 7.22
Photovoltaic solar cells on more and more rooftops (and sides of homes such as these in Holland) catch sunlight and convert it to electrical energy.

that semiconductors are made for computers, or as thin coatings on glass or metal backing. Newer technology is replacing panels composed of these cells. Light and flexible photovoltaic "power sheets" are now produced by machines similar to printing presses that roll out photovoltaic ink onto sheets about the thickness of aluminum foil. Power sheets can be mounted almost everywhere and don't need the sturdy surfaces that solar panels require.

The production of solar power is not confined to photovoltaics. Sunlight can be reflected by mirrors to water-filled boilers perched on towers. Concentration of sunlight by thousands of mirrors can heat water to more than four times its normal boiling point, which becomes superhot steam to drive turbines that generate electricity. Although parabolic mirrors are sometimes used at solar thermal power plants, others use inexpensive easy-to-install small flat ones, each about the size of a big-screen television. Computerized tracking keeps each mirror focused at the optimal angle throughout the day. When the Sun isn't shining, some facilities run the turbines with natural gas. Also, solar power can be combined with traditional fossil fuel power plants to increase their efficiencies. This is *solar hybridization.* Watch for more hybridization of solar power.

Even the wind, caused by unequal warming of Earth's surface, is a form of solar power. The energy of wind can be used to turn generator turbines within specially equipped windmills. Wind power is much about location—placing turbines where wind blows steady and strong, and where it overcomes the objections of residents who don't want their views compromised. That can be out at sea, away from shores. Where water isn't too deep, turbine towers can be anchored to the ocean bottom. In deeper water the towers can be mounted on floating platforms. Like solar power, wind produces power with no carbon footprint.

Interestingly, wind power can be useful when the wind isn't blowing, when it has been used to compress air in tanks or caverns underground. The compressed air can then be used to run a generator. Wind energy can also be used to produce hydrogen, which can be transported and stored for various uses.

Hydrogen is the least polluting of all fuels. Most hydrogen in America is produced from natural gas, where high temperatures and pressures separate hydrogen from hydrocarbon molecules. A downside to hydrogen separation from hydrocarbon compounds is the unavoidable production of carbon dioxide, a greenhouse gas. A simpler and cleaner method that doesn't produce greenhouse gases is *electrolysis*—

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- Watch for the downscaling of today's large-scale power grids as local solar power becomes more widespread for buildings and vehicles. Smaller local grids in dense urban areas will remain. Big power plants of all kinds may become unnecessary, with the exception of those located near virgin steel mills—for a while. Most steel mills are already powered electrically.

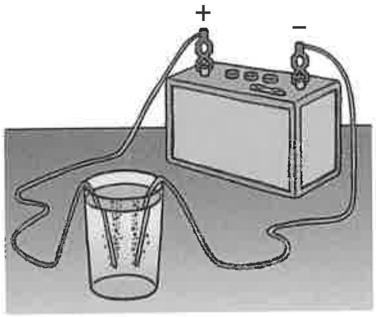


FIGURE 7.23
When electric current passes through conducting water, bubbles of hydrogen form at one wire and bubbles of oxygen form at the other. This is *electrolysis.* A fuel cell does the opposite—hydrogen and oxygen enter the fuel cell and are combined to produce electricity and water.

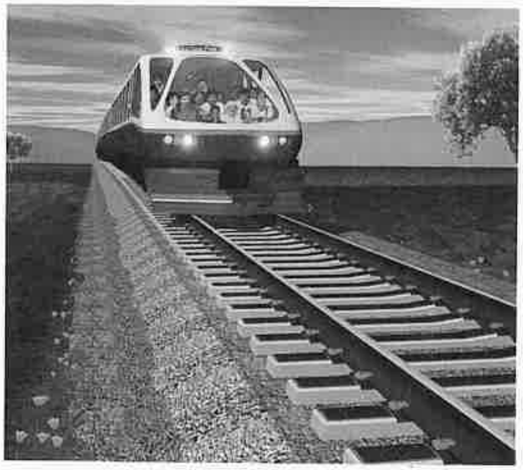


FIGURE 7.24

The power harvested by photovoltaic cells can be used to separate hydrogen for fuel-cell transportation. Plans for trains that run on solar power collected on railroad-track ties are presently at the drawing board stage (www.SuntrainUSA.com).

electrically splitting water into its constituent parts. Figure 7.23 shows how you can perform this in a lab or at home. Place two platinum wires that are connected to the terminals of an ordinary battery into a glass of water (with an electrolyte such as salt dissolved in the water for conductivity). Be sure the wires don't touch each other. Bubbles of hydrogen form on one wire, and bubbles of oxygen form on the other. A fuel cell is similar, but runs backwards. Hydrogen and oxygen gas are compressed at electrodes and electric current is produced, along with water. The space shuttle uses fuel cells to meet its electrical needs while producing drinking water for the astronauts. Here on Earth, fuel-cell researchers are developing fuel cells for buses, automobiles, and trains.

A hydrogen economy may likely start with railroad trains powered with fuel cells. Hydrogen can be obtained via solar cells, many along train tracks and on the rail ties themselves (Figure 7.24). Solar energy can extract hydrogen from water. It is important to know that hydrogen is not a *source* of energy. It takes energy to make hydrogen (to extract it from water and hydrocarbon compounds). Like electricity, it needs an energy source and is a way of storing and transporting that energy. Again, for emphasis, hydrogen is *not* an energy source.

The energy of ocean waves is being tapped off the coast of Portugal, where bobbing pontoons at the surface turn generators on the ocean floor. Of greater interest is the energy of ocean tides, another clean source of energy currently being tapped in various locations. Positioned across an estuary or inlet, the surging of rising and falling ocean tides turns turbines to produce electrical power, much as the flow of water from dams turns turbines in hydroelectric plants. The River Rance in France has been churning out electric power for more than 40 years, as have others in Canada and Russia. Interestingly, this form of energy is neither nuclear nor from the Sun. It comes from the rotational energy of our planet. Watch for larger-scale tidal power plants.

The most concentrated source of usable energy is that stored in nuclear fuels—uranium and plutonium. For the same weight of fuel, nuclear reactions release about 1 million times more energy than do chemical or food reactions. Watch for renewed interest in this form of power that doesn't pollute the atmosphere. Interestingly, Earth's interior is kept hot because of nuclear power, which has been with us since time zero.

A by-product of nuclear power in Earth's interior is geothermal energy. Geothermal energy is held in underground reservoirs of hot rock and hot water. Geothermal energy relatively close to the surface is predominantly limited to areas of volcanic activity, such as Iceland, New Zealand, Japan, and Hawaii. In these locations, heated water is tapped to provide steam for driving electric generators.

In other locations, another method holds promise for producing electricity. That's dry-rock geothermal power (Figure 7.25). With this method, water is pumped into hot fractured rock far below the surface. When the water turns to steam, it is piped to a turbine at the surface. After turning the turbine, it is pumped back into the ground for reuse. In this way, electricity is produced cleanly.

As the world population increases, so does our need for energy, especially since per capita demand is also growing. With the rules of physics to guide them, technologists are presently researching newer and cleaner ways to develop energy sources. But they race to keep ahead of a growing world population and greater demand in the developing world. Unfortunately, so long as controlling population is politically and religiously incorrect, human misery becomes the check to unrestrained population growth. H. G. Wells once wrote (in *The Outline of History*), "Human history becomes more and more a race between education and catastrophe."

Sooner or later, all the sunlight that falls on Earth will be radiated back into space. Energy in any ecosystem is always in transit—you can rent it, but you can't own it.

Fuel cells are electrochemical devices that combine stored hydrogen with atmospheric oxygen to generate electricity and water vapor. Vehicles operating on fuel cells produce no CO_2 emissions directly. (They do indirectly only if the source of energy to produce hydrogen is via fossil-fuel plants.)

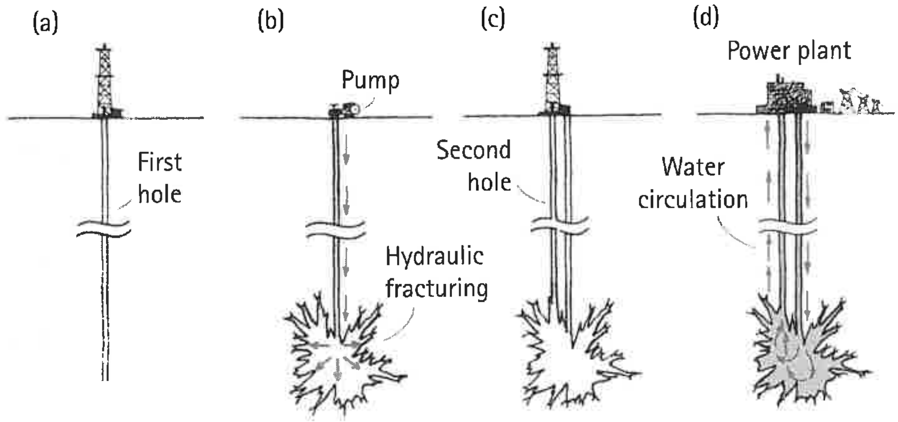


FIGURE 7.25

Dry-rock geothermal power. (a) A hole is sunk several kilometers into dry granite. (b) Water is pumped into the hole at high pressure and fractures surrounding rock to form cavities with increased surface area. (c) A second hole is sunk nearby. (d) Water is circulated down one hole and through the fractured rock, where it is superheated, before rising through the second hole. After driving a turbine, it is recirculated into the hot rock again, making a closed cycle.

Junk Science

Scientists have to be open to new ideas. That's how science grows. But there is a body of established knowledge that can't be easily overthrown. That includes energy conservation, which is woven into every branch of science and supported by countless experiments from the atomic to the cosmic scale. Yet no concept has inspired more "junk science" than energy. Wouldn't it be wonderful if we could get energy for nothing, to possess a machine that gives out more energy than is put into it? That's what many practitioners of junk science offer. Gullible investors put their money into some of these schemes. But none of the schemes passes the test of being real science. Perhaps some day a flaw in the law of energy conservation will be discovered. If it ever is, scientists will rejoice at the breakthrough. But so far, energy conservation is as solid as any knowledge we have. Don't bet against it.

SUMMARY OF TERMS

Work The product of the force and the distance moved by the force:

$$W = Fd$$

(More generally, work is the component of force in the direction of motion times the distance moved.)

Power The time rate of work:

$$\text{Power} = \frac{\text{work done}}{\text{time interval}}$$

(More generally, power is the rate at which energy is expended.)

Energy The property of a system that enables it to do work.

Mechanical energy Energy due to the position of something or the movement of something.

Potential energy The energy that something possesses because of its position.

Kinetic energy Energy of motion, quantified by the relationship

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

Work-energy theorem The work done on an object equals the change in kinetic energy of the object.

$$\text{Work} = \Delta\text{KE}$$

(Work can also transfer other forms of energy to a system.)

Conservation of energy Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.

Machine A device, such as a lever or pulley, that increases (or decreases) a force or simply changes the direction of a force.

Conservation of energy for machines The work output of any machine cannot exceed the work input. In an ideal machine, where no energy is transformed into thermal energy, $\text{work}_{\text{input}} = \text{work}_{\text{output}}$; $(Fd)_{\text{input}} = (Fd)_{\text{output}}$.

Lever Simple machine consisting of a rigid rod pivoted at a fixed point called the fulcrum.

Efficiency The percentage of the work put into a machine that is converted into useful work output. (More generally, useful energy output divided by total energy input.)

SUMMARY OF EQUATIONS

Work = force × distance: $W = Fd$

Power $= \frac{\text{work}}{\text{time}}$: $P = \frac{W}{t}$

Gravitational potential energy = weight × height: PE = mgh

Kinetic energy $= \frac{1}{2}$ mass × speed^2: KE $= \frac{1}{2} mv^2$

Work energy theorem: Work = ΔKE

REVIEW QUESTIONS

1. When is energy most evident?

Work

2. A force sets an object in motion. When the force is multiplied by the time of its application, we call the quantity *impulse,* which changes the *momentum* of that object. What do we call the quantity force × distance?
3. Cite an example in which a force is exerted on an object without doing work on the object.
4. Which requires more work—lifting a 50-kg sack a vertical distance of 2 m or lifting a 25-kg sack a vertical distance of 4 m?

Power

5. If both sacks in the preceding question are lifted their respective distances in the same time, how does the power required for each compare? How about for the case in which the lighter sack is moved its distance in half the time?

Mechanical Energy

6. Exactly what is it that enables an object to do work?

Potential Energy

7. A car is raised a certain distance in a service-station lift and therefore has potential energy relative to the floor. If it were raised twice as high, how much potential energy would it have relative to the floor?
8. Two cars are raised to the same elevation on service-station lifts. If one car is twice as massive as the other, how do their gains of potential energies compare?
9. When is the potential energy of something significant?

Kinetic Energy

10. A moving car has kinetic energy. If it speeds up until it is going 4 times as fast, how much kinetic energy does it have in comparison?

Work-Energy Theorem

11. Compared with some original speed, how much work must the brakes of a car supply to stop a car that is moving 4 times as fast? How will the stopping distance compare?
12. If you push a crate horizontally with 100 N across a 10-m factory floor and friction between the crate and the floor is a steady 70 N, how much kinetic energy is gained by the crate?
13. How does speed affect the friction between a road and a skidding tire?

Conservation of Energy

14. What will be the kinetic energy of a pile driver ram when it undergoes a 10-kJ decrease in potential energy?
15. An apple hanging from a limb has potential energy because of its height. If it falls, what becomes of this energy just before it hits the ground? When it hits the ground?
16. What is the source of energy in sunshine?

Machines

17. Can a machine multiply input force? Input distance? Input energy? (If your three answers are the same, seek help, for the last question is especially important.)
18. If a machine multiplies force by a factor of 4, what other quantity is diminished, and by how much?
19. A force of 50 N is applied to the end of a lever, which is moved a certain distance. If the other end of the lever moves one-third as far, how much force can it exert?

Efficiency

20. What is the efficiency of a machine that miraculously converts all the input energy to useful output energy?
21. If an input of 100 J in a pulley system increases the potential energy of a load by 60 J, what is the efficiency of the system?

Recycled Energy

22. What is recycled energy?

Energy for Life

23. In what sense are our bodies machines?

Sources of Energy

24. What is the ultimate source of energy for fossil fuels, dams, and windmills?
25. What is the ultimate source of geothermal energy?
26. Can we correctly say that hydrogen is a new source of energy? Why or why not?

PLUG AND CHUG

Work = force × distance: $W = Fd$

1. Calculate the work done when a force of 1 N moves a book 2 m.
2. Calculate the work done when a 20-N force pushes a cart 3.5 m.
3. Calculate the work done in lifting a 500-N barbell 2.2 m above the floor. (What is the gain of potential energy of the barbell when it is lifted to this height?)

Power = work/time: $P = W/t$

4. Calculate the watts of power expended when a force of 2 N moves a book 2 m in a time interval of 1 s.
5. Calculate the power expended when a 20-N force pushes a cart 3.5 m in a time of 0.5 s.
6. Calculate the power expended when a 500-N barbell is lifted 2.2 m in 2 s.

Gravitational potential energy = weight × height: PE = mgh

7. How many joules of potential energy does a 1-kg book gain when it is elevated 4 m? When it is elevated 8 m?
8. Calculate the increase in potential energy when a 20-kg block of ice is lifted a vertical distance of 2 m.
9. Calculate the change in potential energy of 8 million kg of water dropping 50 m over Niagara Falls.

Kinetic energy = $\frac{1}{2}$ mass × speed^2: KE = $\frac{1}{2}mv^2$

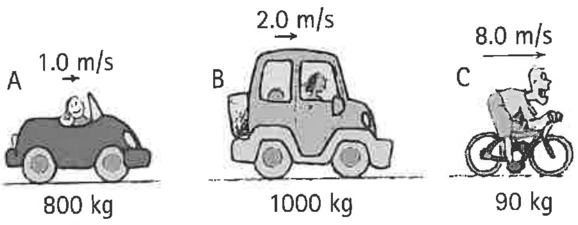
10. Calculate the number of joules of kinetic energy a 1-kg book has when tossed at a speed of 2 m/s.
11. Calculate the kinetic energy of a 3-kg toy cart that moves at 4 m/s.
12. Calculate the kinetic energy of the same cart moving at twice the speed.

Work-energy theorem: Work = ΔKE

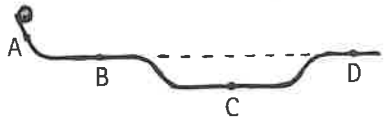
13. How much work is required to increase the kinetic energy of a car by 5000 J?
14. What change in kinetic energy does an airplane experience on takeoff if it is moved a distance of 500 m by a sustained net force of 5000 N?

RANKING

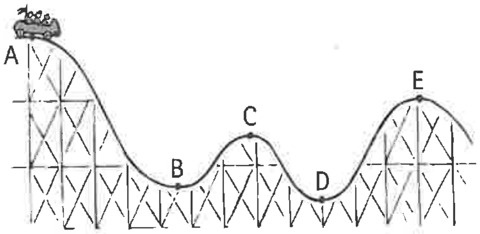
1. The mass and speed of the three vehicles, A, B, and C, are shown. Rank them from greatest to least for



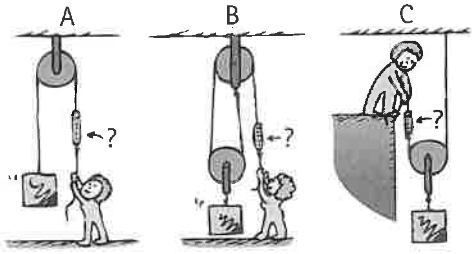
   a. momentum.
   b. kinetic energy.
   c. work done to bring them up to their respective speeds from rest.
2. A ball is released from rest at the left of the metal track shown here. Assume it has only enough friction to roll, but not to lessen its speed. Rank these quantities from greatest to least at each point:



   a. Momentum
   b. KE
   c. PE
3. The roller coaster ride starts from rest at point A. Rank these quantities from greatest to least at each point:



   a. Speed
   b. KE
   c. PE
4. Rank the scale readings from most to least. (Ignore friction.)



EXERCISES

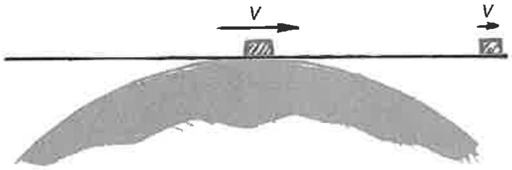
1. Why is it easier to stop a lightly loaded truck than a heavier one that has equal speed?
2. Why do you do no work on a 25-kg backpack when you walk a horizontal distance of 100 mm?
3. If your friend pushes a lawnmower 4 times as far as you do while exerting only half the force, which one of you does more work? How much more?
4. Why does one get tired when pushing against a stationary wall when no work is done on the wall?
5. Which requires more work: stretching a strong spring a certain distance or stretching a weak spring the same distance? Defend your answer.
6. Two people who weigh the same climb a flight of stairs. The first person climbs the stairs in 30 s, and the second person climbs them in 40 s. Which person does more work? Which uses more power?
7. The Sun puts out twice as much solar energy in 2 hours as it does in 1 hour. But the solar *power* of the Sun is the same from one hour to the next. Distinguish between the terms *solar energy* and *solar power.*
8. In determining the potential energy of Tenny's drawn bow (Figure 7.9), would it be an underestimate or an overestimate to multiply the force with which she holds the arrow in its drawn position by the distance she pulled it? Why do we say the work done is the *average* force × distance?
9. When a rifle with a longer barrel is fired, the force of expanding gases acts on the bullet for a longer distance. What effect does this have on the velocity of the emerging bullet? (Do you see why long-range cannons have such long barrels?)
10. Your friend says that the kinetic energy of an object depends on the reference frame of the observer. Explain why you agree or disagree.
11. You and a flight attendant toss a ball back and forth in an airplane in flight. Does the KE of the ball depend on the speed of the airplane? Carefully explain.
12. You watch your friend take off in a jet plane, and you comment on the kinetic energy she has acquired. But she says she experiences no such increase in kinetic energy. Who is correct?
13. When a jumbo jet slows and descends on approach to landing, there is a decrease in both its kinetic and potential energy. Where does this energy go?
14. Explain how "elastic potential energy" dramatically changed the sport of pole vaulting when flexible fiberglass poles replaced stiffer wooden poles.
15. At what point in its motion is the KE of a pendulum bob at a maximum? At what point is its PE at a maximum? When its KE is at half its maximum value, how much PE does it have relative to its PE at the center of the swing?
16. A physics instructor demonstrates energy conservation by releasing a heavy pendulum bob, as shown in the sketch, allowing it to swing to and fro. What would happen if, in his exuberance, he gave the bob a slight shove as it left his nose? Explain.

17. Does the International Space Station have gravitational PE? KE? Explain.
18. What does the work-energy theorem say about the speed of a satellite in circular orbit?
19. A moving hammer hits a nail and drives it into a wall. If the hammer hits the nail with twice the speed, how much deeper will the nail be driven? If it hits with 3 times the speed?
20. Why does the force of gravity do no work on (a) a bowling ball rolling along a bowling alley and (b) a satellite in circular orbit about Earth?
21. Why does the force of gravity do work on a car that rolls down a hill but no work when it rolls along a level part of the road?
22. Does the string that supports a pendulum bob do work on the bob as its swings to and fro? Does the force of gravity do any work on the bob?
23. A crate is pulled across a horizontal floor by a rope. At the same time, the crate pulls back on the rope, in accord with Newton's third law. Does the work done on the crate by the rope then equal zero? Explain.
24. On a playground slide, a child has potential energy that decreases by 1000 J while her kinetic energy increases by 900 J. What other form of energy is involved, and how much?
25. Someone wanting to sell you a Superball claims that it will bounce to a height greater than the height from which it is dropped. Can this be?
26. Why can't a Superball released from rest reach its original height when it bounces from a rigid floor?
27. Consider a ball thrown straight up in the air. At what position is its kinetic energy at a maximum? Where is its gravitational potential energy at a maximum?
28. Discuss the design of the roller coaster shown in the sketch in terms of the conservation of energy.

29. Suppose that you and two classmates are discussing the design of a roller coaster. One classmate says that each summit must be lower than the previous one. Your other classmate says this is nonsense, for as long as the first one is the highest, it doesn't matter what height the others are. What do you say?
30. Consider the identical balls released from rest on Tracks A and B, as shown. When they reach the right ends of the tracks, which will have the greater speed? Why is this question easier to answer than the similar one (Exercise 40) in Chapter 3?

31. Does a car burn more gasoline when its lights are turned on? Does the overall consumption of gasoline depend on whether or not the engine is running while the lights are on? Defend your answer.

32. Suppose an object is set sliding, with a speed less than escape velocity, on an infinite frictionless plane in contact with the surface of Earth, as shown. Describe its motion. (Will it slide forever at a constant velocity? Will it slide to a stop? In what way will its energy changes be similar to that of a pendulum?)



33. If a golf ball and a Ping-Pong ball both move with the same kinetic energy, can you say which has the greater speed? Explain in terms of the definition of KE. Similarly, in a gaseous mixture of heavy molecules and light molecules with the same average KE, can you say which have the greater speed?

34. Running a car's air conditioner usually increases fuel consumption. But, at certain speeds, a car with its windows open and with the air conditioner turned off can consume more fuel. Explain.

35. Why bother using a machine if it cannot multiply work input to achieve greater work output?

36. When the girl in Figure 7.16 jacks up a car, how can applying so little force produce sufficient force to raise the car?

37. What famous equation describes the relationship between mass and energy?

38. You tell your friend that no machine can possibly put out more energy than is put into it, and your friend states that a nuclear reactor puts out more energy than is put into it. What do you say?

39. This may seem like an easy question for a physics type to answer: With what force does a rock that weighs 10 N strike the ground if dropped from a rest position 10 m high? In fact, the question cannot be answered unless you know more. Why?

40. Your friend is confused about ideas discussed in Chapter 4 that seem to contradict ideas discussed in this chapter. For example, in Chapter 4, we learned that the net force is zero for a car traveling along a level road at constant velocity, and, in this chapter, we learned that work is done in such a case. Your friend asks, "How can work be done when the net force equals zero?" Explain.

41. In the absence of air resistance, a ball thrown vertically upward with a certain initial KE will return to its original level with the same KE. When air resistance is a factor affecting the ball, will it return to its original level with the same, less, or more KE? Does your answer contradict the law of energy conservation?

42. You're on a rooftop and you throw one ball downward to the ground below and another upward. The second ball, after rising, falls and also strikes the ground below. If air resistance can be neglected, and if your downward and upward initial speeds are the same, how will the speeds of the balls compare upon striking the ground? (Use the idea of energy conservation to arrive at your answer.)

43. Going uphill, the gasoline engine in a gasoline–electric hybrid car provides 75 horsepower while the total power propelling the car is 90 horsepower. Burning gasoline provides the 75 horsepower. What provides the other 15 horsepower?

44. When a driver applies brakes to keep a car going downhill at constant speed and constant kinetic energy, the potential energy of the car decreases. Where does this energy go? Where does most of it go with a hybrid vehicle?

45. Does the KE of a car change more when it goes from 10 to 20 km/h or when it goes from 20 to 30 km/h?

46. Can something have energy without having momentum? Explain. Can something have momentum without having energy? Defend your answer.

47. When the mass of a moving object is doubled with no change in speed, by what factor is its momentum changed? By what factor is its kinetic energy changed?

48. When the velocity of an object is doubled, by what factor is its momentum changed? By what factor is its kinetic energy changed?

49. Which, if either, has greater momentum: a 1-kg ball moving at 2 m/s or a 2-kg ball moving at 1 m/s? Which has greater kinetic energy?

50. A car has the same kinetic energy when traveling north as when it turns around and travels south. Is the momentum of the car the same in both cases?

51. If an object's KE is zero, what is its momentum?

52. If your momentum is zero, is your kinetic energy necessarily zero also?

53. If two objects have equal kinetic energies, do they necessarily have the same momentum? Defend your answer.

54. Two lumps of clay with equal and opposite momenta have a head-on collision and come to rest. Is momentum conserved? Is kinetic energy conserved? Why are your answers the same or different?

55. Scissors for cutting paper have long blades and short handles, whereas metal-cutting shears have long handles and short blades. Bolt cutters have very long handles and very short blades. Why is this so?

56. Consider the swinging-balls apparatus. If two balls are lifted and released, momentum is conserved as two balls pop out the other side with the same speed as the released balls at impact. But momentum would also be conserved if one ball popped out at twice the speed. Can you explain why this never happens? (And can you explain why this exercise is in Chapter 7 rather than in Chapter 6?)

57. An inefficient machine is said to "waste energy." Does this mean that energy is actually lost? Explain.

58. If an automobile were to have a 100% efficient engine, transferring all of the fuel's energy to work, would the engine be warm to your touch? Would its exhaust heat the surrounding air? Would it make any noise? Would it vibrate? Would any of its fuel go unused?

59. To combat wasteful habits, we often speak of "conserving energy," by which we mean turning off lights and hot water when they are not being used and keeping thermostats at a moderate level. In this chapter, we also speak of "energy conservation." Distinguish between these two usages.

60. When an electric company can't meet its customers' demand for electricity on a hot summer day, should the problem be called an "energy crisis" or a "power crisis"? Explain.

61. Your friend says that one way to improve air quality in a city is to have traffic lights synchronized so that motorists can travel long distances at constant speed. What physics principle supports this claim?

62. The energy we require to live comes from the chemically stored potential energy in food, which is transformed into other energy forms during the metabolism process. What happens to a person whose combined work and heat output is less than the energy consumed? What happens when the person's work and heat output is greater than the energy consumed? Can an undernourished person perform extra work without extra food? Defend your answers.

63. Once used, can energy be regenerated? Is your answer consistent with the common term *renewable energy*?

64. What do international peace, cooperation, and security have to do with addressing the world's energy needs?

PROBLEMS

1. The second floor of a house is 6 m above the street level. How much work is required to lift a 300-kg refrigerator to the second-story level?

2. (a) How much work is done when you push a crate horizontally with 100 N across a 10-m factory floor? (b) If the force of friction on the crate is a steady 70 N, show that the KE gained by the crate is 300 J. (c) Show that 700 J is turned into heat.

3. This question is typical on some driver's license exams: A car moving at 50 km/h skids 15 m with locked brakes. How far will the car skid with locked brakes at 150 km/h?

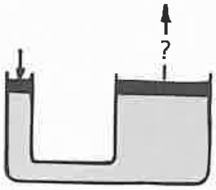
4. Belly-flop Bernie dives from atop a tall flagpole into a swimming pool below. His potential energy at the top is 10,000 J (relative to the surface of the pool). What is his kinetic energy when his potential energy reduces to 1000 J?

5. Nellie Newton applies a force of 50 N to the end of a lever, which is moved a certain distance. If the other end of the lever moves one-third as far, show that the force it exerts is 150 N.

6. Consider an ideal pulley system. If you pull one end of the rope 1 m downward with a 50-N force, show that you can lift a 200-N load one-quarter of a meter high.

7. In raising a 5000-N piano with a pulley system, the workers note that for every 2 m of rope pulled downward, the piano rises 0.2 m. Ideally, show that 500 N is required to lift the piano.

8. In the hydraulic machine shown, you observe that when the small piston is pushed down 10 cm, the large piston is raised 1 cm. If the small piston is pushed down with a force of 100 N, what is the most weight that the large piston can support?



9. How many watts of power do you expend when you exert a force of 1 N that moves a book 2 m in a time interval of 1 s?

•10. Emily holds a banana of mass m over the edge of a bridge of height h. She drops the banana and it falls to the river below. Use conservation of energy to show that the speed of the banana just before hitting the water is $v = \sqrt{2gh}$.

CHAPTER 7 ONLINE RESOURCES

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- 7.11, 7.14, 7.17, 7.18, 7.19

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- Energy

Videos

- Bowling Ball and Conservation of Energy
- Machines: Pulleys
- Conservation of Energy: Numerical Example

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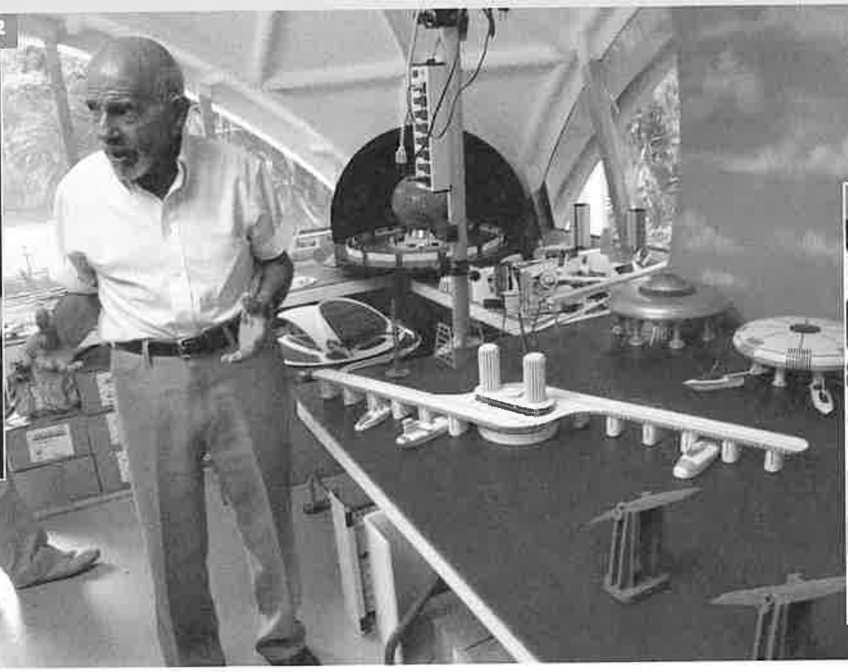
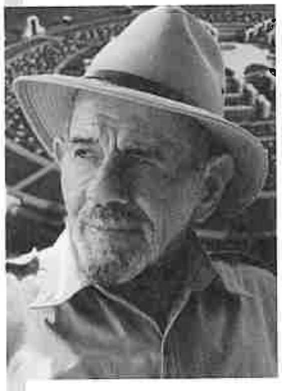
8 Rotational Motion



1 Burl Grey, my sign-painting buddy, stimulated my interest in science at the impressionable age of 25. 2 He introduced me to futurist Jacque Fresco, the most passionate teacher I have ever met, who inspired my love of teaching. 3 Jacque also positively influenced my lifelong friend, cartoonist Ernie Brown, who among many things, designed the *Conceptual Physics* cover logos that go back to the first edition.



Futurist thinker Jacque Fresco was the foremost influence in my transition from being a sign painter to pursuing a life in physics. I met Fresco through my sign-painting partner, Burl Grey, in Miami, Florida. With my wife Millie and with Ernie Brown, a close friend and cartoonist, I attended Fresco's dynamic series of weekly lectures in Miami Beach and sometimes at his home in Coral Gables. Charismatic Jacque has always been a futurist, believing that the best path to a better future is via science and technology and that a community with more engineers than lawyers is more likely to be a better one. His topics revolved around the importance of expanded technology to better living, locally and globally. As a teacher, Jacque was and is the very best. He certainly was an enormous influence in my own teaching. He taught me to introduce concepts new to a student by first comparing them to familiar ones—teaching by analogy. He felt that little or nothing would be learned if not tied to something similar, familiar, and already understood. He had a built-in "crap detector" that ensured emphasis on the central parts of an idea. After every lecture, I, my wife, and Ernie left with knowledge that was valued. The experience convinced me to take advantage of the GI Bill (I was a noncombat Korean War vet), get a college education, and pursue a career in science.

Jacque Fresco, with his associate, Roxanne Meadows, founded *The Venus Project* and the nonprofit organization *Future By Design* that reflect the culmination of Fresco's life work: the integration of the best of science and technology into a comprehensive plan for a new society based on human and environmental concerns—a global vision of hope for the future of humankind in our technological age. His vision is well stated in his many books and publications, on the web, and most recently in a movie, *Zeitgeist Addendum,* that features his visionary ideas. Now in his 90s, he continues to inspire young and old worldwide.

In typical lecture lessons, Jacque treated the distinctions between closely related ideas as well as their similarity. I recall one of his lessons distinguishing between linear motion and rotational motion. Where does a child move faster on a merry-go-round—near the outside rail or near the inside rail—or do they have the same speed? Because the distinction between linear speed and rotational speed is poorly understood, Jacque said that asking this question to different people results in different answers. Just as "tail-end Charlie" at the end of a line of skaters making a turn moves faster than skaters near the center of the curve, so it is that railroad-train wheels on the outside track of a curve travel faster than wheels on the inside track. Jacque explained how slight tapering of the wheel rims make this possible. This and other similarities and distinctions are treated in this chapter.

Circular Motion

Linear speed, which we simply called *speed* in previous chapters, is the distance traveled per unit of time. A point on the outside edge of a merry-go-round or turntable travels a greater distance in one complete rotation than a point nearer the center. Traveling a greater distance in the same time means a greater speed. Linear speed is greater on the outer edge of a rotating object than it is closer to the axis. The linear speed of something moving along a circular path can be called **tangential speed** because the direction of motion is tangent to the circumference of the circle. For circular motion, we can use the terms *linear speed* and *tangential speed* interchangeably. Units of linear or tangential speed are usually m/s or km/h.

Rotational speed (sometimes called *angular speed*) involves the number of rotations or revolutions per unit of time. All parts of the rigid merry-go-round and turntable turn about the axis of rotation in the same amount of time. Thus, all parts share the same rate of rotation, or the same *number of rotations* or *revolutions per unit of time.* It is common to express rotational rates in revolutions per minute (RPM).[1] For example, most phonograph turntables, which were common in mom and dad's time, rotate at $33\frac{1}{3}$ RPM. A ladybug sitting anywhere on the surface of the turntable revolves at $33\frac{1}{3}$ RPM.

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Tutorial
Rotational Motion

fyi

- When an object turns about an internal axis, the motion is a *rotation*, or spin. A merry-go-round or a turntable rotates about a central internal axis. When an object turns about an external axis, the motion is a *revolution*. Earth makes one revolution about the Sun each year, while it rotates about its polar axis once per day.

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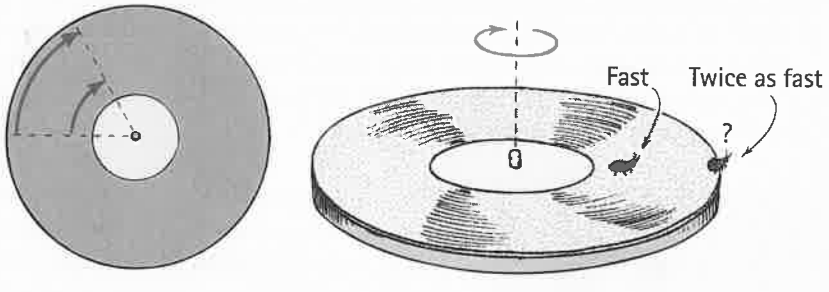

(a) (b)

FIGURE 8.1
INTERACTIVE FIGURE

(a) When the turntable rotates, a point farther from the center travels a longer path in the same time and has a greater tangential speed. (b) A ladybug twice as far from the center moves twice as fast.

Tangential speed and rotational speed are related. Have you ever ridden on a big, round, rotating platform in an amusement park? The faster it turns, the faster your tangential speed. This makes sense; the greater the RPMs, the faster your speed in meters per second. We say that tangential speed is *directly proportional* to rotational speed at any fixed distance from the axis of rotation.

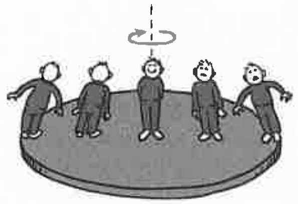

FIGURE 8.2
INTERACTIVE FIGURE

The tangential speed of each person is proportional to the rotational speed of the platform multiplied by the distance from the central axis.

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[1] Physics types usually describe rotational speed, ω, in terms of the number of "radians" turned in a unit of time. There are a little more than 6 radians in a full rotation (2π radians, to be exact). When a direction is assigned to rotational speed, we call it *rotational velocity* (often called *angular velocity*). Rotational velocity is a vector whose magnitude is the rotational speed. By convention, the rotational velocity vector lies along the axis of rotation, and point in the direction of advance of a conventional right-handed screw.

When a row of people, locked arm in arm at the skating rink, makes a turn, the motion of "tail-end Charlie" is evidence of a greater tangential speed.

Tangential speed, unlike rotational speed, depends on radial distance (the distance from the axis). At the very center of the rotating platform, you have no speed at all; you merely rotate. But, as you approach the edge of the platform, you find yourself moving faster and faster. Tangential speed is directly proportional to distance from the axis for any given rotational speed.

So we see that tangential speed is proportional to both radial distance and rotational speed.[2]

$$\text{Tangential speed} \sim \text{radial distance} \times \text{rotational speed}$$

In symbol form,

$$v \sim r\omega$$

where v is tangential speed and ω (Greek letter omega) is rotational speed. You move faster if the rate of rotation increases (bigger ω). You also move faster if you move farther from the axis (bigger r). Move out twice as far from the rotational axis at the center and you move twice as fast. Move out 3 times as far and you have 3 times as much tangential speed. If you find yourself in any kind of rotating system, your tangential speed depends on how far you are from the axis of rotation.

Why will a person with one leg shorter than the other tend to walk in circles when lost?

CHECK POINT

1. Imagine a ladybug sitting halfway between the rotational axis and the outer edge of the turntable in Figure 8.1b. When the turntable has a rotational speed of 20 RPM and the bug has a tangential speed of 2 cm/s, what will be the rotational and tangential speeds of her friend who sits at the outer edge?
2. Trains ride on a pair of tracks. For straight-line motion, both tracks are the same length. Not so for tracks along a curve. Which track is longer, the one on the outside of the curve or the one on the inside?

Check Your Answers

1. Since all parts of the turntable have the same rotational speed, her friend also rotates at 20 RPM. Tangential speed is a different story: Since she is twice as far from the axis of rotation, she moves twice as fast—4 cm/s.
2. Similar to Figure 8.1, the track on the outside of the curve is longer—just as the circumference of a circle of greater radius is longer.

FIGURE 8.3

Cathy Candler asks her class which set of cups will self-correct when she rolls them along a pair of "meterstick tracks."

When tangential speed undergoes change, we speak of a *tangential acceleration.* Any change in tangential speed indicates an acceleration parallel to tangential motion. For example, a person on a rotating platform that speeds up or slows down undergoes a tangential acceleration. We'll soon see that anything moving in a curved path undergoes another kind of acceleration—one directed to the center of curvature. This is *centripetal acceleration.* In the interest of "information overload," we'll not go into the details of tangential or centripetal acceleration.

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[2] If you take a follow-up physics course, you will learn that when the proper units are used for tangential speed v, rotational speed ω, and radial distance r, the direct proportion of v to both r and ω becomes the exact equation $v = r\omega$. So the tangential speed will be directly proportional to r when all parts of a system simultaneously have the same ω, as for a wheel or disk (or a flyswatter!).

Wheels on Railroad Trains

Why does a moving railroad train stay on the tracks? Most people assume that the wheel flanges keep the wheels from rolling off. But if you look at these flanges, you'll likely note they are rusty. They seldom touch the track, except when they follow slots that switch the train from one set of tracks to another. So how do the wheels of a train stay on the tracks? They stay on the track because their rims are slightly tapered.

If you roll a tapered cup across a surface, it makes a curved path (Figure 8.4). The wider part of the cup has a greater radius, rolls a greater distance per revolution, and therefore has a greater tangential speed than the narrower end. If you fasten a pair of cups together at their wide ends (simply taping them together) and roll the pair along a pair of parallel tracks (Figure 8.5), the cups will remain on the track and center themselves whenever they roll off center. This occurs because when the pair rolls to the left of center, say, the wider part of the left cup rides on the left track while the narrow part of the right cup rides on the right track. This steers the pair toward the center. If it "overshoots" toward the right, the process repeats, this time toward the left, as the wheels tend to center themselves. Likewise for a railroad train, where passengers feel the train swaying as these corrective actions occur.

This tapered shape is essential on the curves of railroad tracks. On any curve, the distance along the outer part is longer than the distance along the inner part (as we saw in Figure 8.1a). So, whenever a vehicle follows a curve, its outer wheels travel faster than its inner wheels. For an automobile, this is not a problem because the wheels are freewheeling and roll independently of each other. For a train, however, like the pair of fastened cups, pairs of wheels are firmly connected and rotate together. Opposite wheels have the same RPM at any time. But, due to the slightly tapered rim of the wheel, its tangential speed along the track depends on whether it rides on the narrow part of the rim or the wide part. On the wide part, it travels faster. So, when a train rounds a curve, wheels on the outer track ride on the wider part of the tapered rims, while opposite wheels ride on their narrow parts. In this way, the wheels have different tangential speeds for the same rotational speed. This is $v \sim r\omega$ in action! Can you see that if the wheels were not tapered, scraping would occur and the wheels would squeal when a train rounds a curve?

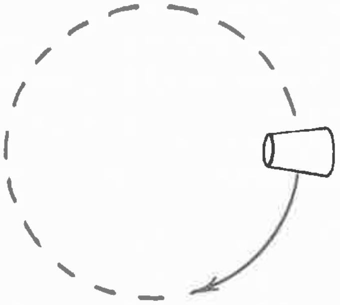


FIGURE 8.4

Because the wide part of the cup rolls faster than the narrow part, the cup rolls in a curve.

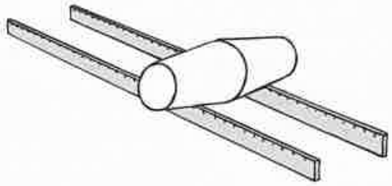


FIGURE 8.5

Two fastened cups stay on the tracks as they roll because, when they roll off center, the different tangential speeds due to the taper cause them to self-correct toward the center of the track.

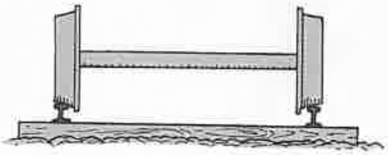
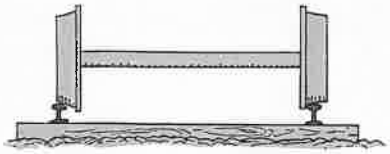
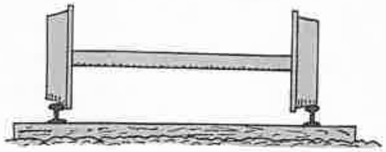


FIGURE 8.6

Wheels of a railroad train are slightly tapered (shown exaggerated here).



Narrow part of left wheel goes slower, so wheels curve to left



Wide part of left wheel goes faster, so wheels curve to right

FIGURE 8.7

(Top) Along a track that curves to the left, the right wheel rides on its wide part and goes faster while the left wheel rides on its narrow part and goes slower. (Bottom) The opposite is true when the track curves to the right.

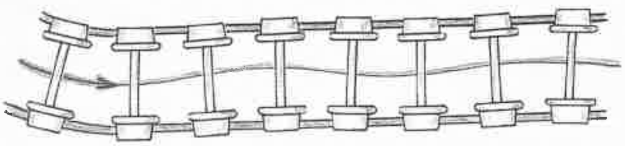


FIGURE 8.8

After rounding a curve, a train often oscillates on the straightaway as the wheels self-correct.

Rotational Inertia

Just as an object at rest tends to stay at rest and an object in motion tends to remain moving in a straight line, *an object rotating about an axis tends to remain rotating about the same axis unless interfered with by some external influence.* (We shall see shortly that this external influence is properly called a *torque.*) The property of an object to resist changes in its rotational state of motion is called **rotational inertia.**[3] Bodies that are rotating tend to remain rotating, while nonrotating bodies tend to remain nonrotating. In the absence of outside influences, a rotating top keeps rotating, while a top at rest remains at rest.

Like inertia for linear motion, rotational inertia depends on mass. The thick stone disk that rotates beneath a potter's wheel is very massive, and, once it is spinning, it tends to remain spinning. But, unlike linear motion, rotational inertia depends on the distribution of the mass about the axis of rotation. The greater the distance between an object's mass concentration and the axis, the greater the rotational inertia. This is evident in industrial flywheels that are constructed so that most of their mass is concentrated far from the axis, along the rim. Once rotating, they have a greater tendency to remain rotating. When at rest, they are more difficult to get rotating.

Industrial flywheels provide a practical means of storing energy in electric power plants. When the plants generate continuous electricity, energy not needed when power demand is low is diverted to massive flywheels, which are the counterpart of electric batteries—but environmentally sound with no toxic metals nor hazardous waste. The whirling wheels are then connected to generators to release the power when it's needed. When combined with other flywheels, banks of ten or more of them connected to power grids offset fluctuations between supply and demand and help them run more smoothly. Cheers for rotational inertia!

The greater the rotational inertia of an object, the greater the difficulty in changing its rotational state. This fact is employed by a circus tightrope walker who carries a long pole to aid balance. Much of the mass of the pole is far from the axis of rotation, its midpoint. The pole, therefore, has considerable rotational inertia. If the tightrope walker starts to topple over, a tight grip on the pole rotates the pole. But the rotational inertia of the pole resists, giving the tightrope walker time to readjust his or her balance. The longer the pole, the better. And better still if massive objects are attached to the ends. But a tightrope walker with no pole can at least extend his or her arms full length to increase the body's rotational inertia.

The rotational inertia of the pole, or of any object, depends on the axis about which it rotates.[4] Compare the different rotations of a pencil (Figure 8.11). Consider

fyi

- An idea put forward in past years for boosting efficiency in electric rail travel was massive rotor disks—flywheels—beneath the flooring of railroad cars. When brakes were applied, rather than slowing the cars by converting braking energy to heat via friction, the braking energy would be diverted to revving the flywheels, which then could operate generators to supply electric energy for operating the train. The massiveness of the rotors turned out to make the scheme impractical. But the idea hasn't been lost. Today's hybrid automobiles do much the same thing—not mechanically, but electrically. Braking energy is diverted to electric batteries, which are then used for operating the automobile.

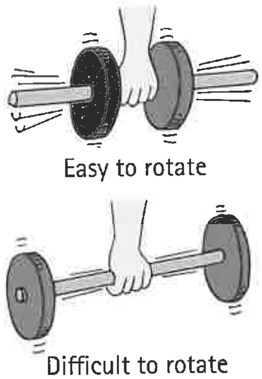


FIGURE 8.9

Rotational inertia depends on the distribution of mass relative to the axis of rotation.

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Videos

Rotational Inertia Using Weighted Pipes
Rotational Inertia Using a Hammer
Rotational Inertia with a Weighted Rod

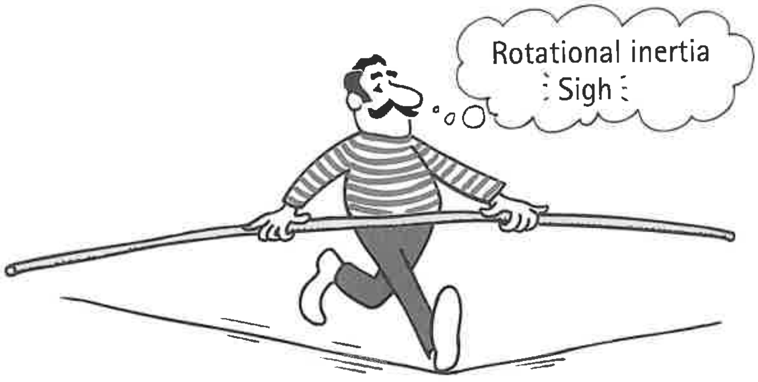

FIGURE 8.10

The tendency of the pole to resist rotation aids the acrobat.

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[3] Often called *moment of inertia.*

three axes—one about its central core parallel to the length of the pencil, where the lead is; the second about the perpendicular midpoint axis; and the third about an axis perpendicular to one end. Rotational inertia is very small about the first position, and it's easy to rotate the pencil between your fingertips because most all the mass is very close to the axis. About the second axis, like that used by the tightrope walker in the preceding illustration, rotational inertia is greater. About the third axis, at the end of the pencil so that it swings like a pendulum, rotational inertia is greater still.

A long baseball bat held near its end has more rotational inertia than a short bat. Once it is swinging, it has a greater tendency to keep swinging, but it is harder to bring it up to speed. A short bat, with less rotational inertia, is easier to swing—which explains why baseball players sometimes "choke up" on a bat by grasping it closer to the more massive end. Similarly, when you run with your legs bent, you reduce their rotational inertia so you can rotate them back and forth more quickly. A long-legged person tends to walk with slower strides than a person with short legs. The different strides of creatures with different leg lengths are especially evident in animals. Giraffes, horses, and ostriches run with a slower gait than dachshunds, mice, and bugs.

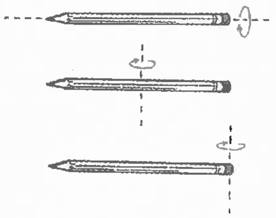


FIGURE 8.11
The pencil has different rotational inertias about different rotational axes.

FIGURE 8.12
You bend your legs when you run to reduce rotational inertia.

FIGURE 8.13
Short legs have less rotational inertia than long legs. An animal with short legs has a quicker stride than people with long legs, just as a baseball batter can swing a short bat more quickly than a long one.

Because of rotational inertia, a solid cylinder starting from rest will roll down an incline faster than a hoop. Both rotate about a central axis, and the shape that has most of its mass far from its axis is the hoop. So, for its weight, a hoop has more rotational inertia and is harder to start rolling. Any solid cylinder will outroll any hoop on the same incline. This doesn't seem plausible at first, but remember that any two objects, regardless of mass, will fall together when dropped. They will also slide together when released on an inclined plane. When rotation is introduced, the object with the larger rotational inertia *relative to its own mass* has the greater resistance to a change in its motion. Hence, any solid cylinder will roll down any incline with more acceleration than any hollow cylinder, regardless of mass or radius. A hollow cylinder has more "laziness per mass" than a solid cylinder. Try it and see!

Figure 8.15 compares rotational inertias for various shapes and axes. It is not important for you to learn the equations shown in the figure, but can you see how they vary with the shape and axis?

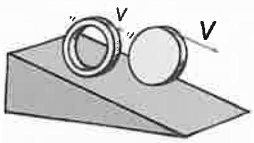


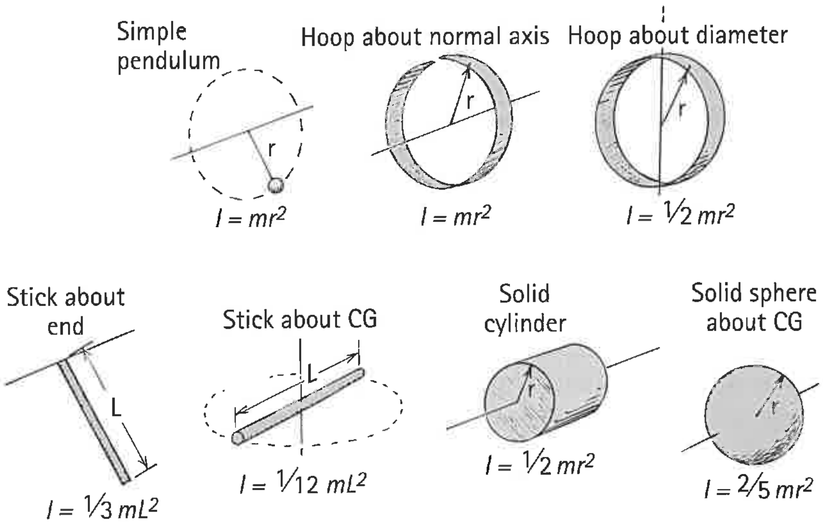
FIGURE 8.14
A solid cylinder rolls down an incline faster than a hoop, whether or not they have the same mass or outer diameter. A hoop has greater rotational inertia relative to its mass than a cylinder does.

---

[4] When the mass of an object is concentrated at the radius r from the axis of rotation (as for a simple pendulum bob or a thin ring), rotational inertia I is equal to the mass m multiplied by the square of the radial distance. For this special case, $I = mr^2$.

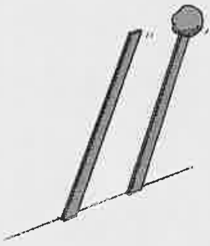
FIGURE 8.15

Rotational inertias of various objects, each of mass m, about indicated axes.



Note how rotational inertia very much depends on the location of the axis of rotation. A stick rotated about one end, for example, has 4 times the rotational inertia than when rotated about its center.

CHECK POINT



1. Consider balancing a hammer upright on the tip of your finger. The head is likely heavier than the handle. Is it easier to balance with the end of the handle on your fingertip, with the head at the top, or the other way around with the head at your fingertip and the end of the handle at the top?
2. Consider a pair of metersticks standing nearly upright against a wall. If you release them, they'll rotate to the floor in the same time. But what if one has a massive hunk of clay stuck to its top end? Will it rotate to the floor in a longer or shorter time?
3. Just for fun, and since we're discussing round things, why are manhole covers circular in shape?

Check Your Answers

1. Stand the hammer with the handle at your fingertip and the head at the top. Why? Because it will have more rotational inertia this way and be more resistant to a rotational change. (Try this yourself by trying to balance a spoon both ways on your fingertip.) Those acrobats you see on stage who balance a long pole have an easier task when their friends are at the top of the pole. A pole empty at the top has less rotational inertia and is more difficult to balance!
2. Try it and see! (If you don't have clay, fashion something equivalent.)
3. Not so fast on this one. Give it some thought. If you don't come up with an answer, *then* look to the end of the chapter for an answer.

Torque

Hold the end of a meterstick horizontally with your hand. Dangle a weight from it near your hand and you can feel the stick twist. Now slide the weight farther from your hand and you can feel that the twist is greater. But the weight is the same. The force acting on your hand is the same. What's different is the *torque.*

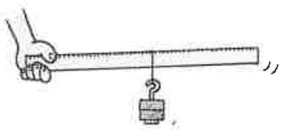


FIGURE 8.16

Move the weight farther from your hand and feel the difference between force and torque.

A torque (rhymes with *dork*) is the rotational counterpart of force. Force tends to change the motion of things; torque tends to twist or change the state of rotation of things. If you want to make a stationary object move or a moving object change speed, apply force. If you want to make a stationary object rotate or a rotating object change rotational speed, apply torque.

Just as rotational inertia differs from regular inertia, torque differs from force. Both rotational inertia and torque involve distance from the axis of rotation. In the case of torque, this distance, which provides leverage, is called the *lever arm.* It is the shortest distance between the applied force and the rotational axis. We define **torque** as the product of this lever arm and the force that tends to produce rotation:

$$\text{Torque} = \text{lever arm} \times \text{force}$$

FIGURE 8.17

Mary Beth Monroe demonstrates a "torque feeler" before she passes it around for her students to try.

Torques are intuitively familiar to youngsters playing on a seesaw. Kids can balance a seesaw even when their weights are unequal. Weight alone doesn't produce rotation—torque does also—and children soon learn that the distance they sit from the pivot point is every bit as important as their weight. The torque produced by the boy on the right in Figure 8.18 tends to produce clockwise rotation, while torque produced by the girl on the left tends to produce counterclockwise rotation. If the torques are equal, making the net torque zero, no rotation is produced.

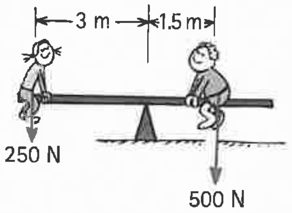


FIGURE 8.18

INTERACTIVE FIGURE

No rotation is produced when the torques balance each other.

Suppose that the seesaw is arranged so that the half-as-heavy girl is suspended from a 4-m rope hanging from her end of the seesaw (Figure 8.19). She is now 5 m from the fulcrum, and the seesaw is still balanced. We see that the lever-arm distance is still 3 m and not 5 m. The lever arm about any axis of rotation is the perpendicular distance from the axis to the line along which the force acts. This will always be the shortest distance between the axis of rotation and the line along which the force acts.

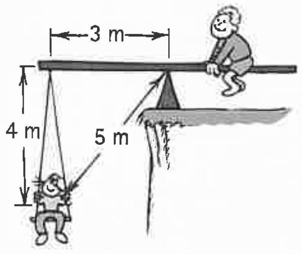


FIGURE 8.19

The lever arm is still 3 m.

This is why the stubborn bolt shown in Figure 8.20 is more likely to turn when the applied force is perpendicular to the handle, rather than at an oblique angle as shown in the first figure. In the first figure, the lever arm is shown by the dashed line and is less than the length of the wrench handle. In the second figure, the lever arm is equal to the length of the wrench handle. In the third figure, the lever arm is extended with a piece of pipe to provide more leverage and a greater torque.

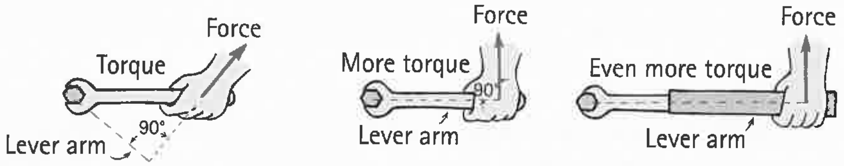


FIGURE 8.20

INTERACTIVE FIGURE

Although the magnitudes of the force are the same in each case, the torques are different.

If and when all clocks go digital, will clockwise and counterclockwise have meaning to future generations?

Recall the equilibrium rule in Chapter 2—that the sum of the forces acting on a body or any system must equal zero for mechanical equilibrium. That is, $\Sigma F = 0$. We now see an additional condition. The *net torque* on a body or on a system must also be zero for mechanical equilibrium, $\Sigma\tau = 0$, where τ stands for torque. Anything in mechanical equilibrium doesn't accelerate linearly or rotationally.

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Difference Between Torque and Weight

Why a Ball Rolls Down a Hill

CHECK POINT

1. If a pipe effectively extends a wrench handle to 3 times its length, by how much will the torque increase for the same applied force?
2. Consider the balanced seesaw in Figure 8.18. Suppose the girl on the left suddenly gains 50 N, such as by being handed a bag of apples. Where should she sit in order to balance, assuming the heavier boy does not move?

Check Your Answers

1. Three times more leverage for the same force produces 3 times more torque. (Caution: This method of increasing torque sometimes results in shearing off the bolt!)
2. She should sit $\frac{1}{2}$ m closer to the center. Then her lever arm is 2.5 m. This checks: $300\text{ N} \times 2.5\text{ m} = 500\text{ N} \times 1.5\text{ m}$.

Center of Mass and Center of Gravity

Toss a baseball into the air, and it will follow a smooth parabolic trajectory. Toss a baseball bat spinning into the air, and its path is not smooth; its motion is wobbly, and it seems to wobble all over the place. But, in fact, it wobbles about a very special place, a point called the **center of mass (CM).**

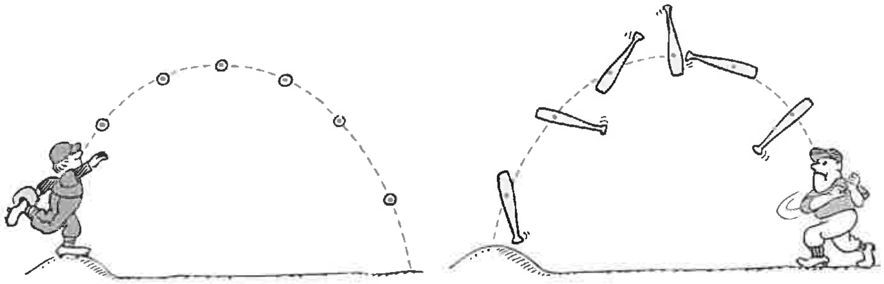

FIGURE 8.21

The center of mass of the baseball and that of the bat follow parabolic trajectories.

For a given body, the center of mass is the average position of all the mass that makes up the object. For example, a symmetrical object, such as a ball, has its center of mass at its geometrical center; by contrast, an irregularly shaped body, such as a baseball bat, has more of its mass toward one end. The center of mass of a baseball bat, therefore, is toward the thicker end. A solid cone has its center of mass exactly one-fourth of the way up from its base.

Center of gravity (CG) is a term popularly used to express center of mass. The center of gravity is simply the average position of weight distribution. Since weight and mass are proportional, center of gravity and center of mass refer to the same point of an object.[5] The physicist prefers to use the term *center of mass,* for an object has a center of mass whether or not it is under the influence of gravity. However, we shall use either term to express this concept, and we shall favor the term *center of gravity* when weight is part of the picture.

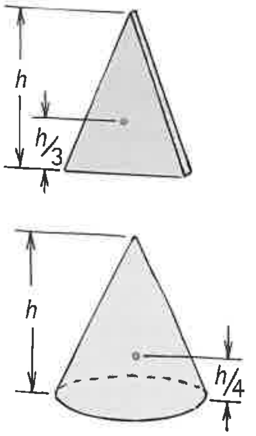

FIGURE 8.22

The center of mass for each object is shown by the red dot.

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[5] For almost all objects on and near Earth's surface, these terms are interchangeable. A small difference between center of gravity and center of mass can occur for an object large enough so that gravity varies from one part to another. For example, the center of gravity of the Empire State Building is about 1 millimeter below its center of mass. This is due to the lower stories being pulled a little more strongly by Earth's gravity than the upper stories. For everyday objects (including tall buildings), we can use the terms *center of gravity* and *center of mass* interchangeably.

The multiple-flash photograph (Figure 8.23) shows a top view of a wrench sliding across a smooth horizontal surface. Note that its center of mass, indicated by the white dot, follows a straight-line path, while other parts of the wrench wobble as they move across the surface. Since there is no external force acting on the wrench, its center of mass moves equal distances in equal time intervals. The motion of the spinning wrench is the combination of the straight-line motion of its center of mass and the rotational motion about its center of mass.

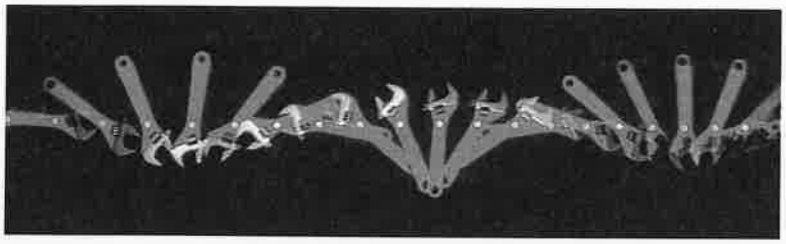

FIGURE 8.23

The center of mass of the spinning wrench follows a straight-line path.

If the wrench were instead tossed into the air, no matter how it rotates, its center of mass (or center of gravity) would follow a smooth parabolic arc. The same is true for an exploding cannonball (Figure 8.24). The internal forces that act in the explosion do not change the center of gravity of the projectile. Interestingly enough, if air resistance can be neglected, the center of gravity of the dispersed fragments as they fly though the air will be in the same location as the center of gravity would have been if the explosion hadn't occurred.

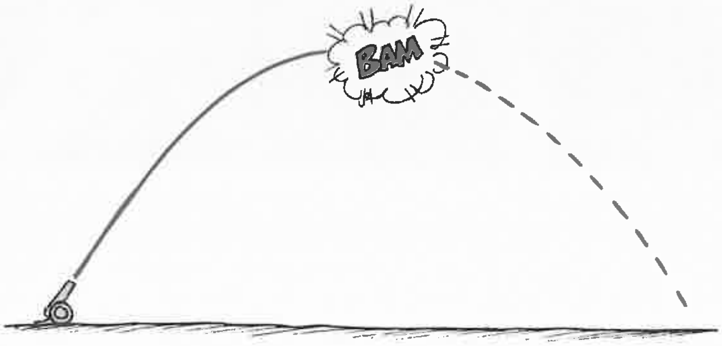

FIGURE 8.24

The center of mass of the cannonball and its fragments moves along the same path before and after the explosion.

CHECK POINT

1. Where is the CG of a donut?
2. Can an object have more than one CG?

Check Your Answers

1. In the center of the hole!
2. No. A rigid object has one CG. If it is nonrigid, such as a piece of clay or putty, and is distorted into different shapes, then its CG may change as its shape changes. Even then, it has one CG for any given shape.

LOCATING THE CENTER OF GRAVITY

The center of gravity of a uniform object, such as a meterstick, is at its midpoint, for the stick acts as if its entire weight were concentrated there. If you support that single point, you support the entire stick. Balancing an object provides a simple method of locating its center of gravity. In Figure 8.25, the many small arrows represent the pull of gravity all along the meterstick. All of these can be combined into a resultant force acting through the center of gravity. The entire weight of the stick may be thought of as acting at this single point. Hence, we can balance the stick by applying a single upward force in a direction that passes through this point.

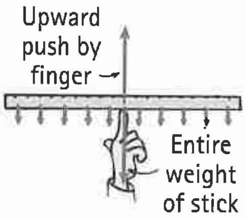

FIGURE 8.25

The weight of the entire stick behaves as if it were concentrated at the stick's center.

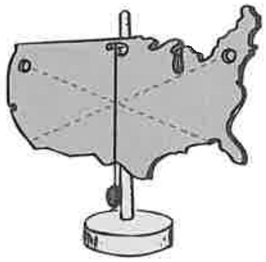

FIGURE 8.26

Finding the center of gravity for an irregularly shaped object.

The center of gravity of any freely suspended object lies directly beneath (or at) the point of suspension (Figure 8.26). If a vertical line is drawn through the point of suspension, the center of gravity lies somewhere along that line. To determine exactly where it lies along the line, we have only to suspend the object from some other point and draw a second vertical line through that point of suspension. The center of gravity lies where the two lines intersect.

The center of mass of an object may be a point where no mass exists. For example, the center of mass of a ring or a hollow sphere is at the geometrical center where no matter exists. Similarly, the center of mass of a boomerang is outside the physical structure, not within the material of the boomerang (Figure 8.27).

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Learning the Center of Gravity

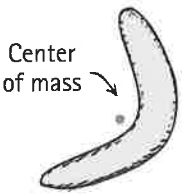


FIGURE 8.27

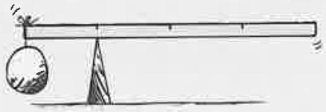
The center of mass can be outside the mass of a body.

FIGURE 8.28

The athlete executes a "Fosbury flop" to clear the bar while her center of gravity passes beneath the bar.

CHECK POINT

1. Where is the center of mass of Earth's atmosphere?
2. A uniform meterstick supported at the 25-cm mark balances when a 1-kg rock is suspended at the 0-cm end. What is the mass of the meterstick?



Check Your Answers

1. Like a giant basketball, Earth's atmosphere is a spherical shell with its center of mass at Earth's center.
2. The mass of the meterstick is 1 kg. Why? The system is in equilibrium, so any torques must be balanced: The torque produced by the weight of the rock is balanced by the equal but oppositely directed torque produced by the weight of the stick *applied at its CG, the 50-cm mark.* The support force at the 25-cm mark is applied midway between the rock and the stick's CG, so the lever arms about the support point are equal (25 cm). This means that the weights (and hence the masses) of the rock and stick are also equal. (Note that we don't have to go through the laborious task of considering the fractional parts of the stick's weight on either side of the fulcrum, for the CG of the whole stick really is at one point—the 50-cm mark!) Interestingly, the CG of the rock + stick system is at the 25-cm mark—directly above the fulcrum.

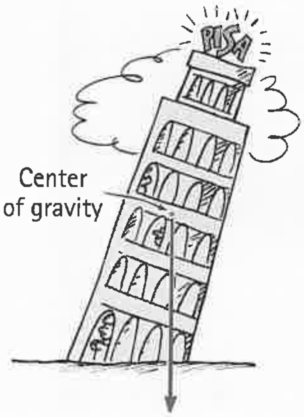


FIGURE 8.29

The center of gravity of the Leaning Tower of Pisa lies above its base of support, so the tower is in stable equilibrium.

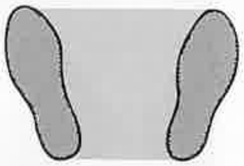


FIGURE 8.30

When you stand, your center of gravity is somewhere above the base area bounded by your feet. Why do you keep your legs far apart when you have to stand in the aisle of a bumpy-riding bus?

STABILITY

The location of the center of gravity is important for stability (Figure 8.29). If we draw a line straight down from the center of gravity of an object of any shape and it falls inside the base of the object, it is in stable **equilibrium;** it will balance. If it falls outside the base, it is unstable. Why doesn't the famous Leaning Tower of Pisa topple over? As we can see in Figure 8.29, a line from the center of gravity of the tower to the level of the ground falls inside its base, so the Leaning Tower has stood for several centuries. If the tower leaned far enough so that the center of gravity extended beyond the base, an unbalanced torque would topple the tower.

When you stand erect (or lie flat), your center of gravity is within your body. Why is the center of gravity lower in an average woman than it is in an average man of the same height? Is your center of gravity always at the same point in your body? Is it always inside your body? What happens to it when you bend over?

If you are fairly flexible, you can bend over and touch your toes without bending your knees. Ordinarily, when you bend over and touch your toes, you extend your lower extremity as shown in the left half of Figure 8.31, so that your center of gravity is above a base of support, your feet. If you attempt to do this when standing against a wall, however, you cannot counterbalance yourself, and your center of gravity soon protrudes beyond your feet, as shown in the right half of Figure 8.31.

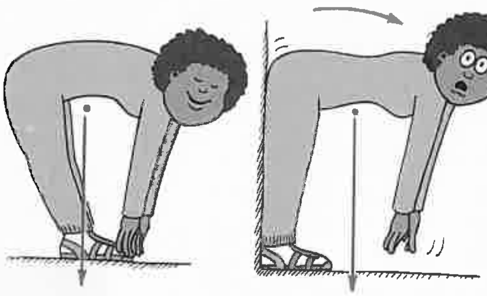


FIGURE 8.31

You can lean over and touch your toes without falling over only if your center of gravity is above the area bounded by your feet.

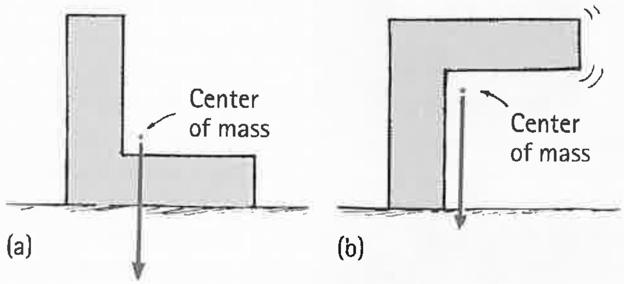


FIGURE 8.32

The center of mass of the L-shaped object is located where no mass exists. In (a), the center of mass is above the base of support, so the object is stable. In (b), it is not above the base of support, so the object is unstable and will topple over.

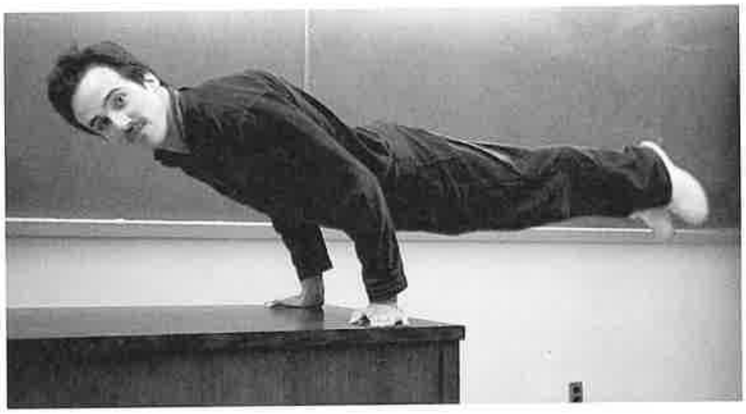


FIGURE 8.33
Where is Alexei's center of gravity relative to his hands?

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Toppling

You rotate because of an unbalanced torque. This is evident in the two L-shaped objects shown in Figure 8.34. Both are unstable and will topple unless fastened to the level surface. It is easy to see that even if both shapes have the same weight, the one on the right is more unstable. This is because of the greater lever arm and, hence, a greater torque.

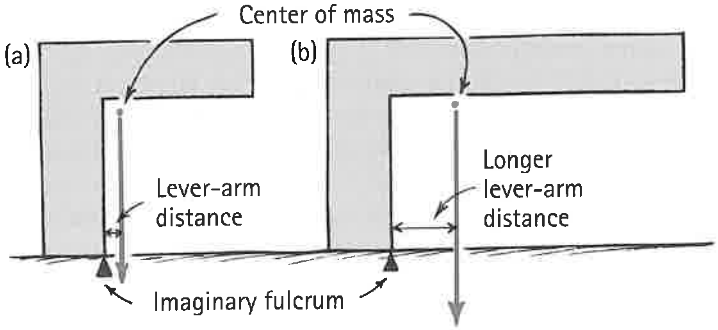


FIGURE 8.34
The greater torque acts on (b) for two reasons. What are they?

Try balancing the pole end of a broom upright on the palm of your hand. The support base is quite small and relatively far beneath the center of gravity, so it's difficult to maintain balance for very long. After some practice, you can do it if you learn to make slight movements of your hand to respond exactly to variations in balance. You learn to avoid underresponding or overresponding to the slightest variations in balance. The intriguing Segway Human Transporter (Figure 8.35) does much the same. Variations in balance are quickly sensed by gyroscopes, and an internal computer regulates a motor to keep the vehicle upright. The computer regulates corrective adjustments of the wheel speed in a way quite similar to the way in which your brain coordinates your adjustive action when balancing a long pole on the palm of your hand. Both feats are truly amazing.

To reduce the likelihood of tipping, it is usually advisable to design objects with a wide base and low center of gravity. The wider the base, the higher the center of gravity must be raised before the object tips over.

FIGURE 8.35
Gyroscopes and computer-assisted motors make continual adjustments in the self-balancing electric scooters to keep the combined CGs of Mark, Tenny, and the vehicles above the wheelbase.

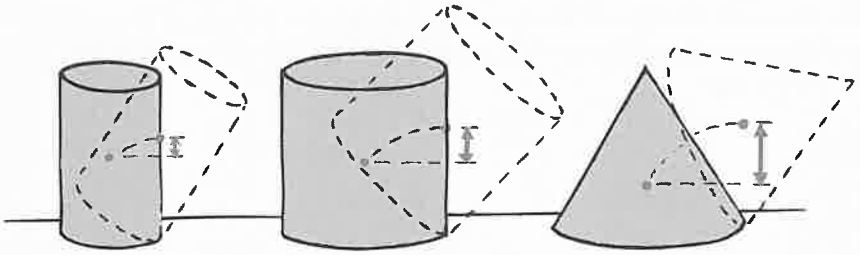
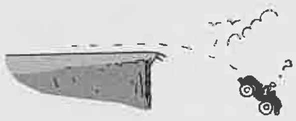


FIGURE 8.36

Stability is determined by the vertical distance that the center of gravity is raised in tipping. An object with a wide base and a low center of gravity is more stable.

CHECK POINT

1. Why is it dangerous to slide open the top drawers of a fully loaded file cabinet that is not secured to the floor?
2. When a car drives off a cliff, why does it rotate forward as it falls?



Check Your Answers

1. The filing cabinet is in danger of tipping because the CG may extend beyond the support base. If it does, then torque due to gravity tips the cabinet.
2. When all wheels are on the ground, the car's CG is above a support base and no tipping occurs. But when the car drives off a cliff, the front wheels are first to leave the ground and the car is supported only by the rear wheels. The CG then extends beyond the support base, and rotation occurs. Interestingly, the speed of the car relates to how much time the CG is not supported, and hence, the amount the car rotates while it falls.

Centripetal Force

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Centripetal Force

Any force directed toward a fixed center is called a **centripetal force.** *Centripetal* means "center-seeking" or "toward the center." When we whirl a tin can on the end of a string, we find that we must keep pulling on the string—exerting a centripetal force (Figure 8.37). The string transmits the centripetal force, which pulls the can into a circular path. Gravitational and electrical forces can produce centripetal forces. The Moon, for example, is held in an almost circular orbit by gravitational force directed toward the center of Earth. The orbiting electrons in atoms experience an electrical force toward the central nuclei. Anything that moves in a circular path does so because it's acted upon by a centripetal force.

Centripetal force depends on the mass m, tangential speed v, and radius of curvature r of the circularly moving object. In lab, you'll likely use the exact relationship

$$F = \frac{mv^2}{r}$$

Notice that speed is squared, so twice the speed needs 4 times the force. The inverse relationship with the radius of curvature tells us that half the radial distance requires twice the force.

Centripetal force is not a basic force of nature; it is simply the name given to any force, whether string tension, gravitational, electrical, or whatever, that is directed toward a fixed center. If the motion is circular and executed at constant speed, this force is at right angles to the path of the moving object.

When an automobile rounds a corner, the friction between the tires and the road provides the centripetal force that holds the car in a curved path (Figure 8.39).

FIGURE 8.37

The force exerted on the whirling can is toward the center.

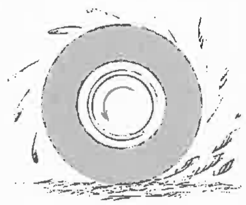

FIGURE 8.38

The centripetal force (adhesion of mud on the spinning tire) is not great enough to hold the mud on the tire, so it flies off in straight-line tangents.

If this friction is insufficient (due to oil or gravel on the pavement, for example), the tires slide sideways and the car fails to make the curve; the car tends to skid tangentially off the road.

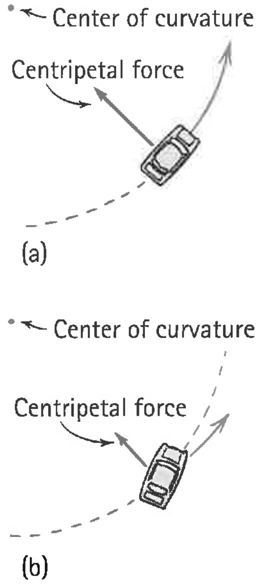

FIGURE 8.39

(a) When a car goes around a curve, there must be a force pushing the car toward the center of the curve. (b) A car skids on a curve when the centripetal force (friction of road on tires) is not great enough.

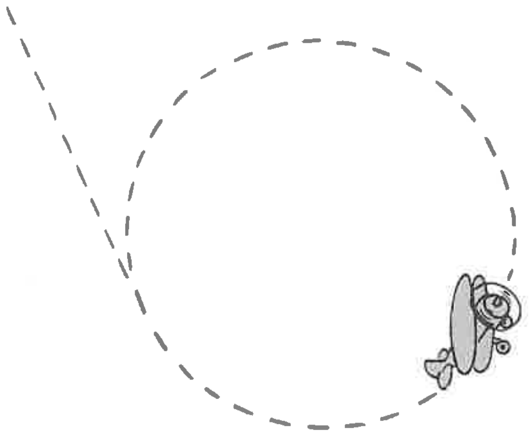

FIGURE 8.40

Large centripetal forces on the wings of an aircraft enable it to fly in circular loops. The acceleration away from the straight-line path the aircraft would follow in the absence of centripetal force is often several times greater than the acceleration due to gravity, *g*. For example, if the centripetal acceleration is 50 m/s^2 (5 times as great as 10 m/s^2), we say that the aircraft is undergoing 5 *g*'s. For a pilot, the number of *g*'s is defined by the force on the seat of his or her pants. So at the bottom of the loop where the pilot's weight lines up with the centripetal force, the pilot experiences 6 *g*'s. Typical fighter aircraft are designed to withstand accelerations up to 8 or 9 *g*'s. The pilot as well as the aircraft must withstand this amount of acceleration. Pilots of fighter aircraft wear pressure suits to prevent blood from flowing away from the head toward the legs, which could cause a blackout.

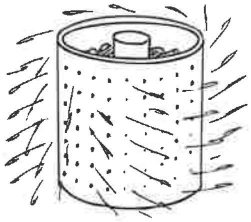

FIGURE 8.41

The clothes are forced into a circular path, but the water is not.

Centripetal force plays the main role in the operation of a centrifuge. A familiar example is the spinning tub in an automatic washing machine (Figure 8.41). In its spin cycle, the tub rotates at high speed and produces a centripetal force on the wet clothes, which are forced into a circular path by the inner wall of the tub. The tub exerts great force on the clothes, but the holes in the tub prevent the exertion of the same force on the water in the clothes. The water escapes tangentially out the holes. Strictly speaking, the clothes are forced away from the water; the water is not forced away from the clothes. Think about that.

Practicing Physics: Water-Bucket Swing

Half fill a bucket of water and swing it in a vertical circle, as Marshall Ellenstein demonstrates. The bucket and water accelerate toward the center of your swing. If you swing the bucket fast enough, the water won't fall out at the top. Interestingly, although it won't fall *out,* it still falls. The trick is to swing the bucket fast enough so that the bucket falls as fast as the water inside the bucket falls. Can you see that because the bucket is circling the water moves tangentially—and stays in the bucket? In Chapter 10, we'll learn that an orbiting space shuttle similarly falls while in orbit. The trick is to impart sufficient tangential velocity to the shuttle so that it falls around the curved Earth rather than into it.

Centrifugal Force

Although centripetal force is center directed, an occupant inside a rotating system seems to experience an outward force. This apparent outward force is called **centrifugal force.** *Centrifugal* means "center-fleeing" or "away from the center." In the case of the whirling can, it is a common misconception to believe that a centrifugal force pulls outward on the can. If the string holding the whirling can breaks (Figure 8.42), the can doesn't move radially outward, but goes off in a tangent straight-line path—because *no* force acts on it. We illustrate this further with another example.

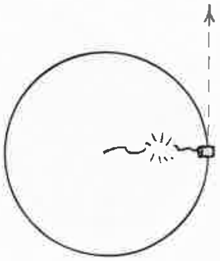

FIGURE 8.42

When the string breaks, the whirling can moves in a straight line, tangent to—not outward from—the center of its circular path.

Suppose you are a passenger in a car that suddenly stops short. You pitch forward toward the dashboard. When this occurs, you don't say that something forced you forward. In accord with the law of inertia, you pitched forward because of the absence of a force, which seat belts would have provided. Similarly, if you are in a car that rounds a sharp corner to the left, you tend to pitch outward to the right—not because of some outward or centrifugal force, but because there is no centripetal force holding you in circular motion (again, the purpose of seat belts). The idea that a centrifugal force bangs you against the car door is a misconception. (Sure, you push out against the door, but only because the door pushes in on you—Newton's third law.)

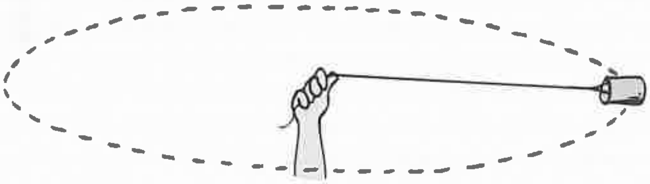

FIGURE 8.43

The only force that is exerted on the whirling can (neglecting gravity) is directed *toward* the center of circular motion. This is a centripetal force. No *outward* force acts on the can.

Likewise, when you swing a tin can in a circular path, no force pulls the can outward—the only force on the can is the string pulling it inward. There is no outward force on the can. Now suppose there is a ladybug inside the whirling can (Figure 8.44). The can presses against the bug's feet and provides the centripetal force that holds it in a circular path. From our outside stationary frame of reference, we see no centrifugal force exerted on the ladybug, just as no centrifugal force banged us against the car door. The centrifugal force effect is caused not by a real force, but by inertia—the tendency of the moving object to follow a straight-line path. But try telling that to the ladybug!

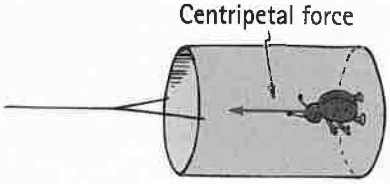

FIGURE 8.44

The can provides the centripetal force necessary to hold the ladybug in a circular path.

Centrifugal Force in a Rotating Reference Frame

If we stand at rest and watch somebody whirling a can overhead in a horizontal circle, we see that the force on the can is centripetal, just as it is on a ladybug inside the can. The bottom of the can exerts a force on the ladybug's feet. Neglecting gravity, no other force acts on the ladybug. But, as viewed from inside the frame of reference of the revolving can, things appear very different.[6]

In the rotating frame of the ladybug, in addition to the force of the can on the ladybug's feet, there is an apparent centrifugal force that is exerted on the ladybug. Centrifugal force *in a rotating reference frame* is a force in its own right, as real as the pull of gravity. However, there is a fundamental difference. Gravitational force is an

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[6] A frame of reference wherein a free body exhibits no acceleration is called an *inertial* frame of reference. Newton's laws are seen to hold exactly in an inertial frame. A rotating frame of reference, in contrast, is an accelerating frame of reference. Newton's laws are not valid in an accelerating frame of reference.

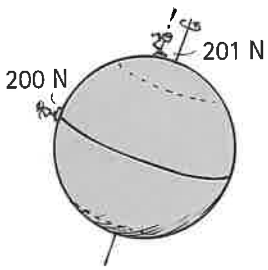

FIGURE 8.45
In the frame of reference of the spinning Earth, we experience a centrifugal force that slightly decreases our weight. Like an outside horse on a merry-go-round, we have the greatest tangential speed farthest from Earth's axis, at the equator. Centrifugal force is therefore maximum for us when we are at the equator and zero for us at the poles, where we have no tangential speed. So, strictly speaking, if you want to lose weight, walk toward the equator!

interaction between one mass and another. The gravity we experience is our interaction with Earth. But for centrifugal force in the rotating frame, no such agent exists—there is no interaction counterpart. Centrifugal force *feels* like gravity, but with no agent pulling. Nothing produces it; it is a result of rotation. For this reason, physicists call it an "inertial" force (or sometimes a *fictitious* force)—an *apparent* force—and not a real force like gravity, electromagnetic forces, and nuclear forces. Nevertheless, to observers who are in a rotating system, centrifugal force feels like, and is interpreted to be, a very real force. Just as gravity is ever present at Earth's surface, centrifugal force is ever present in a rotating system.

CHECK POINT

A heavy iron ball is attached by a spring to the rotating platform, as shown in the sketch. Two observers, one in the rotating frame and one on the ground at rest, observe its motion. Which observer sees the ball being pulled outward, stretching the spring? Which sees the spring pulling the ball into circular motion?

Check Your Answer

The observer in the reference frame of the rotating platform states that a centrifugal force pulls radially outward on the ball, which stretches the spring. The observer in the rest frame states that a centripetal force supplied by the stretched spring pulls the ball into circular motion. Only the observer in the rest frame can identify an action–reaction pair of forces; where action is spring on ball, reaction is ball on spring. The rotating observer can't identify a reaction counterpart to the centrifugal force because there isn't any!

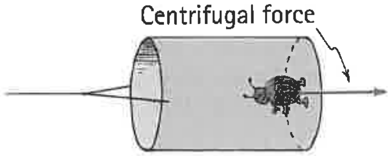

FIGURE 8.46
From the reference frame of the ladybug inside the whirling can, it is being held to the bottom of the can by a force that is directed away from the center of circular motion. The ladybug calls this outward force a *centrifugal* force, which is as real to it as gravity.

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Simulated Gravity

Simulated Gravity

Consider a colony of ladybugs living inside a bicycle tire—a balloon tire with plenty of room inside. If we toss the bicycle wheel through the air or drop it from an airplane high in the sky, the ladybugs will be in a weightless condition. They will float freely while the wheel is in free fall. Now spin the wheel. The ladybugs will feel themselves pressed to the outer part of the tire's inner surface. If the wheel is spun at just the right speed, the ladybugs will experience *simulated gravity* that will feel like the gravity they are accustomed to. Gravity is simulated by centrifugal force. The "down" direction to the ladybugs will be what we would call radially outward, away from the center of the wheel.

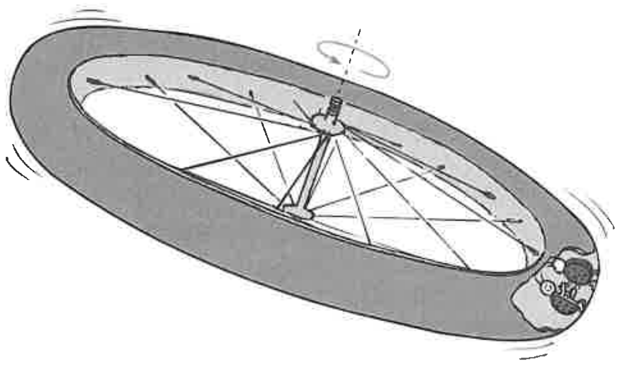

FIGURE 8.47
If the spinning wheel freely falls, the ladybugs inside will experience a centrifugal force that feels like gravity when the wheel spins at the appropriate rate. To the occupants, the direction "up" is toward the center of the wheel and "down" is radially outward.

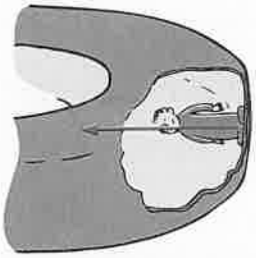

FIGURE 8.48

The interaction between the man and the floor, as seen from a stationary frame of reference outside the rotating system. The floor presses against the man (action) and the man presses back on the floor (reaction). The only force exerted on the man is by the floor. It is directed toward the center and is a centripetal force.

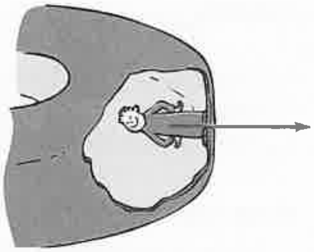

FIGURE 8.49

As seen from inside the rotating system, in addition to the man–floor interaction, there is a centrifugal force exerted on the man at his center of mass. It seems as real as gravity. Yet, unlike gravity, it has no reaction counterpart—there is nothing out there that he can pull back on. Centrifugal force is not part of an interaction, but it is a consequence of rotation. It is therefore called an apparent force, or a *fictitious force.*

Humans today live on the outer surface of this spherical planet and are held here by gravity. The planet has been the cradle of humankind. But we will not stay in the cradle forever. We are becoming a spacefaring people. Occupants of today's space vehicles feel weightless because they experience no *support force.* They're not pressed against a supporting floor by gravity, nor do they experience a centrifugal force due to spinning. Over extended periods, this can cause loss of muscle strength and detrimental changes in the body, such as loss of calcium from the bones. But future space travelers need not be subject to weightlessness. Their space habitats will probably spin, like the ladybug's spinning wheel, effectively supplying a support force and nicely simulating gravity.

The significantly smaller International Space Station doesn't rotate. Therefore, its crew members have to adjust to living in a weightless environment. Rotating habitats may follow later, perhaps in huge, lazily rotating structures where occupants will be held to the inner surfaces by centrifugal force. Such a rotating habitat supplies a simulated gravity so that the human body can function normally. Structures of small diameter would have to rotate at high rates to provide a simulated gravitational acceleration of 1 *g*. Sensitive and delicate organs in our inner ears sense rotation. Although there appears to be no difficulty at a single revolution per minute (RPM) or so, many people find it difficult to adjust to rates greater than 2 or 3 RPM (although some easily adapt to 10 or so RPM). To simulate normal Earth gravity at 1 RPM requires a large structure—one about 2 km in diameter. Centrifugal acceleration is directly proportional to the radial distance from the hub, so a variety of *g* states is possible. If the structure rotates so that inhabitants on the inside of the outer edge experience 1 *g*, then halfway to the axis they would experience 0.5 *g*. At the axis itself they would experience weightlessness (0 *g*). The variety of fractions of *g* possible from the rim of a rotating space habitat holds promise for a most different and (at this writing) as yet unexperienced environment. In this still very hypothetical structure, we would be able to perform ballet at 0.5 *g*, diving and acrobatics at 0.2 *g* and lower-*g* states, and three-dimensional soccer (and new sports not yet conceived) in very low *g* states.

A rotating habitat need not be a huge wheel. Gravity could be simulated in a pair of circling pods connected by a long cable.

CHECK POINT

If Earth were to spin faster about its axis, your weight would be less. If you were in a rotating space habitat that increased its spin rate, you'd "weigh" more. Explain why greater spin rates produce opposite effects in these cases.

Check Your Answer

You're on the *outside* of the spinning Earth, but you'd be on the *inside* of a spinning space habitat. A greater spin rate on the outside of the Earth tends to throw you *off* a weighing scale, causing it to show a decrease in weight, but *against* a weighing scale *inside* the space habitat to show an increase in weight.

Angular Momentum

Things that rotate, whether a colony in space, a cylinder rolling down an incline, or an acrobat doing a somersault, remain rotating until something stops them. A rotating object has an "inertia of rotation." Recall, from Chapter 6, that all moving objects have "inertia of motion" or *momentum*—the product of mass and velocity. This kind of momentum is **linear momentum.** Similarly, the "inertia of rotation" of rotating objects is called **angular momentum.** A planet orbiting the Sun, a rock whirling at the end of a string, and the tiny electrons whirling about atomic nuclei all have angular momentum.

Angular momentum is defined as the product of rotational inertia and rotational velocity:

$$\text{Angular momentum} = \text{rotational inertia} \times \text{rotational velocity}$$

It is the counterpart of linear momentum:

$$\text{Linear momentum} = \text{mass} \times \text{velocity}$$

Like linear momentum, angular momentum is a vector quantity and has direction as well as magnitude. In this book, we won't treat the vector nature of angular momentum (or even of torque, which also is a vector), except to acknowledge the remarkable action of the gyroscope. The rotating bicycle wheel in Figure 8.50 shows what happens when a torque caused by Earth's gravity acts to change the direction of its angular momentum (which is along the wheel's axle). The pull of gravity that normally acts to topple the wheel over and change its rotational axis causes it instead to *precess* about a vertical axis. You must do this yourself while standing on a turntable to fully believe it. You probably won't fully understand it unless you do follow-up study sometime in the future.

FIGURE 8.50

Angular momentum keeps the wheel axle nearly horizontal when a torque supplied by Earth's gravity acts on it. Instead of causing the wheel to topple, the torque causes the wheel's axle to turn slowly around the circle of students. This is called *precession.*

For the case of an object that is small compared with the radial distance to its axis of rotation, such as a tin can swinging from a long string or a planet orbiting in a circle around the Sun, the angular momentum can be expressed as the magnitude of its linear momentum, mv, multiplied by the radial distance, r (Figure 8.51). In shorthand notation,

$$\text{Angular momentum} = mvr$$

Just as an external net force is required to change the linear momentum of an object, an external net torque is required to change the angular momentum of an object. We can state a rotational version of Newton's first law (the law of inertia):

> **An object or system of objects will maintain its angular momentum unless acted upon by an external net torque.**

Our solar system has angular momentum that includes the Sun, the spinning and orbiting planets, and myriad other smaller bodies. The angular momentum of the solar system today will be its angular momentum for eons to come. Only an external torque from outside the solar system can change it. In the absence of such a torque, we say the angular momentum of the solar system is conserved.

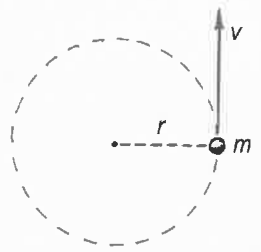

FIGURE 8.51

A small object of mass m whirling in a circular path of radius r with a speed v has angular momentum mvr.

Conservation of Angular Momentum

Just as the linear momentum of any system is conserved if no net force acts on the system, angular momentum is conserved if no net torque acts. The **law of conservation of angular momentum** states:

> **If no external net torque acts on a rotating system, the angular momentum of that system remains constant.**

This means that, with no external torque, the product of rotational inertia and rotational velocity at one time will be the same as at any other time.

An interesting example illustrating the conservation of angular momentum is shown in Figure 8.52. The man stands on a low-friction turntable with weights extended. His rotational inertia, I, with the help of the extended weights, is relatively large in this position. As he slowly turns, his angular momentum is the product of his rotational inertia and rotational velocity, ω. When he pulls the weights inward, the rotational inertia of his body and the weights is considerably reduced. What is the result? His rotational speed increases! This example is best appreciated by the turning person who feels changes in rotational speed that seem to be mysterious. But it's straightforward physics! This procedure is used by a figure skater who starts to whirl with her arms and perhaps a leg extended and then draws her arms and leg in to obtain a greater rotational speed. Whenever a rotating body contracts, its rotational speed increases.

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Videos

Conservation of Angular Momentum Using a Rotating Platform

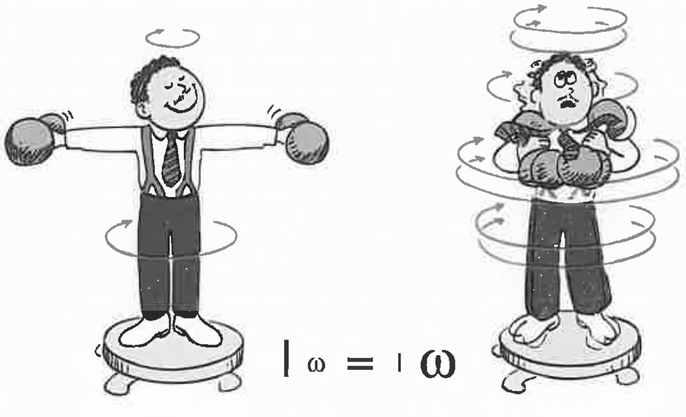


FIGURE 8.52

INTERACTIVE FIGURE

Conservation of angular momentum. When the man pulls his arms and the whirling weights inward, he decreases his rotational inertia I, and his rotational speed ω correspondingly increases.

Why do short acrobats have an advantage in tumbling or in other end-over-end rotational motions?

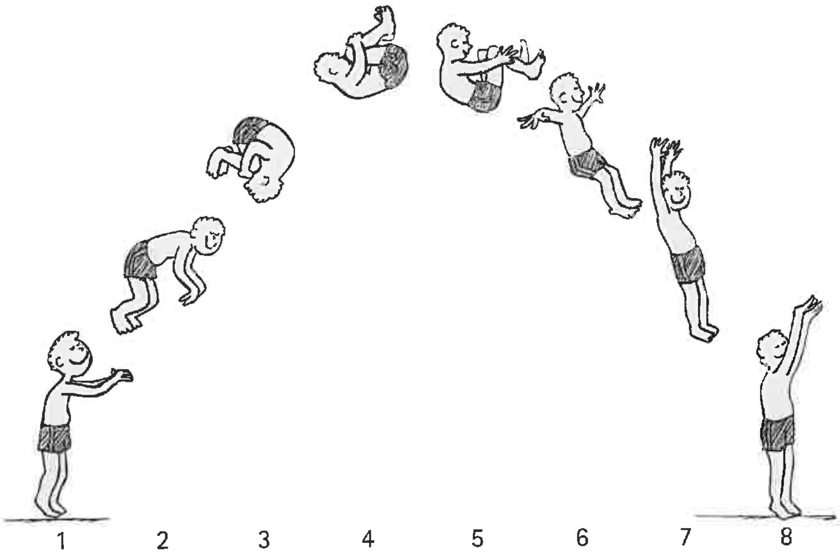


FIGURE 8.53

Rotational speed is controlled by variations in the body's rotational inertia as angular momentum is conserved during a forward somersault.

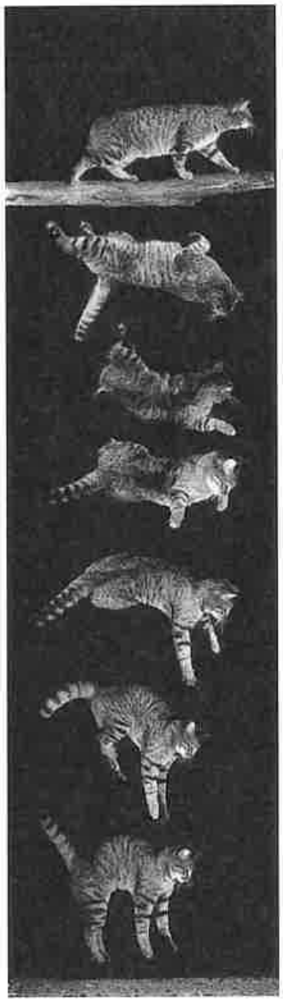


FIGURE 8.54

Time-lapse photo of a falling cat.

Similarly, when a gymnast is spinning freely in the absence of unbalanced torques on his or her body, angular momentum does not change. However, rotational speed can be changed by simply making variations in rotational inertia. This is done by moving some part of the body toward or away from the axis of rotation.

If a cat is held upside down and dropped, it is able to execute a twist and to land upright, even if it has no initial angular momentum. Zero-angular-momentum twists and turns are performed by turning one part of the body against the other. While falling, the cat rearranges its limbs and tail several times to change its rotational inertia repeatedly until it lands feet downward. During this maneuver the total angular momentum remains zero (Figure 8.54). When it is over, the cat is not turning. This maneuver rotates the body through an angle, but it does not create continuing rotation. To do so would violate angular momentum conservation.

Humans can perform similar twists without difficulty, though not as fast as a cat. Astronauts have learned to make zero-angular-momentum rotations as they orient their bodies in preferred directions when floating freely in space.

The law of conservation of angular momentum is seen in the motions of planets and the shapes of galaxies. It is fascinating to note that the conservation of angular momentum tells us that the Moon is getting farther away from Earth. This is because the Earth's daily rotation is slowly decreasing due to the friction of ocean waters on the ocean bottom, just as an automobile's wheels slow down when brakes are applied. This decrease in Earth's angular momentum is accompanied by an equal increase in the angular momentum of the Moon in its orbital motion about Earth, which results in the Moon's increasing distance from Earth and decreasing speed. This increase of distance amounts to one-quarter of a centimeter per rotation. Have you noticed that the Moon is getting farther away from us lately? Well, it is; each time we see another full Moon, it is one-quarter of a centimeter farther away!

Oh yes—before we end this chapter, we'll give an answer to Check Point Question 3 back on page 128. Manhole covers are circular because a circular cover is the only shape that can't fall into the hole. A square cover, for example, can be tilted vertically and turned so it can drop diagonally into the hole. Likewise for every other shape. If you're working in a manhole and some fresh kids are horsing around above, you'll be glad the cover is round!

SUMMARY OF TERMS

Tangential speed The linear speed tangent to a curved path, such as in circular motion.

Rotational speed The number of rotations or revolutions per unit of time; often measured in rotations or revolutions per second or per minute. (Scientists usually measure it in radians per second.)

Rotational inertia That property of an object that measures its resistance to any change in its state of rotation: if at rest, the body tends to remain at rest; if rotating, it tends to remain rotating and will continue to do so unless acted upon by an external net torque.

Torque The product of force and lever-arm distance, which tends to produce rotation.

$$\text{Torque} = \text{lever arm} \times \text{force}$$

Center of mass (CM) The average position of the mass of an object. The CM moves as if all the external forces acted at this point.

Center of gravity (CG) The average position of weight or the single point associated with an object where the force of gravity can be considered to act.

Equilibrium The state of an object in which it is not acted upon by a net force or a net torque.

Centripetal force A force directed toward a fixed point, usually the cause of circular motion:

$$F = mv^2/r$$

Centrifugal force An outward force apparent in a rotating frame of reference. It is apparent (fictitious) in the sense that it is not part of an interaction but is a result of rotation—with no reaction-force counterpart.

Angular momentum The product of a body's rotational inertia and rotational velocity about a particular axis. For an object that is small compared with the radial distance, it can be expressed as the product of mass, speed, and the radial distance of rotation.

Conservation of angular momentum When no external torque acts on an object or a system of objects, no change of angular momentum can occur. Hence, the angular momentum before an event involving only internal torques or no torques is equal to the angular momentum after the event.

REVIEW QUESTIONS

Circular Motion

1. What is meant by tangential speed?
2. Distinguish between tangential speed and rotational speed.
3. What is the relationship between tangential speed and distance from the center of the rotational axis? Give an example.
4. A tapered cup rolled on a flat surface makes a circular path. What does this tell you about the tangential speed of the rim of the wide end of the cup compared with that of the rim of the narrow end?
5. How does the tapered rim of a wheel on a railroad train allow one part of the rim to have a greater tangential speed than another part when it is rolling on a track?

Rotational Inertia

6. What is rotational inertia, and is it similar to inertia as studied in previous chapters?
7. Inertia depends on mass; rotational inertia depends on mass and something else. What?
8. Does the rotational inertia of a particular object differ for different axes of rotation? Can one object have more than one rotational inertia?
9. Consider three axes of rotation for a pencil: along the lead; at right angles to the lead at the middle; at right angles to the lead at one end. Rate the rotational inertias about each axis from small to large.
10. Which is easier to get swinging, a baseball bat held at the end or one held closer to the massive end (choked up)?
11. Why does bending your legs when running enable you to swing your legs to and fro more rapidly?
12. Which will have the greater acceleration rolling down an incline, a hoop or a solid disk?

Torque

13. What does a torque tend to do to an object?
14. What is meant by the "lever arm" of a torque?
15. How do clockwise and counterclockwise torques compare when a system is balanced?

Center of Mass and Center of Gravity

16. If you toss a stick into the air, it appears to wobble all over the place. Specifically, what place?
17. Where is the center of mass of a baseball? Where is its center of gravity? Where are these centers for a baseball bat?

Locating the Center of Gravity

18. If you hang at rest by your hands from a vertical rope, where is your center of gravity with respect to the rope?
19. Where is the center of mass of a soccer ball?

Stability

20. What is the relationship between center of gravity and support base for an object in stable equilibrium?
21. Why doesn't the Leaning Tower of Pisa topple over?
22. In terms of center of gravity, support base, and torque, why can you not stand with heels and back to a wall and then bend over to touch your toes and return to your stand-up position?

Centripetal Force

23. When you whirl a can at the end of a string in a circular path, what is the direction of the force you exert on the can?

24. Is it an inward force or an outward force that is exerted on the clothes during the spin cycle of an automatic washing machine?

Centrifugal Force

25. If the string that holds a whirling can in its circular path breaks, what kind of force causes it to move in a straight-line path—centripetal, centrifugal, or no force? What law of physics supports your answer?

26. If you are in a car that rounds a curve, and you are not wearing a seat belt, and you slide across your seat and slam against a car door, what kind of force is responsible for your slide—centripetal, centrifugal, or no force? Why is the correct answer "no force"?

Centrifugal Force in a Rotating Reference Frame

27. Why is centrifugal force in a rotating frame called a "fictitious force"?

Simulated Gravity

28. How can gravity be simulated in an orbiting space station?

Angular Momentum

29. Distinguish between linear momentum and angular momentum.

30. What is the law of inertia for rotating systems in terms of angular momentum?

Conservation of Angular Momentum

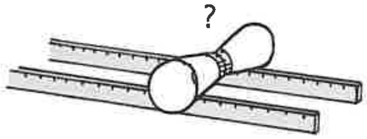
31. What does it mean to say that angular momentum is conserved?

32. If a skater who is spinning pulls her arms in so as to reduce her rotational inertia by half, by how much will her angular momentum increase? By how much will her rate of spin increase? (Why are your answers different?)

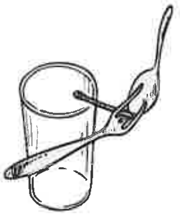
PROJECTS

1. Write a letter to Grandpa and tell him how you're learning to distinguish between closely related concepts, using the examples of force and torque. Tell him how the two are similar, and how they're different. Suggest where he can find "hands-on" things in his home that can illustrate the difference between the two. Also cite an example that shows how the net force on an object can be zero while the net torque isn't, as well as an example showing vice versa. (Now make your Grandpa's day and *send* the letter to him!)

2. Fasten a pair of foam cups together at their wide ends and roll them along a pair of metersticks that simulate railroad tracks. Note how they self-correct whenever their path departs from the center. Question: If you taped the cups together at their narrow ends, so they tapered oppositely as shown, would the pair of cups self-correct or self-destruct when rolling slightly off center?



3. Fasten a fork, spoon, and wooden match together as shown. The combination will balance nicely—on the edge of a glass, for example. This happens because the center of gravity actually "hangs" below the point of support.

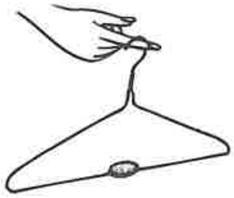


4. Stand with your heels and back against a wall and try to bend over and touch your toes. You'll find that you have to stand away from the wall to do so without toppling over. Compare the minimum distance of your heels from the wall with that of a friend of the opposite sex. Who can touch their toes with their heels nearer to the wall—males or females? On the average and in proportion to height, which sex has the lower center of gravity?

5. First ask a friend to stand facing a wall with her toes touching the wall, then ask her to stand on the balls of her feet without toppling backward. Your friend won't be able to do it. Now you explain why it can't be done.

6. Rest a meterstick on two extended forefingers as shown. Slowly bring your fingers together. At what part of the stick do your fingers meet? Can you explain why this always happens, no matter where you start your fingers?

7. Place the hook of a wire coat hanger over your finger. Carefully balance a coin on the straight wire on the bottom directly under the hook. You may have to flatten the wire with a hammer or fashion a tiny platform with tape. With a surprisingly small amount of practice you can swing the hanger and balanced coin back and forth and then in a circle. Centripetal force holds the coin in place.



PLUG AND CHUG

Torque = Lever Arm × Force

1. Calculate the torque produced by a 50-N perpendicular force at the end of a 0.2-m-long wrench.
2. Calculate the torque produced by the same 50-N force when a pipe extends the length of the wrench to 0.5 m.

Centripetal Force: $F = mv^2/r$

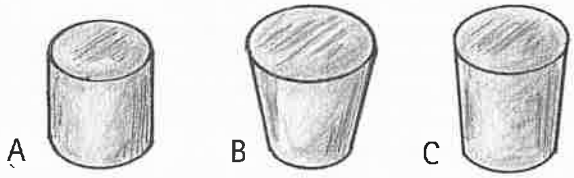
3. Calculate the tension in a horizontal string that whirls a 2-kg toy in a circle of radius 2.5 m when it moves at 3 m/s on an icy surface.
4. Calculate the force of friction that keeps a 75-kg person sitting on the edge of a horizontal rotating platform when the person sits 2 m from the center of the platform and has a tangential speed of 3 m/s.

Angular Momentum = mvr

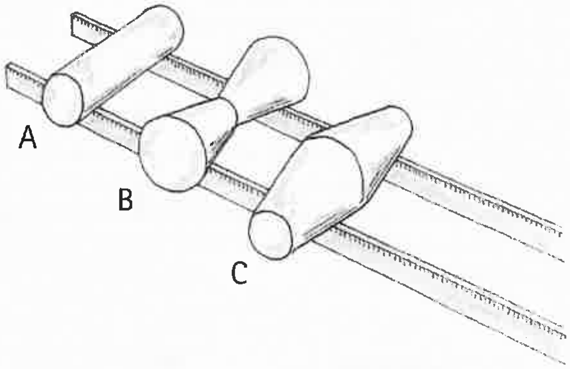
5. Calculate the angular momentum of the person in the previous problem.
6. If the person's speed doubles and all else remains the same, what will be the person's angular momentum?

RANKING

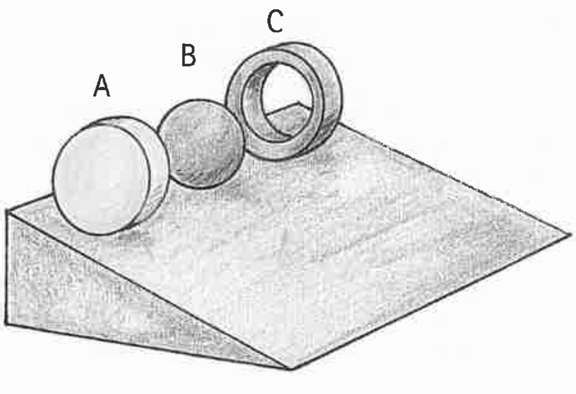
1. The three cups are rolled on a level surface. Rank the cups by the amount they depart from a straight-line path (most curved to least curved).



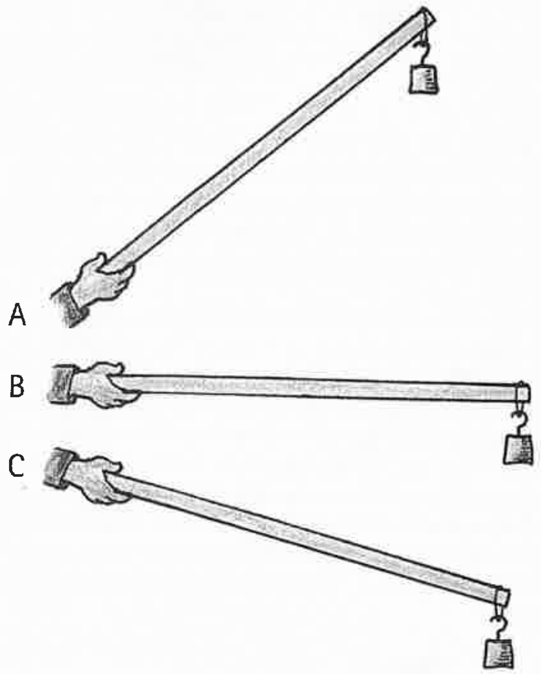
2. Three types of rollers are placed on slightly inclined parallel meterstick tracks as shown. From greatest to least, rank the rollers in terms of their ability to remain stable as they roll.



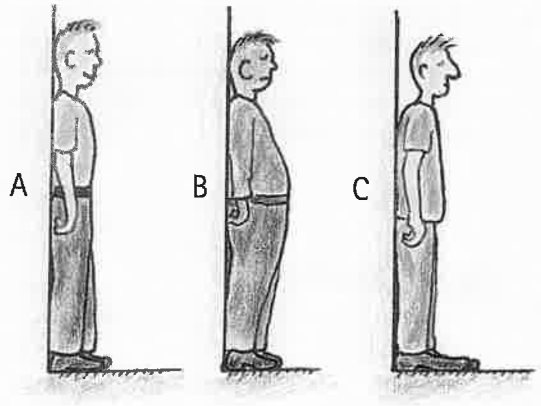
3. Beginning from a rest position, a solid disk A, a solid ball B, and a hoop C race down an inclined plane. Rank them in order for finishing: winner, second place, and third place.



4. You hold a meterstick horizontally with the same mass suspended at the end. Rank the torque needed to keep the stick steady, from largest to smallest.



5. Three physics majors stand with their backs against a wall. They are all in good physical shape. Their task is to lean over and touch their toes without toppling over. Rank their chances for success from highest to lowest.

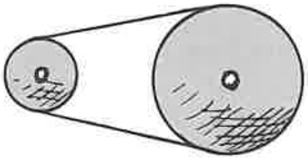


EXERCISES

1. While riding on a carnival Ferris wheel, Sam Nasty horses around and climbs out of his chair and along the spoke so he is halfway to the axis. How does his rotational speed compare with that of his friends who remain in the chair? How does his tangential speed compare? Why are your answers different?

2. An automobile speedometer is configured to read speed proportional to the rotational speed of its wheels. If larger wheels, such as those of snow tires, are used, will the speedometer reading be high, or low—or no different?

3. A large wheel is coupled to a wheel with half the diameter, as shown. How does the rotational speed of the smaller wheel compare with that of the larger wheel? How do the tangential speeds at the rims compare (assuming the belt doesn't slip)?



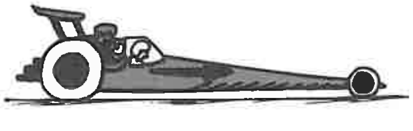
4. Dan and Sue cycle at the same speed. The tires on Dan's bike are larger in diameter than those on Sue's bike. Which wheels, if either, have the greater rotational speed?

5. Use the equation $v = r\omega$ to explain why the end of a flyswatter moves much faster than your wrist when swatting a fly.

6. The wheels of railroad trains are tapered, a feature especially important on curves. How, if at all, does the amount of taper relate to the curving of the tracks?

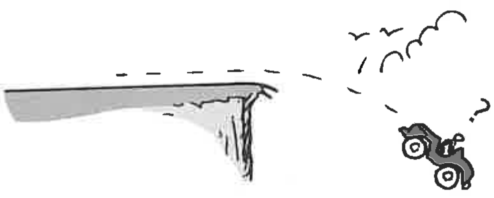
7. Flamingos are frequently seen standing on one leg with the other lifted. Is rotational inertia enhanced with long legs? What can you say about the bird's center of mass with respect to the foot on which it stands?

8. The front wheels of a racing vehicle are located far out in front to help keep the vehicle from nosing upward when it accelerates. What physics concepts play a role here?

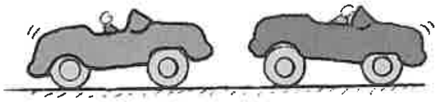


9. In this chapter, we learned that an object may *not* be in mechanical equilibrium even when $\Sigma F = 0$. Explain.

10. When a car drives off a cliff it rotates forward as it falls. For a higher speed off the cliff, will it rotate more, or less? (Consider the time that the unbalanced torque acts.)



11. Why does a car nose up when accelerating and nose down when braking?



12. Which will have the greater acceleration rolling down an incline—a bowling ball or a volleyball? Defend your answer.

13. A softball and a basketball start from rest and roll down an incline. Which ball reaches the bottom first? Defend your answer.

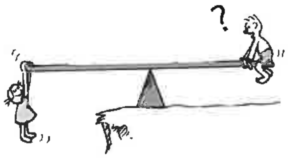
14. How would a ramp help you to distinguish between two identical-looking spheres of the same weight, one solid and the other hollow?

15. Which will roll down an incline faster—a can of water or a can of ice?

16. Why are lightweight tires preferred over lightweight frames in bicycle racing?

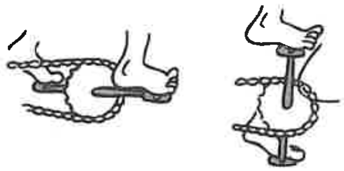
17. A youngster who has entered a soapbox derby (in which 4-wheel unpowered vehicles roll from rest down a hill) asks if large massive wheels or lightweight ones should be used. Also, should the wheels have spokes or be solid? What advice do you offer?

18. Is the net torque changed when a partner on a seesaw stands or hangs from her end instead of sitting? (Does the weight or the lever arm change?)



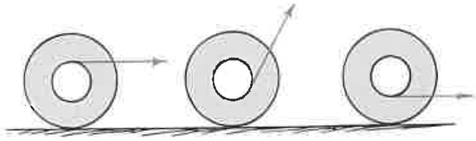
19. Can a force produce a torque when there is no lever arm?

20. When you pedal a bicycle, maximum torque is produced when the pedal sprocket arms are in the horizontal position, and no torque is produced when they are in the vertical position. Explain.



21. When the line of action of a force intersects the center of mass of an object, can that force produce a torque about the object's center of mass?

22. The spool is pulled in three ways, as shown. There is sufficient friction for rotation. In what direction will the spool roll in each case?



23. When a bowling ball leaves your hand, it may not spin. But farther along the alley, it does spin. What produces the spinning?

24. Why does sitting closest to the center of a vehicle provide the most comfortable ride in a bus traveling on a bumpy road, in a ship in a choppy sea, or in an airplane in turbulent air?

25. Which is more difficult—doing sit-ups with your knees bent, or with your legs straight out? Why?

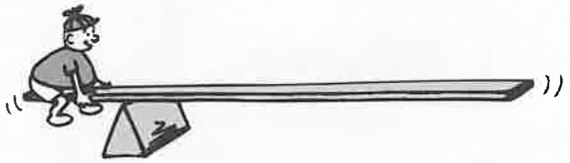
26. Explain why a long pole is more beneficial to a tightrope walker if the pole droops.

27. Why must you bend forward when carrying a heavy load on your back?

28. Why is the wobbly motion of a single star an indication that the star has one or more planets orbiting around it?

29. Why is it easier to carry the same amount of water in two buckets, one in each hand, than in a single bucket?

30. Nobody at the playground wants to play with the obnoxious boy, so he fashions a seesaw as shown so he can play by himself. Explain how this is done.

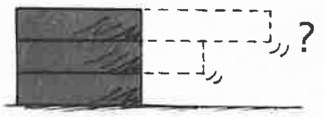


31. Where is the center of mass of Earth's atmosphere?

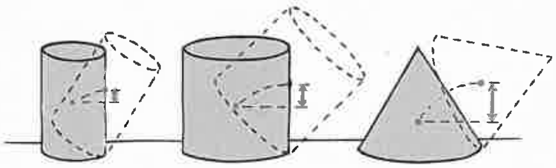
32. Using the ideas of torque and center of gravity, explain why a ball rolls down a hill.

33. Why is it important to secure file cabinets to the floor, especially cabinets with heavy loads in top drawers?

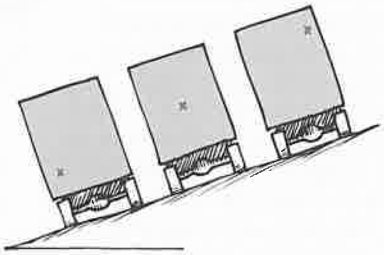
34. How can the three bricks be stacked so that the top brick has maximum horizontal displacement from the bottom brick? For example, stacking them like the dotted lines suggest would be unstable and the bricks would topple. (*Hint:* Start with the top brick and work down. At every interface the CG of the bricks above must not extend beyond the end of the supporting brick.)



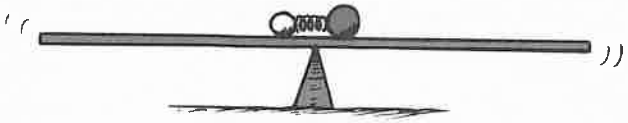
35. Describe the comparative stabilities of the three objects shown in terms of work and potential energy.



36. The centers of gravity of the three trucks parked on a hill are shown by the Xs. Which truck(s) will tip over?



37. A long track balanced like a seesaw supports a golf ball and a more massive billiard ball with a compressed spring between the two. When the spring is released, the balls move away from each other. Does the track tip clockwise, tip counterclockwise, or remain in balance as the balls roll outward? What principles do you use for your explanation?



38. When a long-range cannonball is fired toward the equator from a northern (or southern) latitude, it lands west of its "intended" longitude. Why? (*Hint:* Consider a flea jumping from partway out to the outer edge of a rotating turntable.)

39. A racing car on a flat circular track needs friction between the tires and the track to maintain its circular motion. How much more friction is required for twice the speed?

40. Can an object move along a curved path if no force acts on it? Defend your answer.

41. As a car speeds up when rounding a curve, does the centripetal force on the car also increase? Defend your answer.

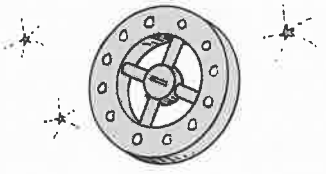
42. When you are in the front passenger seat of a car turning to the left, you may find yourself pressed against the right-side door. Why do you press against the door? Why does the door press on you? Does your explanation involve a centrifugal force, or Newton's laws?

43. Friction is needed for a car rounding a curve. But, if the road is banked, friction may not be required at all. What, then, supplies the needed centripetal force? (*Hint:* Consider vector components of the normal force on the car.)

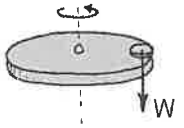
44. Under what conditions could a fast-moving car remain on a banked track covered with slippery ice?

45. Explain why a centripetal force does *not* do work on a circularly moving object.

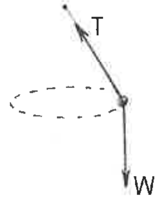
46. The occupant inside a rotating space habitat of the future feels that she is being pulled by artificial gravity against the outer wall of the habitat (which becomes the "floor"). Explain what is going on in terms of Newton's laws and centripetal force.



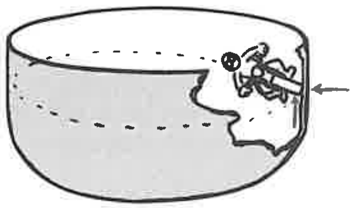
47. The sketch shows a coin at the edge of a turntable. The weight of the coin is shown by the vector **W**. Two other forces act on the coin—the normal force and a force of friction that prevents it from sliding off the edge. Draw in force vectors for both of these.



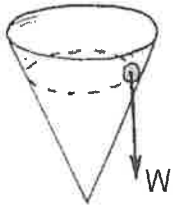
48. The sketch shows a conical pendulum. The bob swings in a circular path. The tension **T** and weight **W** are shown by vectors. Draw a parallelogram with these vectors and show that their resultant lies in the plane of the circle. (See the parallelogram rule in Chapter 5.) What is the name of this resultant force?



49. A motorcyclist is able to ride on the vertical wall of a bowl-shaped track as shown. Friction of the wall on the tires is shown by the vertical red vector. (a) How does the magnitude of this vertical vector compare with the weight of the motorcycle and rider? (b) Does the horizontal red vector represent the normal force acting on the bike and rider, the centripetal force, both, or neither? Defend your answer.



50. Consider a ball rolling around in a circular path on the inner surface of a cone. The weight of the ball is shown by the vector **W**. Without friction, only one other force acts on the ball—a normal force. (a) Draw in the vector for the normal force the length of the vector depends on the next step, (b). (b) Using the parallelogram rule, show that the resultant of the two vectors is along the radial direction of the ball's circular path. (Yes, the normal is appreciably larger than the weight!)



51. You sit at the middle of a large turntable at an amusement park as it is set spinning and then allowed to spin freely. When you crawl toward the edge of the turntable, does the rate of the rotation increase, decrease, or remain unchanged? What physics principle supports your answer?

52. A sizable quantity of soil is washed down the Mississippi River and deposited in the Gulf of Mexico each year. What effect does this tend to have on the length of a day? (Hint: Relate this to the previous exercise.)

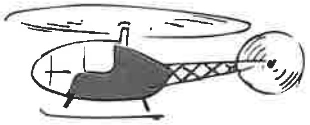
53. If all of Earth's inhabitants moved to the equator, how would this affect Earth's rotational inertia? How would it affect the length of a day?

54. Strictly speaking, as more and more skyscrapers are built on the surface of Earth, does the day tend to become longer or shorter? And, strictly speaking, does the falling of autumn leaves tend to lengthen or shorten the 24-hour day? What physics principle supports your answers?

55. If the world's populations moved to the North Pole and the South Pole, would the 24-hour day become longer, shorter, or stay the same?

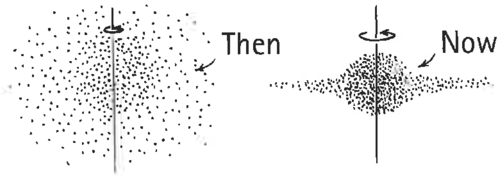
56. If the polar ice caps of Earth were to melt, the oceans would be deeper. Strictly speaking, what effect would this have on Earth's rotation?

57. Why does a typical small helicopter with a single main rotor have a second small rotor on its tail? Describe the consequence if the small rotor fails in flight.



58. A toy train is initially at rest on a track fastened to a bicycle wheel, which is free to rotate. How does the wheel respond when the train moves clockwise? When the train backs up? Does the angular momentum of the wheel–train system change during these maneuvers? How would the resulting motions be affected if the train were much more massive than the track? Or vice versa?

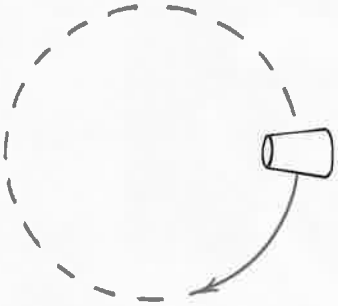
59. We believe that our galaxy was formed from a huge cloud of gas. The original cloud was far larger than the present size of the galaxy, was more or less spherical, and was rotating very much more slowly than the galaxy is now. In this sketch, we see the original cloud and the galaxy as it is now (seen edgewise). Explain how the inward pull of gravity and the conservation of angular momentum contribute to the galaxy's present shape and why it rotates faster now than when it was a larger, spherical cloud.



60. Earth is not spherical but bulges at the equator. Jupiter bulges more. What is the cause of these bulges?

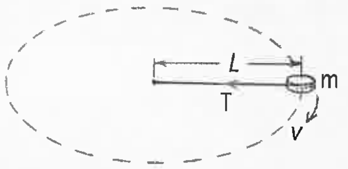
PROBLEMS

1. The diameter of the base of a tapered drinking cup is 6 cm. The diameter of its mouth is 9 cm. The path of the cup curves when you roll it on the top of a table. Which end, the base or the mouth, rolls faster? How much faster?



2. To tighten a bolt, you push with a force of 80 N at the end of a wrench handle that is 0.25 m from the axis of the bolt. (a) What torque are you exerting? (b) If you move your hand inward to be only 0.10 m from the bolt, to achieve the same torque show that you should exert 200 N of force. (c) Do your answers depend on the direction of your push relative to the direction of the wrench handle?
3. The rock and meterstick balance at the 25-cm mark, as shown. The meterstick has a mass of 1 kg. What must be the mass of the rock?

4. Mary Beth uses a torque feeler that consists of a meterstick held at the 0-cm end with a weight dangling from various positions along the stick (see Figure 8.17). When the stick is held horizontally, torque is produced when a 1-kg mass hangs from the 50-cm mark. How much more torque is exerted when it is hung from the 75-cm mark? The 100-cm mark?
5. An ice puck of mass m revolves on an icy surface in a circle at speed v at the end of a horizontal string of length L. The tension in the string is T.



   a. Write the equation for centripetal force, and substitute the values T and L appropriately. Then with a bit of elementary algebra, rearrange the equation so that it solves for mass.
   b. Show that the mass of the puck is 5 kg when the length of the string is 2 m, string tension is 10 N, and the tangential speed of the puck is 2 m/s.
6. If a trapeze artist rotates once each second while sailing through the air and contracts to reduce her rotational inertia to one-third of what it was, how many rotations per second will result?
- 7. A small space telescope at the end of a tether line of length L moves at linear speed v about a central space station.
   a. What will be the linear speed of the telescope if the length of the line is reduced to 0.33 L?
   b. If the initial linear speed of the telescope is 1.0 m/s, what is its speed when pulled in to one-third its initial distance from the space station?

CHAPTER 8 ONLINE RESOURCES

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Tutorial

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- Rotational Inertia Using Weighted Pipes
- Rotational Inertia Using a Hammer
- Rotational Inertia with a Weighted Rod
- Difference Between Torque and Weight
- Why a Ball Rolls Down a Hill
- Locating the Center of Gravity
- Toppling
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- Simulated Gravity
- Conservation of Angular Momentum Using a Rotating Platform

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9 Gravity

1 Neil deGrasse Tyson emphasizes the universal nature of gravity in his standing-room-only lectures. 2 Contrary to what most people think, the gravitational force on the spacewalking astronaut is nearly as strong as it is when at Earth's surface. So why doesn't the astronaut fall to Earth? We'll see in the next chapter that the astronaut, like all Earth satellites, continually falls *around* Earth. 3 Tomas Brage uses a classroom model of a Cavendish apparatus to measure G.

According to popular legend, Isaac Newton was sitting under an apple tree when the idea struck him that what pulls apples from trees is the same force that keeps the Moon circling Earth. Newton didn't discover gravity, as is commonly thought. What he discovered is that gravity extends beyond Earth—that it is universal. It pulls any corners of planets inward to form spheres, pulls planets toward the Sun, raises ocean tides, and accounts for the shapes of galaxies. However, since he was very shy and sensitive to criticism, Newton put his writings about gravity in a drawer, untouched for some 20 years. As will be soon explained, Newton was prodded by a friend to publish his results.

Once Newton published his findings, he did much more than explain how the Sun pulls on planets and how planets pull on moons, and did much more than solve the mystery of ocean tides. Newton took a giant step further and showed that nature plays by natural rules and operates by natural laws—at a time when rules and laws were decreed by kings and other high officials. Newton's findings went on to show that natural law is neither capricious nor malevolent—nature is indifferent to the human condition. This was an enormous break with established tradition. Knowledge of nature's laws provided hope and inspiration to scientists, writers, artists, philosophers, and people of all walks of life. Newton's way of looking at nature ushered in the Age of Reason. The ideas and insights of Isaac Newton truly changed the world and elevated the human condition.

The Newtonian Synthesis

From the time of Aristotle, the circular motion of heavenly bodies was regarded as natural. The ancients believed that the stars, the planets, and the Moon moved in divine circles. As far as the ancients were concerned, this circular motion required no explanation. Isaac Newton, however, recognized that a force of some kind must act on the planets, whose orbits, he knew, were ellipses; otherwise, their paths would be straight lines. Others of his time, influenced by Aristotle, supposed that any force on a planet would be directed along its path. Newton, however, reasoned that the force on each planet would be directed toward a fixed central point—toward the Sun. This, the force of gravity, was the same force that pulls an apple off a tree. Newton's stroke of intuition, that the force between Earth and an apple is the same force that pulls moons and planets and everything else in our universe, was a revolutionary break with the prevailing notion that there were two sets of natural laws: one for earthly events, and another, altogether different, for motion in the heavens. This union of terrestrial laws and cosmic laws is called the Newtonian synthesis.

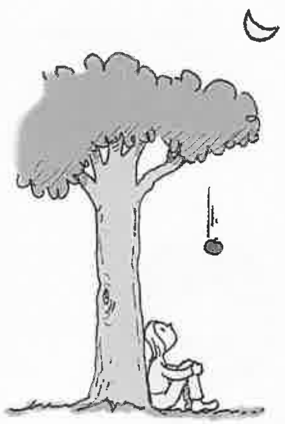

FIGURE 9.1
Could the gravitational pull on the apple reach to the Moon?

The Universal Law of Gravity

To test his hypothesis that Earth gravity reaches to the Moon, Newton compared the fall of an apple with the "fall" of the Moon. He realized that the Moon falls in the sense that *it falls away from the straight line it would follow if there were no forces acting on it.* Because of its tangential velocity, it "falls around" the round Earth (more about this in the next chapter). By simple geometry, the Moon's distance of fall per second could be compared with the distance that an apple or anything that far away would fall in 1 second. Newton's calculations didn't check. Disappointed, but recognizing that brute fact must always win over a beautiful hypothesis, he placed his papers in a drawer, where, as mentioned earlier, they remained for nearly 20 years. During this period, he founded and developed the field of optics, for which he first became famous.

The tangential velocity of a planet or moon moving in a circle is at right angles to the force of gravity.

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Tutorial
Motion and Gravity

Newton's interest in mechanics was rekindled with the advent of a spectacular comet in 1680 and another 2 years later. He returned to the Moon problem at the prodding of his astronomer friend Edmund Halley, for whom the second comet was later named. He made corrections in the experimental data used in his earlier method and obtained excellent results. Only then did he publish what is one of the most far-reaching generalizations of the human mind: the **law of universal gravitation.**[1]

Everything pulls on everything else in a beautifully simple way that involves only mass and distance. According to Newton, every body attracts every other body with a force that, for any two bodies, is directly proportional to the product of their masses and inversely proportional to the square of the distance separating them. This statement can be expressed as

$$\text{Force} \sim \frac{\text{mass}_1 \times \text{mass}_2}{\text{distance}^2}$$

---

[1] This is a dramatic example of the painstaking effort and cross-checking that go into the formulation of a scientific theory. Contrast Newton's approach with the failure to "do one's homework," the hasty judgments, and the absence of cross-checking that so often characterize the pronouncements of people advocating less-than-scientific theories.

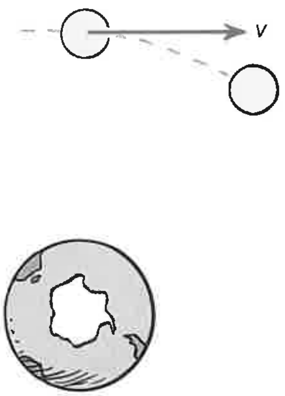

FIGURE 9.2

The tangential velocity of the Moon about Earth allows it to fall around Earth rather than directly into it. If this tangential velocity were reduced to zero, what would be the fate of the Moon?

Expressed in symbol shorthand,

$$F \sim \frac{m_1 m_2}{d^2}$$

where m_1 and m_2 are the masses of the bodies and d is the distance between their centers. Thus, the greater the masses m_1 and m_1, the greater the force of attraction between them, in direct proportion to the masses.[2] The greater the distance of separation d, the weaker the force of attraction, in inverse proportion to the square of the distance between their centers of mass.

CHECK POINT

1. In Figure 9.2, we see that the Moon falls around Earth rather than straight into it. If the Moon's tangential velocity were zero, how would it move?
2. According to the equation for gravitational force, what happens to the force between two bodies if the mass of one of the bodies is doubled? If both masses are doubled?
3. Gravitational force acts on all bodies in proportion to their masses. Why, then, doesn't a heavy body fall faster than a light body?

Check Your Answers

1. If the Moon's tangential velocity were zero, it would fall straight down and crash into Earth!
2. When one mass is doubled, the force between it and the other one doubles. If both masses double, the force is 4 times as much.
3. The answer goes back to Chapter 4. Recall Figure 4.12, in which heavy and light bricks fall with the same acceleration because both have the same ratio of weight to mass. Newton's second law ($a = F/m$) reminds us that greater force acting on greater mass does not result in greater acceleration.

The Universal Gravitational Constant, *G*

The proportionality form of the universal law of gravitation can be expressed as an exact equation when the constant of proportionality G is introduced. G is called the *universal gravitational constant.* Then the equation is

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

FIGURE 9.3

As the rocket gets farther from Earth, gravitational strength between the rocket and Earth decreases.

The units of G make the force come out in newtons. The magnitude of G is the same as the gravitational force between two 1-kilogram masses that are 1 meter apart: 0.0000000000667 newton.

$$G = 6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$$

This is an extremely small number.[3] It shows that gravity is a very weak force compared with electrical forces. The large net gravitational force we feel as weight is because of the enormity of atoms in planet Earth that are pulling on us.

PhysicsPlace.com™
Video
Von Jolly's Method of Measuring the Attraction Between Two Masses

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[2] Note the different role of mass here. Thus far, we have treated mass as a measure of inertia, which is called *inertial mass.* Now we see mass as a measure of gravitational force, which in this context is called *gravitational mass.* It is experimentally established that the two are equal, and, as a matter of principle, the equivalence of inertial and gravitational mass is the foundation of Einstein's general theory of relativity.

[3] The numerical value of G depends entirely on the units of measurement we choose for mass, distance, and time. The international system of choice is: for mass, the kilogram; for distance, the meter; and for time, the second. Scientific notation is discussed in Appendix A at the end of this book.

Interestingly, Newton could calculate the product of *G* and Earth's mass, but not either one alone. Calculating *G* alone was first done by the English physicist Henry Cavendish in 1798, a century after Newton's time.

Cavendish measured *G* by measuring the tiny force between lead masses with an extremely sensitive torsion balance, as Professor Brage shows in the opening photo at the beginning of this chapter. A simpler method was later developed by Philipp von Jolly, who attached a spherical flask of mercury to one arm of a sensitive balance (Figure 9.4). After the balance was put in equilibrium, a 6-ton lead sphere was rolled beneath the mercury flask. The gravitational force between the two masses was measured by the weight needed on the opposite end of the balance to restore equilibrium. All the quantities, m_1, m_2, F, and d, were known, from which the constant *G* was calculated:

$$G = \frac{F}{\left(\frac{m_1 m_2}{d^2}\right)} = 6.67 \times 10^{-11}\ \text{N/kg}^2/\text{m}^2 = 6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2$$

Just as sheet music guides a musician playing music, equations guide a physics student to understand how concepts are connected.

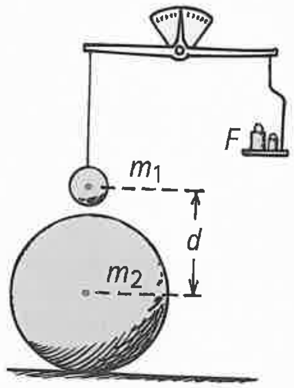

FIGURE 9.4

Jolly's method of measuring *G*. Balls of mass m_1 and m_2 attract each other with a force *F* provided by the weights needed to restore balance.

The value of *G* shows that gravity is the weakest of the presently known four fundamental forces. (The other three are the electromagnetic force and two kinds of nuclear forces.) We sense gravitation only when masses like that of Earth are involved. If you stand on a large ship, the force of attraction between you and the ship is too weak for ordinary measurement. The force of attraction between you and Earth, however, can be measured. It is your weight. Your weight depends not only on your mass but also on your distance from the center of Earth. At the top of a mountain, your mass is the same as it is anywhere else, but your weight is slightly less than it is at ground level. That's because your distance from Earth's center is greater.

Once the value of *G* was known, the mass of Earth was easily calculated. The force that Earth exerts on a mass of 1 kg at its surface is 10 N (more precisely, 9.8 N). The distance between the 1-kg mass and the center of Earth is Earth's radius, 6.4×10^6 m. Therefore, from $F = G\frac{m_1 m_2}{d^2}$, where m_1 is the mass of Earth,

$$9.8\ \text{N} = 6.67 \times 10^{-11}\text{N} \cdot \text{m}^2/\text{kg}^2 \, \frac{1\ \text{kg} \times m_1}{(6.4 \times 10^6\text{m})^2}$$

which leads to $m_1 = 6 \times 10^{24}$ kg.

In the 18th century, when *G* was first measured, people all over the world were excited about it. That's because newspapers everywhere announced the discovery as one that measured the mass of the planet Earth. How exciting that Newton's formula gives the mass of the entire planet, with all its oceans, mountains, and inner parts yet to be discovered. *G* and the mass of Earth were measured when a great portion of Earth's surface was still undiscovered.

Just as π relates circumference and diameter for circles, *G* relates gravitational force to mass and distance.

CHECK POINT

If there is an attractive force between all objects, why do we not feel ourselves gravitating toward massive buildings in our vicinity?

Check Your Answer

Gravity certainly does pull us to massive buildings and everything else in the universe. The forces between buildings and us are relatively small because their masses are small compared with the mass of Earth. The forces due to the stars are extremely tiny because of their great distances from us. These tiny forces escape our notice when they are overwhelmed by the overpowering attraction to Earth. Physicist Paul A. M. Dirac, 1933 Nobel Prize recipient, put it this way: "Pick a flower on Earth and you move the farthest star!"

You can never change only one thing! Every equation reminds us of this—you can't change a term on one side without affecting the other side.

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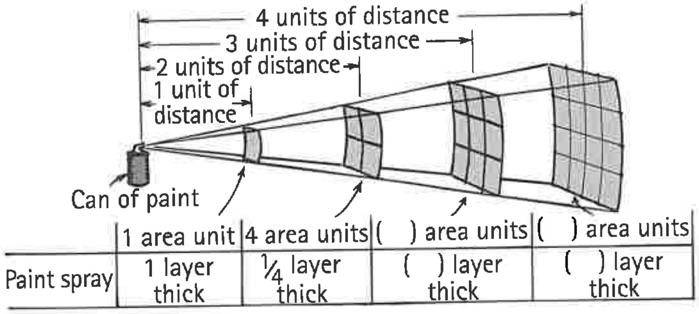
Video
Inverse-Square Law

Gravity and Distance: The Inverse-Square Law

We can better understand how gravity weakens with distance by considering how paint from a paint gun spreads with increasing distance (Figure 9.5). Suppose we position a paint gun at the center of a sphere with a radius of 1 meter, and a burst of paint spray travels 1 m to produce a square patch of paint that is 1 mm thick. How thick would the patch be if the experiment were done in a sphere with twice the radius? If the same amount of paint travels in straight lines for 2 m, it will spread to a patch twice as tall and twice as wide. The paint would then be spread over an area 4 times as big, and its thickness would be only 1/4 mm.



	1 area unit	4 area units	( ) area units	( ) area units
Paint spray	1 layer thick	¼ layer thick	( ) layer thick	( ) layer thick

FIGURE 9.5

The inverse-square law. Paint spray travels radially away from the nozzle of the can in straight lines. Like gravity, the "strength" of the spray obeys the inverse-square law.

Can you see from the figure that, for a sphere of radius 3 m, the thickness of the paint patch would be only 1/9 mm? Can you see the thickness of the paint decreases as the square of the distance increases? This is known as the **inverse-square law.** The inverse-square law holds for gravity and for all phenomena wherein the effect from a localized source spreads uniformly throughout the surrounding space: the electric field about an isolated electron, light from a match, radiation from a piece of uranium, and sound from a cricket.

Newton's law of gravity as written applies to particles and spherical bodies, as well as to nonspherical bodies sufficiently far apart. The distance term *d* in Newton's equation is the distance between the centers of masses of the objects. Note in Figure 9.6 that the apple that normally weighs 1 N at Earth's surface weighs only 1/4 as much when it is twice the distance from Earth's center. The greater the distance

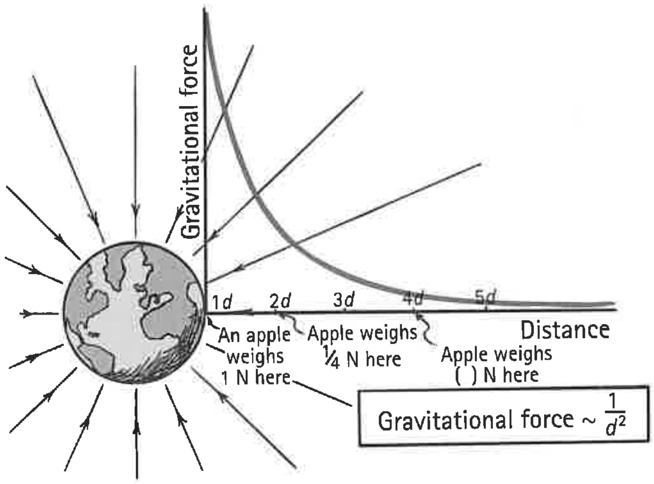


FIGURE 9.6

INTERACTIVE FIGURE

If an apple weighs 1 N at Earth's surface, it would weigh only 1/4 N twice as far from the center of Earth. At 3 times the distance, it would weigh only 1/9 N. Gravitational force versus distance is plotted in color. What would the apple weigh at 4 times the distance? Five times the distance?

from Earth's center, the less the weight of an object. A child who weighs 300 N at sea level will weigh only 299 N atop Mt. Everest. For greater distances, force is less. For very great distances, Earth's gravitational force approaches zero. The force *approaches* zero, but never reaches zero. Even if you were transported to the far reaches of the universe, the gravitational field of home would still be with you. It may be overwhelmed by the gravitational fields of nearer and/or more massive bodies, but it is there. The gravitational field of every material object, however small or however far, extends through all of space.

FIGURE 9.7

According to Newton's equation, her weight (not her mass) decreases as she increases her distance from Earth's center.

CHECK POINT

1. By how much does the gravitational force between two objects decrease when the distance between their centers is doubled? Tripled? Increased tenfold?
2. Consider an apple at the top of a tree that is pulled by Earth's gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity be 1/4 as strong? Defend your answer.

Check Your Answers

1. It decreases to 1/4, 1/9, and 1/100 the original value.
2. No, because an apple at the top of the twice-as-tall apple tree is not twice as far from Earth's center. The taller tree would need a height equal to the Earth's radius (6,370 km) for the apple's weight at its top to reduce to 1/4 N. Before its weight decreases by 1%, an apple or any object must be raised 32 km—nearly 4 times the height of Mt. Everest. So, as a practical matter, we disregard the effects of everyday changes in elevation.

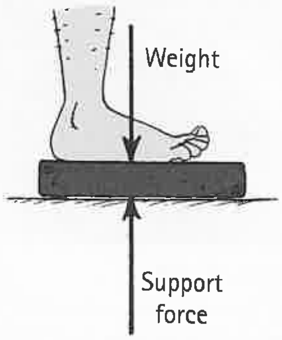


FIGURE 9.8

When you step on a weighing scale, two forces act on it: a downward force of gravity, *mg*, and an upward support force. These two forces are equal and opposite when no acceleration occurs, and they squeeze a spring-like device inside the scale that is calibrated to show your weight.

Weight and Weightlessness

The force of gravity, like any force, can produce acceleration. Objects under the influence of gravity accelerate toward each other. Because we are almost always in contact with Earth, we think of gravity as something that presses us against Earth rather than as something that accelerates us. The pressing against Earth is the sensation we interpret as **weight.**

Stand on a bathroom scale that is supported on a stationary floor. The gravitational force between you and Earth pulls you against the supporting floor and the scale. By Newton's third law, at the same time, the floor and scale push upward on you. Located in between you and the supporting floor are springs inside the bathroom scale. Compression of the springs is read as your weight. If you repeat this weighing procedure in a moving elevator, your weight reading would vary—not during steady motion, but during accelerated motion. If the elevator accelerates upward, the bathroom scale and floor push harder against your feet. So the springs inside the scale are compressed even more. The scale shows an increase in your weight. If the elevator accelerates downward, you sense a decrease in your weight.

In Chapters 2 and 4, we treated the weight of an object as the force due to gravity upon it. When in equilibrium on a firm surface, weight is evidenced by a support force, or, when in suspension, by a supporting rope tension. In either case, with no acceleration, weight equals *mg*. Then, when we discussed rotating environments in Chapter 8, we learned that a support force can occur without regard to gravity. So a broader definition of the weight of something is the force it exerts against a supporting floor or a weighing scale. According to this definition, you are as heavy as

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Videos
Apparent Weightlessness
Weight and Weightlessness

Astronauts inside an orbiting space vehicle have no weight, even though the force of gravity between them and Earth is only slightly less than at ground level.

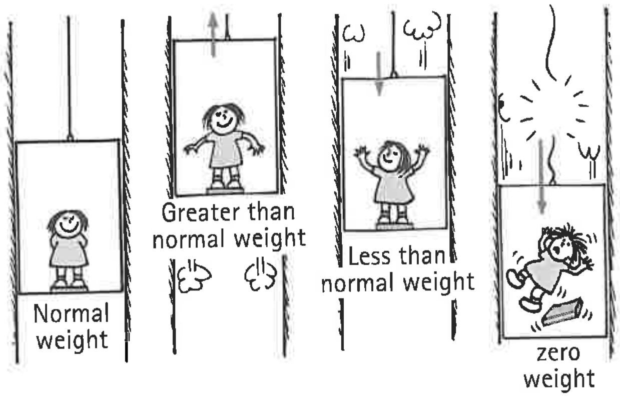

FIGURE 9.9

INTERACTIVE FIGURE

Your weight equals the force with which you press against the supporting floor. If the floor accelerates up or down, your weight varies (even though the gravitational force *mg* that acts on you remains the same).

FIGURE 9.10

These astronauts are in free fall. They feel weightless because they aren't pressed against anything that would provide a support force.

you feel; so, in an elevator that accelerates downward, the supporting force of the floor is less and you weigh less. If the elevator is in free fall, the reading on a weighing scale would be zero. According to the reading, you would be **weightless** (Figure 9.9). Even in this weightless condition, however, there is still a gravitational force acting on you, causing your downward acceleration. But gravity now is not felt as weight because there is no support force.

Astronauts in orbit are without a support force. They are in a sustained state of *weightlessness,* which isn't the absence of gravity, but the absence of a support force. Astronauts sometimes experience "space sickness" until they become accustomed to a state of sustained weightlessness. Astronauts in orbit are in a state of continual free fall.

The International Space Station in Figure 9.12 provides a weightless environment. The station facility and astronauts all accelerate equally toward Earth, at somewhat less than 1 *g* because of their altitude. This acceleration is not sensed at all; with respect to the station, the astronauts experience 0 *g*. Over extended periods of time, this causes loss of muscle strength and other detrimental changes in the body. Future space travelers, however, need not be subjected to weightlessness. As mentioned in the previous chapter, lazily rotating giant wheels or pods at the

FIGURE 9.11

Both are weightless.

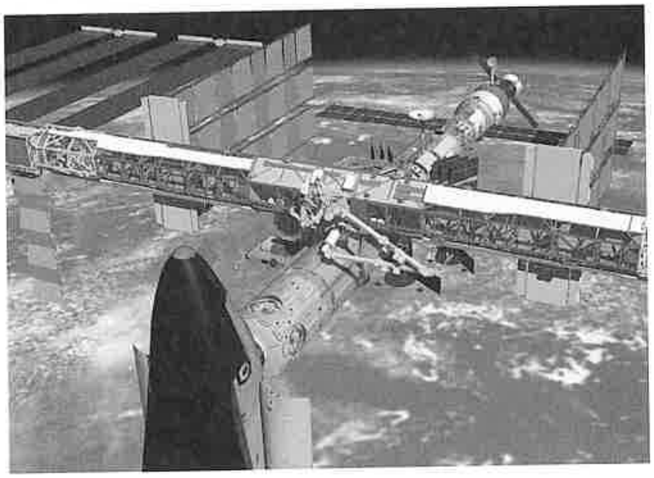

FIGURE 9.12

The inhabitants in this laboratory and docking facility continually experience weightlessness. They are in free fall around Earth. Does a force of gravity act on them?

end of a tether will likely take the place of today's nonrotating space habitats. Rotation effectively supplies a support force and nicely provides weight.

CHECK POINT

In what sense is drifting in space far away from all celestial bodies like stepping down off a stepladder?

Check Your Answer

In both cases, you'd experience weightlessness. Drifting in deep space, you would remain weightless because no discernable force acts on you. Stepping from a stepladder, you would be only momentarily weightless because of a momentary lapse of support force.

Ocean Tides

Seafaring people have always known that there is a connection between the ocean tides and the Moon, but no one could offer a satisfactory theory to explain the two high tides per day. Newton produced the explanation: Ocean tides are caused by *differences* in the gravitational pull between the Moon and Earth on opposite sides of Earth. Gravitational force between the Moon and Earth is stronger on the side of Earth nearer to the Moon, and it is weaker on the side of Earth that is farther from the Moon. This is simply because the gravitational force is weaker with increased distance.

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Tutorial
Tides

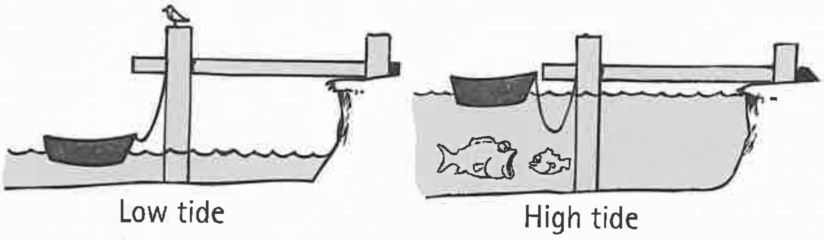

FIGURE 9.13
Ocean tides.

To understand why these different pulls produce tides, let's look at a ball of Jell-O (Figure 9.14). If you exerted the same force on every part of the ball, the ball would remain perfectly round as it accelerated. But if you pull harder on one side than the other, the different pulls would stretch the ball. That's what's happening to this big ball on which we live. Different pulls of the Moon stretch Earth, most notably in its oceans. This stretch is evident in ocean bulges on opposite sides of

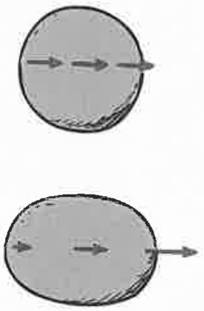

FIGURE 9.14
A ball of Jell-O stays spherical when all parts are pulled equally in the same direction. When one side is pulled more than the other, it is elongated.

FIGURE 9.15
The two tidal bulges produced by differences in gravitational pulls remain relatively fixed relative to the Moon, while Earth spins daily beneath them.

Earth. Hence we experience two sets of ocean tides per day—two high tides and two low tides.

On a world average, the ocean bulges are nearly 1 m above the average surface level of the ocean. Earth spins once per day, so a fixed point on Earth passes beneath both of these bulges each day. This produces two sets of ocean tides per day. Any part of Earth that passes beneath one of the bulges has a high tide. When Earth has made a quarter turn 6 hours later, the water level at the same part of the ocean is nearly 1 m below the average sea level. This is low tide. The water that "isn't there" is under the bulges that make up the high tides. A second high tidal bulge is experienced when Earth makes another quarter turn. So we have two high tides and two low tides daily. Interestingly, while Earth spins, the Moon moves in its orbit and appears at the same position in our sky every 24 hours and 50 minutes, so the two-high-tide cycle is actually at 24-hour-and-50-minute intervals. That is why tides do not occur at the same time every day.

The Sun also contributes to ocean tides, but it's about half as effective as the Moon. Interestingly, the Sun pulls 180 times as hard on Earth as on the Moon. Why aren't tides due to the Sun 180 times as large as tides due to the Moon? Because of the Sun's great distance, the *difference* in gravitational pulls on opposite sides of Earth is very small. In other words, the Sun pulls almost as hard on the far side of Earth as it does on the near side. You'll understand tides more when you tackle "Ocean Tides" in the *Conceptual Physics Practice Book.*[4]

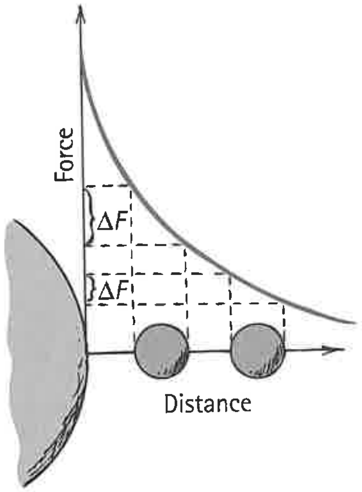

FIGURE 9.16
A plot of gravitational force versus distance (not to scale). The greater the distance from the Sun, the smaller the force F, which varies as $1/d^2$, and the smaller the difference in gravitational pulls on opposite sides of a planet, ΔF.

When the Sun, Earth, and Moon are aligned, the tides due to the Sun and the Moon coincide. Then we have higher-than-average high tides and lower-than-average low tides. These are called **spring tides** (Figure 9.17). (Spring tides have nothing to do with the spring season.) You can tell when the Sun, Earth, and Moon are aligned by the full Moon or by the new Moon. When the Moon is full, Earth is between the Sun and Moon. (If all three are *exactly* in line, then we have a lunar eclipse, for the full Moon passes into Earth's shadow.) A new Moon occurs when the Moon is between the Sun and Earth, when the nonilluminated hemisphere of the Moon faces Earth. (When this alignment is perfect, the Moon blocks the Sun and we have a solar eclipse.) Spring tides occur at the times of a new or full Moon.

FIGURE 9.17
When the attractions of the Sun and the Moon are lined up with each other, spring tides occur.

All spring tides are not equally high because Earth–Moon and Earth–Sun distances vary; the orbital paths of Earth and the Moon are elliptical rather than circular. The Moon's distance from Earth varies by about 10% and its effect in raising tides varies by about 30%. Highest spring tides occur when the Moon and Sun are closest to Earth.

When the Moon is halfway between a new Moon and a full Moon, in either direction (Figure 9.18), the tides due to the Sun and the Moon partly cancel each other. Then, the high tides are lower than average and the low tides are not as low as average low tides. These are called **neap tides.**

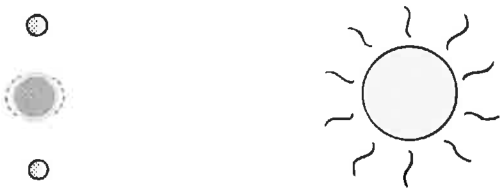

FIGURE 9.18
When the attractions of the Sun and the Moon are about 90° apart (at the time of a half Moon), neap tides occur.

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[4] Newton deduced that *differences* in tidal pulls decrease as the *cube* of the distance between the centers of the bodies. Hence, only relatively close distances result in appreciable tides.

Another factor that affects the tides is the tilt of Earth's axis (Figure 9.19). Even though the opposite tidal bulges are equal, Earth's tilt causes the two daily high tides experienced in most parts of the ocean to be unequal most of the time.

Tides don't occur in ponds because no part of the pond is significantly closer to the Moon or Sun than any other part. With no differences in pulls, no tides are produced. Similarly for the fluids in your body; any tides in your body fluids that are caused by the Moon are negligible. You're not tall enough for tides. What microtides the Moon may produce in your body are only about one two-hundredth the tides produced by a 1-kg melon held 1 m above your head (Figure 9.20).

Our treatment of tides is quite simplified here, for tides are actually more complicated. Interfering land masses and friction with the ocean floor, for example, complicate tidal motions. In many places, the tides break up into smaller "basins of circulation," where a tidal bulge travels like a circulating wave that moves around in a small basin of water that is tilted. For this reason, the high tide may be hours away from an overhead Moon. In mid-ocean, where the range between high and low tide is usually about a meter, variations in range occur in different parts of the world. The range is greatest in some Alaskan fjords and is most notable in the basin of the Bay of Fundy, between New Brunswick and Nova Scotia in eastern Canada, where tidal differences sometimes exceed 15 m. This is largely due to the ocean floor, which funnels shoreward in a V-shape. The tide often comes in faster than a person can run. Don't dig clams near the water's edge at low tide in the Bay of Fundy!

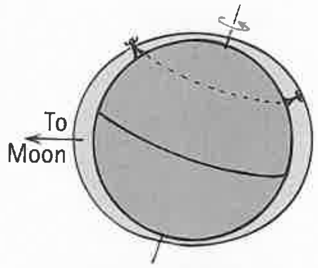

FIGURE 9.19

The inequality of the two high tides per day. Because of Earth's tilt, a person may find the tide nearest the Moon much lower (or higher) than the tide half a day later. Inequalities of tides vary with the positions of the Moon and the Sun.

CHECK POINT

We know that both the Moon and the Sun produce our ocean tides. And we know the Moon plays the greater role because it is closer. Does its closeness mean that it pulls on Earth's oceans with more gravitational force than the Sun?

Check Your Answer

No, the Sun's pull is much stronger. But the *difference* in lunar pulls is more than the *difference* in solar pulls. So our tides are due primarily to the Moon.

FIGURE 9.20

The tidal force difference due to a 1-kg body 1 m over the head of an average height person is about 60 trillionths (6×10^{-11}) N/kg. For an overhead Moon, it is about 0.3 trillionth (3×10^{-13}) N/kg. So holding a melon over your head produces about 200 times as much tidal effect in your body as the Moon does.

TIDES IN EARTH AND ATMOSPHERE

Earth is not a rigid solid but, for the most part, is a semimolten liquid covered by a thin, solid, and pliable crust. As a result, the Moon–Sun tidal forces produce Earth tides as well as ocean tides. Twice each day, the solid surface of Earth rises and falls as much as 1/4 m! As a result, earthquakes and volcanic eruptions have a slightly higher probability of occurring when Earth is experiencing an Earth spring tide—that is, near a full or new Moon.

We live at the bottom of an ocean of air that also experiences tides. Being at the bottom of the atmosphere, we don't notice these tides (just as creatures in deep water likely don't notice ocean tides). In the upper part of the atmosphere is the ionosphere, so named because it contains many ions—electrically charged atoms that are the result of ultraviolet light and intense cosmic ray bombardment. Tidal effects in the ionosphere produce electric currents that alter the magnetic field that surrounds Earth. These are magnetic tides. They, in turn, regulate the degree to which cosmic rays penetrate into the lower atmosphere. The cosmic-ray penetration is evident in subtle changes in the behaviors of living things. The highs and lows of magnetic tides are greatest when the atmosphere is having its spring tides—again, near the full and new Moon.

In addition to ocean tides, the Moon and Sun make atmospheric tides—highest then lowest during a full Moon. Does this explain why some of your friends are weird when the Moon is full?

TIDAL BULGES ON THE MOON

There are two tidal bulges on the Moon for the same reason there are two tidal bulges on Earth—the near and far sides of each body are pulled differently. So the

Moon is pulled slightly away from a spherical shape into a football shape, with its long axis pointing toward Earth. But unlike Earth's tides, the tidal bulges remain in fixed locations, with no "daily" rising and falling of Moon tides. Since the Moon takes 27.3 days to make a single revolution about its own axis (and also about the Earth–Moon axis), the same lunar hemisphere faces Earth all the time. This is not a coincidence; it occurs because the elongated Moon's center of gravity is slightly displaced from its center of mass. So whenever the Moon's long axis is not lined up toward Earth (Figure 9.21), Earth exerts a small torque on the Moon. This tends to twist the Moon toward aligning with Earth's gravitational field, like the torque that aligns a compass needle with a magnetic field. So we see there is a reason why the Moon always shows us its same face.

Interestingly enough, this "tidal lock" is also working on Earth. Our days are getting longer at the rate of 2 milliseconds per century. In a few billion years, our day will be as long as a month, and Earth will always show the same face to the Moon. How about that!

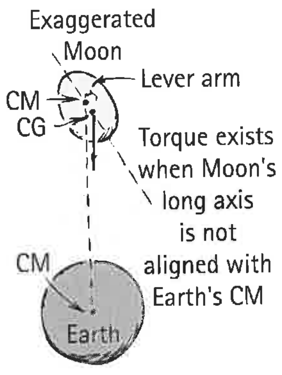

FIGURE 9.21

Earth's pull on the Moon at its center of gravity produces a torque about the Moon's center of mass, which tends to rotate the long axis of the Moon into alignment with Earth's gravitational field (like a compass needle that aligns with a magnetic field). That's why only one side of the Moon faces Earth.

Gravitational Fields

Earth and the Moon pull on each other. This is *action at a distance,* because Earth and Moon interact with each other without being in contact. We can look at this in a different way: We can regard the Moon as being in contact and interacting with the *gravitational field* of Earth. The properties of the space surrounding any massive body can be looked at as altered in such a way that another massive body in this region experiences a force. This alteration of space is a **gravitational field.** It is common to think of rockets and distant space probes being influenced by the gravitational field at their locations in space, rather than by Earth and other planets or stars. The field concept plays an in-between role in our thinking about the forces between different masses.

A gravitational field is an example of a *force field,* for any body with mass experiences a force in the field. Another force field, perhaps more familiar, is a magnetic field. Have you ever seen iron filings lined up in patterns around a magnet? (Look ahead to Figure 24.2 on page 427, for example.) The pattern of the filings shows the strength and direction of the magnetic field at different points in the space around the magnet. Where the filings are closest together, the field is strongest. The direction of the filings shows the direction of the field at each point.

The pattern of Earth's gravitational field can be represented by field lines (Figure 9.22). Like the iron filings around a magnet, the field lines are closer together where the gravitational field is stronger. At each point on a field line, the direction of the field is along the line. Arrows show the field direction. A particle, astronaut, spaceship, or any body in the vicinity of Earth will be accelerated in the direction of the field line at that location.

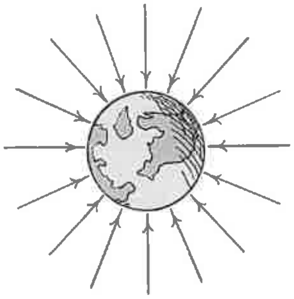

FIGURE 9.22

Field lines represent the gravitational field about Earth. Where the field lines are closer together, the field is stronger. Farther away, where the field lines are farther apart, the field is weaker.

The strength of Earth's gravitational field, like the strength of its force on objects, follows the inverse-square law. It is strongest near Earth's surface and weakens with increasing distance from Earth.[5]

The gravitational field at Earth's surface varies slightly from location to location. Above large subterranean lead deposits, for example, the field is slightly stronger than average. Above large caverns, the field is slightly weaker. To predict what lies beneath Earth's surface, geologists and prospectors of oil and minerals make precise measurements of Earth's gravitational field.

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[5] The strength of the gravitational field g at any point is equal to the force F per unit of mass placed there. So $g = F/m$, and its units are newtons per kilogram (N/kg). The field g also equals the free-fall acceleration of gravity. The units N/kg and m/s^2 are equivalent.

GRAVITATIONAL FIELD INSIDE A PLANET[6]

The gravitational field of Earth exists inside Earth as well as outside. Imagine a hole drilled completely through Earth from the North Pole to the South Pole. Forget about impracticalities, such as the high-temperature molten interior, and consider the motion you would undergo if you fell into such a hole. If you started at the North Pole end, you'd fall and gain speed all the way down to the center, then lose speed all the way "up" to the South Pole. Without air drag, the one-way trip would take nearly 45 minutes. If you failed to grab the edge of the hole when you reached the South Pole, you'd fall back toward the center, and return to the North Pole in the same time.

Your acceleration, *a*, will be progressively less as you continue toward the center of Earth. Why? Because, as you fall toward Earth's center, there is less mass pulling you toward the center. When you are at the center of Earth, the pull down is balanced by the pull up, so the net force on you as you whiz with maximum speed past Earth's center is zero. That's right: you'd have maximum velocity and minimum acceleration at Earth's center! The gravitational field of Earth at its center is zero![7]

The composition of Earth varies, being most dense at its core and least dense at the surface. Inside a hypothetical planet of uniform density, however, the field inside increases linearly—that is, at a steady rate—from zero at its center to *g* at the surface. We won't go into why this is so, but perhaps your instructor will provide the explanation. In any event, a plot of the gravitational field intensity inside and outside a solid planet of uniform density is shown in Figure 9.24.

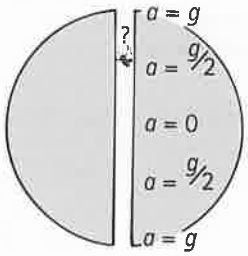

FIGURE 9.23

As you fall faster and faster in a hole bored completely through Earth, your acceleration decreases because the part of Earth's mass beneath you becomes smaller and smaller. Less mass means less attraction until, at the center, where you are pulled equally in all directions, the net force is zero and acceleration is zero. Momentum carries you past the center and against a growing acceleration to the opposite end of the tunnel, where acceleration is again *g*, directed back toward the center.

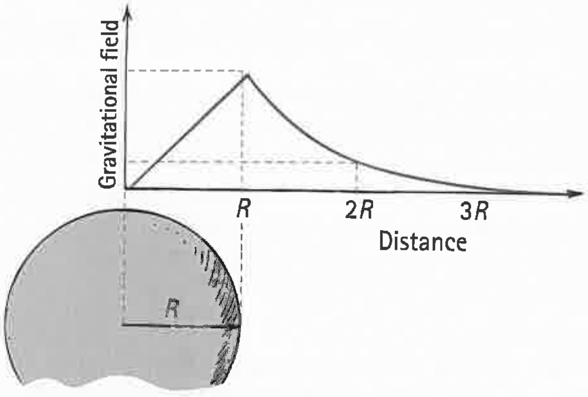

FIGURE 9.24

The gravitational field intensity inside a planet of uniform density is directly proportional to the radial distance from its center and is maximum at its surface. Outside, it is inversely proportional to the square of the distance from its center.

Imagine a spherical cavern at the center of a planet. The cavern would be gravity-free because of the cancellation of gravitational forces in every direction. Amazingly, the size of the cavern doesn't change this fact—even if it constitutes most of the volume of the planet! A hollow planet, like a huge basketball, would have no gravitational field anywhere inside it. Complete cancellation of gravitational forces occurs everywhere inside. To see why, consider the particle *P* in Figure 9.25, which is twice as far from the left side of the planet as it is from the right side. If gravity depended only on distance, *P* would be attracted only 1/4 as much to the left side as to the right side (according to the inverse-square law). But gravity also depends on mass. Imagine a cone reaching to the left from *P* to encompass region A in the figure, and an equal-angle cone reaching to the right encompassing region B. Region A has 4 times the area and therefore 4 times the mass of region B. Since 1/4 of 4 is equal to 1,

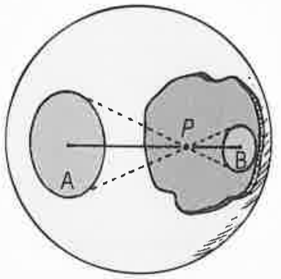

FIGURE 9.25

The gravitational field anywhere inside a spherical shell of uniform thickness and composition is zero, because the field components from all the particles of mass in the shell cancel one another. A mass at point *P*, for example, is attracted just as much to the larger but farther region A as it is to the smaller but closer region B.

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[6] This section may be skipped for a brief treatment of gravitational fields.

[7] Interestingly enough, during the first few kilometers beneath Earth's surface, you'd actually gain acceleration because the density of the compact center is much greater than the density of the surface material. So gravity would be slightly stronger during the first part of a fall. Farther in, gravitation would decrease and would diminish to zero at Earth's center.

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Gravitational Field Inside a Hollow Planet
The Weight of an Object Inside a Hollow Planet but Not at Its Center

P is attracted to the farther but more massive region A with just as much force as it is to the closer but less massive region B. Cancellation occurs. More thought will show that cancellation will occur anywhere inside a planetary shell having uniform density and thickness. A gravitational field would exist within and beyond the shell. At its outer surface and in the space beyond the gravitational field would be the same as if all the mass of the planet were concentrated at its center. Everywhere inside the hollow part, the gravitational field is zero. Anyone inside would be weightless. I call this "yum-yum" physics!

CHECK POINT

1. Suppose you stepped into a hole bored clear through the center of Earth and made no attempt to grab the edges at either end. Neglecting air drag, what kind of motion would you experience?
2. Halfway to the center of Earth, would the force of gravity on you be less than at the surface of Earth?

Check Your Answers

1. You would oscillate back and forth. If Earth were an ideal sphere of uniform density and there were no air drag, your oscillation would be what is called *simple harmonic motion.* Each round-trip would take nearly 90 minutes. Interestingly, we will see in the next chapter that an Earth satellite in close orbit about Earth also takes the same 90 minutes to make a complete round-trip. (This is no coincidence: If you study physics further, you'll learn that "back-and-forth" simple harmonic motion is simply the vertical component of uniform circular motion—interesting stuff.)
2. Gravitational force on you would be less, because there is less mass of Earth below you, which pulls you with less force. If Earth were a uniform sphere of uniform density, gravitational force halfway to the center would be exactly half that at the surface. But since Earth's core is so dense (about 7 times the density of surface rock), gravitational force halfway down would be somewhat more than half. Exactly how much depends on how Earth's density varies with depth, which is information that is unknown today.

Although gravity can be canceled inside a body or between bodies, it cannot be shielded in the same way that electric forces can. In Chapter 22, we will see that electric forces can repel as well as attract, which makes shielding possible. Since gravitation only attracts, a similar kind of shielding cannot occur. Eclipses provide convincing evidence for this. The Moon is in the gravitational field of both the Sun and Earth. During a lunar eclipse, Earth is directly between the Moon and the Sun, and any shielding of the Sun's field by Earth would result in a deviation of the Moon's orbit. Even a very slight shielding effect would accumulate over a period of years and show itself in the timing of subsequent eclipses. But there have been no such discrepancies; past and future eclipses are calculated to a high degree of accuracy using only the simple law of gravitation. No shielding effect in gravitation has ever been found.

Neil deGrasse Tyson nicely describes a falling-through-Earth scenario on *NOVA.*

Einstein's Theory of Gravitation

In the early part of the 20th century, a model for gravity quite unlike Newton's was presented by Einstein in his general theory of relativity. Einstein perceived a gravitational field as a geometrical warping of 4-dimensional space and time; he realized that bodies put dents in space and time somewhat like a massive ball placed in the middle of a large waterbed dents the 2-dimensional surface (Figure 9.26). The more massive the ball, the greater the dent or warp. If we roll a marble across the top of the bed but well away from the ball, the marble will roll in a straight-line path. But if we roll the marble near the ball, it will curve as it rolls across the indented surface of the waterbed. If the curve closes on itself, the marble will orbit the ball in either an oval or a circular path. If you put on your Newtonian glasses, so that you see the ball and marble but not the bed, you might conclude that the marble curves because it is attracted to the ball. If you put on your Einsteinian glasses, so that you see the marble and the indented waterbed but not the "distant" ball, you would likely conclude that the marble curves because the surface on which it moves is curved—in 2 dimensions for the waterbed and in 4 dimensions for space and time.[8] In Chapter 36, we will treat Einstein's theory of gravitation in more detail.

FIGURE 9.26

Warped space-time. Space-time near a star is curved in 4 dimensions in a way similar to the 2-dimensional surface of a waterbed when a heavy ball rests on it.

Black Holes

Suppose you were indestructible and could travel in a spaceship to the surface of a star. Your weight on the star would depend both on your mass and the star's mass and on the distance between the star's center and your belly button. If the star were to burn out and collapse to half its radius with no change in its mass, your weight at its surface, determined by the inverse-square law, would be 4 times as much (Figure 9.27). If the star were to collapse to a tenth of its radius, your weight at its surface would be 100 times as much. If the star kept shrinking, the gravitational field at the surface would become stronger. It would be more and more difficult for a starship to leave. The velocity required to escape, the *escape velocity,* would increase. If a star such as our Sun collapsed to a radius of less than 3 km, the escape velocity from its surface would exceed the speed of light, and nothing—not even light—could escape! The Sun would be invisible. It would be a **black hole.**

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- Contrary to stories about black holes, they're nonaggressive and don't reach out and swallow innocents at a distance. Their gravitational fields are no stronger than the original fields about the stars before collapse—except at distances smaller than the original star radius. Except when they are too close, black holes shouldn't worry future astronauts.

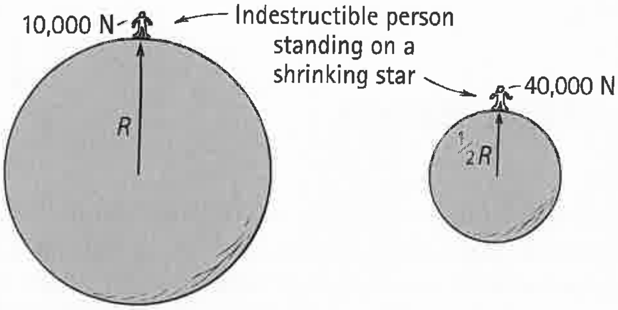

FIGURE 9.27

If a star collapses to half its radius and there is no change in its mass, gravitation at its surface is multiplied by 4.

The Sun, in fact, has too little mass to experience such a collapse, but when some stars with greater mass—now estimated to be at least 1.5 solar masses or more—reach the end of their nuclear resources, they undergo collapse and, unless rotation is high enough, the collapse continues until the stars reach infinite densities. Gravitation near these shrunken stars is so enormous that light cannot escape from their vicinity. They have crushed themselves out of visible existence. The results are black holes, which are completely invisible.

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Tutorial
Black Holes

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[8] Don't be discouraged if you cannot visualize 4-dimensional space-time. Einstein himself often told his friends, "Don't try. I can't do it either." Perhaps we are not too different from the great thinkers around Galileo who couldn't visualize a moving Earth!

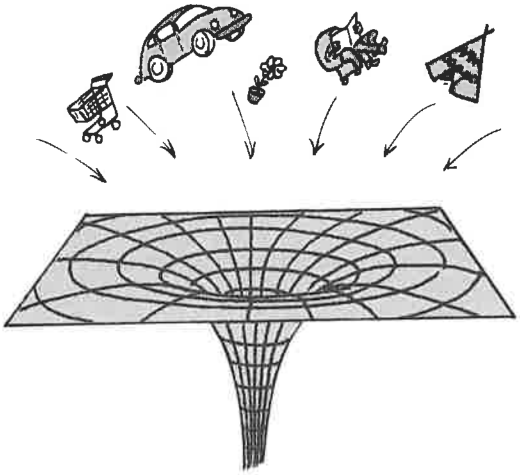

FIGURE 9.28

Anything that falls into a black hole is crushed out of existence. Only mass, angular momentum, and electric charge are retained by the black hole.

A black hole is no more massive than the star from which it collapsed, so the gravitational field in regions at and greater than the original star's radius is no different after the star's collapse than before. But, at closer distances near the vicinity of a black hole, the gravitational field can be enormous—a surrounding warp into which anything that passes too close—light, dust, or a spaceship—is drawn. Astronauts could enter the fringes of this warp and, if they were in a powerful spaceship, they could still escape. After a certain distance, however, they could not, and they would disappear from the observable universe. Any object falling into a black hole would be torn to pieces. No feature of the object would survive except its mass, its angular momentum (if any), and its electric charge (if any).

A theoretical entity with some similarity to a black hole is the "wormhole" (Figure 9.29). Like a black hole, a wormhole is an enormous distortion of space and time. But instead of collapsing toward an infinitely dense point, the wormhole opens out again in some other part of the universe—or even, conceivably, in some other universe! Whereas the existence of black holes has been confirmed, the wormhole remains an exceedingly speculative notion. Some science buffs imagine that the wormhole opens up the possibility of time travel.[9]

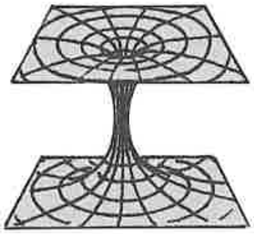

FIGURE 9.29

A speculative wormhole may be the portal to another part of our universe or even to another universe.

How can a black hole be detected if there is literally no way to "see" it? It makes itself felt by its gravitational influence on nearby matter and on neighboring stars. There is now good evidence that some binary star systems consist of a luminous star and an invisible companion with black-hole-like properties orbiting around each other. Even stronger evidence points to more massive black holes at the centers of many galaxies. In a young galaxy, observed as a "quasar," the central black hole sucks in matter that emits great quantities of radiation as it plunges to oblivion. In an older galaxy, stars are observed circling in a powerful gravitational field around an apparently empty center. These galactic black holes have masses ranging from millions to more than 1 billion times the mass of our Sun. The center of our own galaxy, although not so easy to see as the centers of some other galaxies, almost surely hosts a black hole. Discoveries are coming faster than textbooks can report. Check your astronomy web site for the latest update.

Universal Gravitation

We all know that Earth is round. But why is Earth round? It is round because of gravitation. Everything attracts everything else, and so Earth has attracted itself together as far as it can! Any "corners" of Earth have been pulled in; as a result, every part of the surface is equidistant from the center of gravity. This makes it a sphere. Therefore, we see from the law of gravitation that the Sun, the Moon, and Earth are spherical because they have to be (although rotational effects make them slightly ellipsoidal).

If everything pulls on everything else, then the planets must pull on each other. The force that controls Jupiter, for example, is not just the force from the Sun; there are also the pulls from the other planets. Their effect is small in comparison with

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[9] Stephen Hawking, a pioneering expert on black holes, was one of the first to speculate about the existence of wormholes. But, in 2003, to the dismay of many science buffs, he announced his belief that they cannot exist.

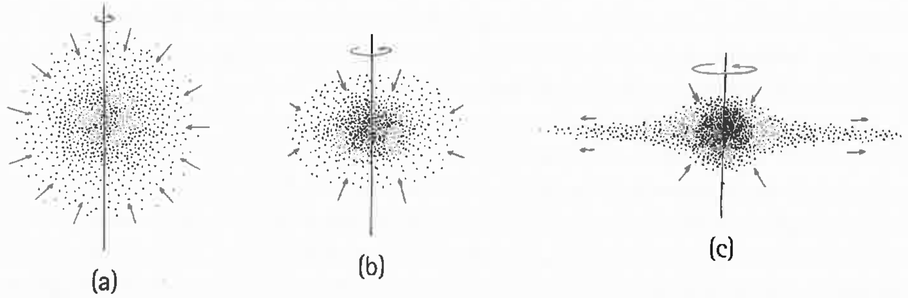

FIGURE 9.30

Formation of the solar system. A slightly rotating ball of interstellar gas (a) contracts due to mutual gravitation and (b) conserves angular momentum by speeding up. The increased momentum of individual particles and clusters of particles causes them (c) to sweep in wider paths about the rotational axis, producing an overall disk shape. The greater surface area of the disk promotes cooling and condensation of matter in swirling eddies—the birthplace of the planets.

the pull of the much more massive Sun, but it still shows. When Saturn is near Jupiter, its pull disturbs the otherwise smooth path traced by Jupiter. Both planets "wobble" in their orbits. The interplanetary forces causing this wobbling are called *perturbations.* By the 1840s, studies of the most recently discovered planet at the time, Uranus, showed that the deviations of its orbit could not be explained by perturbations from all other known planets. Either the law of gravitation was failing at this great distance from the Sun or an unknown eighth planet was perturbing the orbit of Uranus. An Englishman and a Frenchman, J. C. Adams and Urbain Leverrier, each assumed Newton's law to be valid, and they independently calculated where an eighth planet should be. At about the same time, Adams sent a letter to the Greenwich Observatory in England and Leverrier sent a letter to the Berlin Observatory in Germany, both suggesting that a certain area of the sky be searched for a new planet. The request by Adams was delayed by misunderstandings at Greenwich, but Leverrier's request was heeded immediately. The planet Neptune was discovered that very night!

Subsequent tracking of the orbits of both Uranus and Neptune led to the prediction and discovery of Pluto in 1930 at the Lowell Observatory in Arizona. Whatever you may have learned in your early schooling, astronomers now regard Pluto as a *dwarf planet,* a new category of certain asteroids in the Kuiper belt. Regardless of its status, Pluto takes 248 years to make a single revolution about the Sun, so no one will see it in its discovered position again until the year 2178.

Recent evidence suggests that the universe is expanding and accelerating outward, pushed by an antigravity *dark energy* that makes up some 73% of the universe. Another 23% is composed of the yet-to-be-discovered particles of exotic *dark matter.* Ordinary matter, the stuff of stars, cabbages, and kings, makes up only about 4%. The concepts of dark energy and dark matter are late-20th- and 21st-century discoveries. The present view of the universe has progressed appreciably beyond the universe as Newton perceived it.

Yet few theories have affected science and civilization as much as Newton's theory of gravity. The successes of Newton's ideas ushered in the Age of Enlightenment. Newton had demonstrated that, by observation and reason, people could uncover the workings of the physical universe. How profound that all the moons and planets and stars and galaxies have such a beautifully simple rule to govern them, namely,

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

A sphere has the smallest surface area for any volume of matter.

fyi

- A widespread assumption is that when Earth ceased to be regarded as the center of the universe, its place and humankind were demoted and no longer considered special. On the contrary, writings of the time suggest most Europeans viewed humans as filthy and sinful because of Earth's lowly position—farthest from heaven, with hell at its center. Human elevation didn't occur until the Sun, viewed positively, took a center position. We became special by showing we're not so special.

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Discovery of Neptune

The formulation of this simple rule is one of the major reasons for the success in science that followed, for it provided hope that other phenomena of the world might also be described by equally simple and universal laws.

This hope nurtured the thinking of many scientists, artists, writers, and philosophers of the 1700s. One of these was the English philosopher John Locke, who argued that observation and reason, as demonstrated by Newton, should be our best judge and guide in all things. Locke urged that all of nature and even society should be searched to discover any "natural laws" that might exist. Using Newtonian physics as a model of reason, Locke and his followers modeled a system of government that found adherents in the thirteen British colonies across the Atlantic. These ideas culminated in the Declaration of Independence and the Constitution of the United States of America.

SUMMARY OF TERMS

Law of universal gravitation Every body in the universe attracts every other body with a force that, for two bodies, is directly proportional to the product of their masses and inversely proportional to the square of the distance separating them:

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

Inverse-square law A law relating the intensity of an effect to the inverse square of the distance from the cause. Gravity follows an inverse-square law, as do the effects of electric, magnetic, light, sound, and radiation phenomena.

Weight The force that an object exerts on a supporting surface (or, if suspended, on a supporting string), which is often, but not always, due to the force of gravity.

Weightless Being without a support force, as in free fall.

Spring tides High or low tides that occur when the Sun, Earth, and the Moon are all lined up so that the tides due to the Sun and the Moon coincide, making the high tides higher than average and the low tides lower than average.

Neap tides Tides that occur when the Moon is midway between new and full, in either direction. Tides due to the Sun and the Moon partly cancel, making the high tides lower than average and the low tides higher than average.

Gravitational field The influence that a massive body extends into the space around itself, producing a force on another massive body. It is measured in newtons per kilogram (N/kg).

Black hole A concentration of mass resulting from gravitational collapse, near which gravity is so intense that not even light can escape.

REVIEW QUESTIONS

1. What did Newton discover about gravity?
2. What is the Newtonian synthesis?

The Universal Law of Gravity

3. In what sense does the Moon "fall"?
4. State Newton's law of universal gravitation in words. Then do the same with one equation.

The Universal Gravitational Constant, *G*

5. What is the magnitude of gravitational force between two 1-kg bodies that are 1 m apart?
6. What is the magnitude of the gravitational force between Earth and a 1-kg body?
7. What do we call the gravitational force between Earth and your body?
8. When *G* was first measured by Henry Cavendish, newspapers of the time hailed his experiment as the "weighing Earth experiment." Why?

Gravity and Distance: The Inverse-Square Law

9. How does the force of gravity between two bodies change when the distance between them is doubled?
10. How does the thickness of paint sprayed on a surface change when the sprayer is held twice as far away?
11. Where do you weigh more—at the bottom of Death Valley or atop one of the peaks of the Sierra Nevada? Why?

Weight and Weightlessness

12. Would the springs inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that accelerated upward? Downward?
13. Would the springs inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that moved upward at *constant velocity?* Downward at *constant velocity?*
14. When is your weight equal to *mg*?
15. Give an example of when your weight is more than *mg*. Give an example of when it's zero.

Ocean Tides

16. Do tides depend more on the strength of gravitational pull or on the *difference* in strengths? Explain.
17. Why do both the Sun and the Moon exert a greater gravitational force on one side of Earth than the other?
18. Distinguish between *spring tides* and *neap tides.*

Tides in Earth and Atmosphere

19. Do tides occur in the molten interior of Earth for the same reason that tides occur in the oceans?
20. Why are all tides greatest at the time of a full Moon or new Moon?

Tidal Bulges on the Moon

21. Why is there a torque about the Moon's center of mass when the Moon's long axis is not aligned with Earth's gravitational field?
22. Is there a torque about the Moon's center of mass when the Moon's long axis is aligned with Earth's gravitational field? Explain how this compares with a magnetic compass.

Gravitational Fields

23. What is a gravitational field, and how can its presence be detected?

Gravitational Field Inside a Planet

24. What is the magnitude of the gravitational field at Earth's center?
25. For a planet of uniform density, how would the magnitude of the gravitational field halfway to the center compare with the field at the surface?
26. What would be the magnitude of the gravitational field anywhere inside a hollow, spherical planet?

Einstein's Theory of Gravitation

27. Newton viewed the curving of the path of a planet as being caused by a force acting upon the planet. How did Einstein view the curved path of a planet?

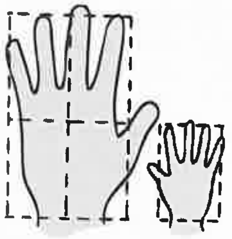
Black Holes

28. If Earth shrank with no change in its mass, what would happen to your weight at the surface?
29. What happens to the strength of the gravitational field at the surface of a star that shrinks?
30. Why is a black hole invisible?

Universal Gravitation

31. What was the cause of perturbations discovered in the orbit of the planet Uranus? What greater discovery did this lead to?
32. What percentage of the universe is presently speculated to be composed of dark matter and dark energy?

PROJECTS



1. Hold your hands outstretched in front of you, one twice as far from your eyes as the other, and make a casual judgment as to which hand looks bigger. Most people see them to be about the same size, although many see the nearer hand as slightly bigger. Almost no one, upon casual inspection, sees the nearer hand as 4 times as big, but, by the inverse-square law, the nearer hand should appear to be twice as tall and twice as wide and therefore seem to occupy 4 times as much of your visual field as the farther hand. Your belief that your hands are the same size is so strong that you likely overrule this information. Now, if you overlap your hands slightly and view them with one eye closed, you'll see the nearer hand as clearly bigger. This raises an interesting question: What other illusions do you have that are not so easily checked?
2. Repeat the eyeballing experiment, only this time use two dollar bills—one regular, and the other folded along its middle lengthwise, and again widthwise, so it has 1/4 the area. Now hold the two in front of your eyes. Where do you hold the folded one so that it looks the same size as the unfolded one? Nice?

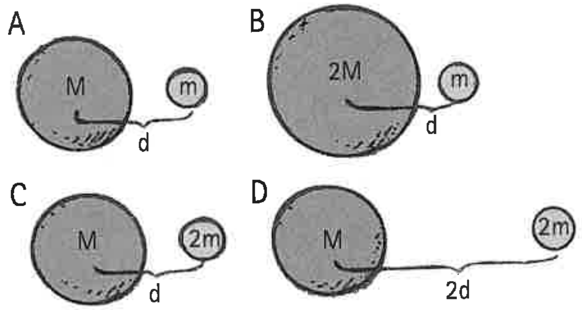
PLUG AND CHUG

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

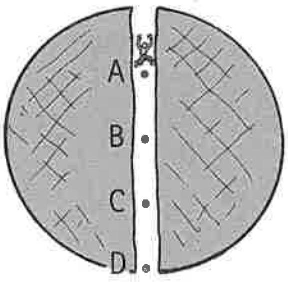
1. Calculate the force of gravity on a 1-kg mass at Earth's surface. The mass of Earth is 6.0×10^{24} kg, and its radius is 6.4×10^{6} m.
2. Calculate the force of gravity on the same 1-kg mass if it were 6.4×10^{6} m above Earth's surface (that is, if it were two Earth radii from Earth's center).
3. Calculate the force of gravity between Earth (mass = 6.0×10^{24} kg) and the Moon (mass = 7.4×10^{22} kg). The average Earth–Moon distance is 3.8×10^{8} m.
4. Calculate the force of gravity between Earth and the Sun (the Sun's mass = 2.0×10^{30} kg; average Earth–Sun distance = 1.5×10^{11} m).
5. Calculate the force of gravity between a newborn baby (mass = 3 kg) and the planet Mars (mass = 6.4×10^{23} kg) when Mars is at its closest to Earth (distance = 5.6×10^{10} m).
6. Calculate the force of gravity between a newborn baby of mass 3 kg and the obstetrician of mass 100 kg, who is 0.5 m from the baby. Which exerts more gravitational force on the baby, Mars or the obstetrician? By how much?

RANKING

1. The planet and its moon gravitationally attract each other. Rank the force of attraction between each pair from greatest to least.



2. Consider the light of multiple candle flames, each of the same brightness. Rank from brightest to dimmest the light that enters your eye for the following situations.
   a. 3 candles seen from a distance of 3 m.
   b. 2 candles seen from a distance of 2 m.
   c. 1 candle seen from a distance of 1 m.
3. Pretend you fall into a hole bored completely through the Earth. Discounting friction and rotational effects, rank, from most to least, at positions A, B, C, and D your



   a. speed of fall.
   b. acceleration of fall.
4. Rank the average gravitational forces from greatest to least between
   a. Sun and Mars.
   b. Sun and the Moon.
   c. Sun and Earth.
5. Rank the microtidal forces on your own body, from greatest to least, produced by the
   a. Moon.
   b. Earth.
   c. Sun.

EXERCISES

1. Comment on whether or not the following label on a consumer product should be cause for concern: *CAUTION: The mass of this product pulls on every other mass in the universe, with an attracting force that is proportional to the product of the masses and inversely proportional to the square of the distance between them.*
2. Gravitational force acts on all bodies in proportion to their masses. Why, then, doesn't a heavy body fall faster than a light body?
3. What would be the path of the Moon if somehow all gravitational forces on it vanished to zero?
4. Is the force of gravity stronger on a piece of iron than on a piece of wood if both have the same mass? Defend your answer.
5. Is the force of gravity stronger on a crumpled piece of paper than on an identical piece of paper that has not been crumpled? Defend your answer.
6. What is the relationship between force and distance in an inverse-square law?
7. A friend says that up above the atmosphere, in space shuttle territory, Earth's gravitational field is zero. Explain how your friend has a misconception, and use the equation for gravitational force in your explanation.
8. A friend says that, since Earth's gravity is so much stronger than the Moon's gravity, rocks on the Moon could be dropped to Earth. What is wrong with this assumption?
9. Another friend says that the Moon's gravity would prevent rocks dropping from the Moon to Earth, but that if the Moon's gravity somehow no longer pulled on its own rocks, then rocks on the Moon would fall to Earth. What is wrong with this assumption?
10. A friend says that the International Space Station shown on the cover of this book is beyond the pull of Earth's gravity. Correct your friend's misconception.
11. Somewhere between Earth and the Moon, gravity from these two bodies on a space pod would cancel. Is this location nearer Earth or the Moon?
12. An apple falls because of the gravitational attraction to Earth. How does the gravitational attraction of Earth to the apple compare? (Does force change when you interchange m_1 and m_2 in the equation for gravity—m_2m_1 instead of m_1m_2?)
13. Larry weighs 300 N at the surface of Earth. What is the weight of Earth in the gravitational field of Larry?
14. Earth and the Moon are attracted to each other by gravitational force. Does the more massive Earth attract the less massive Moon with a force that is greater, smaller, or the same as the force with which the Moon attracts Earth? (With an elastic band stretched between your thumb and forefinger, which is pulled more strongly by the band, your thumb or your forefinger?)
15. If the Moon pulls Earth as strongly as Earth pulls the Moon, why doesn't Earth rotate around the Moon, or

why don't both rotate around a point midway between them?

16. Is the acceleration due to gravity more or less atop Mt. Everest than at sea level? Defend your answer.

17. An astronaut lands on a planet that has the same mass as Earth but twice the diameter. How does the astronaut's weight differ from that on Earth?

18. An astronaut lands on a planet that has twice the mass as Earth and twice the diameter. How does the astronaut's weight differ from that on Earth?

19. If Earth somehow expanded to a larger radius, with no change in mass, how would your weight be affected? How would it be affected if Earth instead shrunk? (*Hint:* Let the equation for gravitational force guide your thinking.)

20. The intensity of light from a central source varies inversely as the square of the distance. If you lived on a planet only half as far from the Sun as our Earth, how would Sun's light intensity compare with that on Earth? How about a planet 10 times farther away than Earth?

21. A small light source located 1 m in front of a 1-m^2 opening illuminates a wall behind. If the wall is 1 m behind the opening (2 m from the light source), the illuminated area covers 4 m^2. How many square meters will be illuminated if the wall is 3 m from the light source? 5 m? 10 m?

22. The planet Jupiter is more than 300 times as massive as Earth, so it might seem that a body on the surface of Jupiter would weigh 300 times as much as on Earth. But it so happens that a body would scarcely weigh 3 times as much on the surface of Jupiter as it would on the surface of Earth. Can you think of an explanation for why this is so? (*Hint:* Let the terms in the equation for gravitational force guide your thinking.)

23. Why does a person in free fall experience weightlessness, while a person falling at terminal velocity does not?

24. Why do the passengers in high-altitude jet planes feel the sensation of weight while passengers in an orbiting space vehicle, such as a space shuttle, do not?

25. Is gravitational force acting on a person who falls off a cliff? On an astronaut inside an orbiting space shuttle?

26. If you were in a car that drove off the edge of a cliff, why would you be momentarily weightless? Would gravity still be acting on you?

27. What two forces act on you while you are in a moving elevator? When are these forces of equal magnitude and when are they not?

28. If you were in a freely falling elevator and you dropped a pencil, it would hover in front of you. Is there a force of gravity acting on the pencil? Defend your answer.

29. Why does a bungee jumper feel weightless during the jump?

30. Since your weight when standing on Earth is the gravitational attraction between you and Earth, would your weight be greater if Earth gained mass? If the Sun gained mass? Why are your answers the same or different?

31. Your friend says that the primary reason astronauts in orbit feel weightless is that they are beyond the main pull of Earth's gravity. Why do you agree or disagree?

32. Explain why the following reasoning is wrong. "The Sun attracts all bodies on Earth. At midnight, when the Sun is directly below, it pulls on you in the same direction as Earth pulls on you; at noon, when the Sun is directly overhead, it pulls on you in a direction opposite to Earth's pull on you. Therefore, you should be somewhat heavier at midnight and somewhat lighter at noon."

33. When will the gravitational force between you and the Sun be greater—today at noon, or tomorrow at midnight? Defend your answer.

34. If the mass of Earth increased, your weight would correspondingly increase. But, if the mass of the Sun increased, your weight would not be affected at all. Why?

35. If somebody tugged hard on your shirt sleeve, it would likely tear. But if all parts of your shirt were tugged equally, no tearing would occur. How does this relate to tidal forces?

36. Most people today know that the ocean tides are caused principally by the gravitational influence of the Moon, and most people therefore think that the gravitational pull of the Moon on Earth is greater than the gravitational pull of the Sun on Earth. What do you think?

37. Would ocean tides exist if the gravitational pull of the Moon (and the Sun) were somehow equal on all parts of the world? Explain.

38. Why aren't high ocean tides exactly 12 hours apart?

39. With respect to spring and neap ocean tides, when are the tides lowest? That is, when is it best for digging clams?

40. Whenever the ocean tide is unusually high, will the following low tide be unusually low? Defend your answer in terms of "conservation of water." (If you slosh water in a tub so that it is extra deep at one end, will the other end be extra shallow?)

41. The Mediterranean Sea has very little sediment churned up and suspended in its waters, mainly because of the absence of any substantial ocean tides. Why do you suppose the Mediterranean Sea has practically no tides? Similarly, are there tides in the Black Sea? In the Great Salt Lake? Your county reservoir? A glass of water? Explain.

42. The human body is composed mostly of water. Why does the Moon overhead cause appreciably less tidal effect in the fluid compartment of your body than a 1-kg melon held over your head?

43. Does the fact that one side of the Moon always faces Earth mean that the Moon rotates about its axis (like a top) or that it doesn't rotate about its axis? Defend your answer.

44. What would be the effect on Earth's tides if the diameter of Earth were very much larger than it is? If Earth were as it presently is, but the Moon were very much larger and had the same mass?

45. Which would produce the greatest microtides in your body, the Earth, the Moon, or the Sun? Why?

46. Exactly why do tides occur in Earth's crust and in Earth's atmosphere?

47. The value of g at Earth's surface is about 9.8 m/s^2. What is the value of g at a distance of twice Earth's radius?

48. If Earth were of uniform density (same mass/volume throughout), what would the value of g be inside Earth at half its radius?

49. If Earth were of uniform density, would your weight increase or decrease at the bottom of a deep mine shaft? Defend your answer.

50. It so happens that an actual *increase* in weight is found even in the deepest mine shafts. What does this tell us about how Earth's density changes with depth?

51. Which requires more fuel—a rocket going from Earth to the Moon or a rocket coming from the Moon to Earth? Why?

52. If you could somehow tunnel inside a uniform-density star, would your weight increase or decrease? If, instead, you somehow stood on the surface of a shrinking star, would your weight increase or decrease? Why are your answers different?

53. If our Sun shrank in size to become a black hole, show from the gravitational force equation that Earth's orbit would not be affected.

54. If Earth were hollow but still had the same mass and same radius, would your weight in your present location be more, less, or the same as it is now? Explain.

55. Some people dismiss the validity of scientific theories by saying that they are "only" theories. The law of universal gravity is a theory. Does this mean that scientists still doubt its validity? Explain.

56. Make up two multiple-choice questions—one that would check a classmate's understanding of the inverse-square law and another that would check a distinction between weight and weightlessness.

PROBLEMS

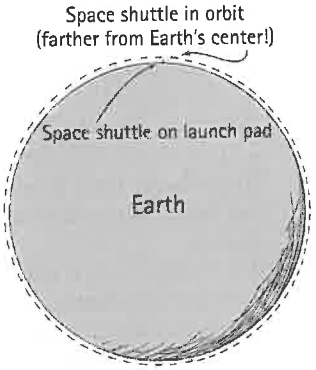
1. Suppose you stood atop a ladder so tall that you were 3 times as far from Earth's center as you presently are. Show that your weight would be one-ninth of its present value.

2. Show that the gravitational force between two planets is quadrupled if the masses of both planets are doubled but the distance between them stays the same.

3. Show that there is no change in the force of gravity between two objects when their masses are doubled and the distance between them is also doubled.

4. Find the change in the force of gravity between two planets when distance between them is *decreased* by 10.

5. Many people mistakenly believe that the astronauts that orbit Earth are "above gravity." Calculate g for space shuttle territory, 200 km above Earth's surface. Earth's mass is 6.0×10^{24} kg, and its radius is 6.38×10^{6} m (6380 km). Your answer is what percentage of 10 m/s^2?



• **6.** Newton's universal law of gravity tells us that $F = G\frac{m_1 m_2}{d^2}$. Newton's second law tells us that $a = \frac{F_{\text{net}}}{m}$.

a. With a bit of algebraic reasoning show that your gravitational acceleration toward any planet of mass M a distance d from its center is $a = \frac{GM}{d^2}$.

b. How does this equation tell you whether or not your gravitational acceleration depends on your mass?

CHAPTER 9 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 9.6, 9.9

Tutorials

- Motion and Gravity
- Tides
- Black Holes

Videos

- Von Jolly's Method of Measuring the Attraction Between Two Masses
- Inverse-Square Law
- Apparent Weightlessness
- Weight and Weightlessness
- Gravitational Field Inside a Hollow Planet
- The Weight of an Object Inside a Hollow Planet but Not at Its Center
- Discovery of Neptune

Quizzes

Flashcards

Links