

# 10 Energy and Work

A greyhound can rapidly go from a standstill to a very speedy run—meaning a very rapid increase in kinetic energy, the energy of motion. How does the greyhound's ability to convert energy from one form to another compare to that of other animals?

We have changed the photos and captions at the start of the chapters and the parts of the text to better interest and engage students. The questions that are raised at the start of the chapters aren't rhetorical; they are questions that will be answered in the flow of the chapter.

## LOOKING AHEAD ▶

### Forms of Energy

This dolphin has lots of **kinetic energy** as it leaves the water. At its highest point its energy is mostly **potential energy**.



You'll learn about several of the most important forms of energy—kinetic, potential, and thermal.

### Work and Energy

The woman does **work** on the jack, applying a force to the handle and pushing it down. This is a *transfer* of energy into the system, increasing the potential energy as the car is lifted.



You'll learn how to calculate the work done by a force, and how this work is related to the change in a system's energy.

### Conservation of Energy

As they slide, their potential energy decreases and their kinetic energy increases, but their total energy is unchanged: It is **conserved**.



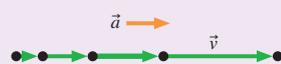
How fast will they be moving when they reach the bottom? You'll use a new before-and-after analysis to find out.

**GOAL** To introduce the concept of energy and to learn a new problem-solving strategy based on conservation of energy.

## LOOKING BACK ◀

### Motion with Constant Acceleration

In Chapter 2 you learned how to describe the motion of a particle that has a constant acceleration. In this chapter, you'll use the constant-acceleration equations to connect work and energy.



A particle's final velocity is related to its initial velocity, its acceleration, and its displacement by

$$(v_x)_f^2 = (v_x)_i^2 + 2a_x \Delta x$$

### STOP TO THINK

A car pulls away from a stop sign with a constant acceleration. After traveling 10 m, its speed is 5 m/s. What will its speed be after traveling 40 m?

- A. 10 m/s
- B. 20 m/s
- C. 30 m/s
- D. 40 m/s

## 10.1 The Basic Energy Model

Energy. It's a word you hear all the time. We use chemical energy to heat our homes and bodies, electric energy to run our lights and computers, and solar energy to grow our crops and forests. We're told to use energy wisely and not to waste it. Athletes and weary students consume "energy bars" and "energy drinks."

But just what is energy? The concept of energy has grown and changed over time, and it is not easy to define in a general way just what energy is. Rather than starting with a formal definition, we'll let the concept of energy expand slowly over the course of several chapters. In this chapter we introduce several fundamental forms of energy, including kinetic energy, potential energy, and thermal energy. Our goal is to understand the characteristics of energy, how energy is used, and, especially important, how energy is transformed from one form into another. Understanding these transformations will allow us to understand and explore a wide variety of physical phenomena. Anything that happens involves a transformation of energy from one form to another, so the range of topics we'll consider in this chapter is extensive.

In solving problems, we'll use a key fact about energy: **Energy is neither created nor destroyed: If one form of energy in a system decreases, it must appear in an equal amount in another form.** Many scientists consider this law of conservation of energy to be the most important of all the laws of nature.

### Systems and Forms of Energy

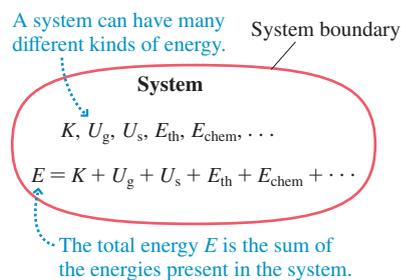
In Chapter 9 we introduced the idea of a *system* of interacting objects. A system can be as simple as a falling acorn or as complex as a city. But whether simple or complex, every system in nature has associated with it a quantity we call its **total energy**  $E$ . The total energy is the sum of the different kinds of energies present in the system. In the table below, we give a brief overview of some of the more important forms of energy; in the rest of the chapter, we'll look at several of these forms of energy in greater detail.

A system may have many of these kinds of energy at one time. For instance, a moving car has kinetic energy of motion, chemical energy stored in its gasoline, thermal energy in its hot engine, and many other forms of energy. **FIGURE 10.1** illustrates the idea that the total energy of the system,  $E$ , is the *sum* of all the different energies present in the system:

$$E = K + U_g + U_s + E_{th} + E_{chem} + \dots \quad (10.1)$$

The energies shown in this sum are the forms of energy in which we'll be most interested in this and the next chapter. The ellipses ( $\dots$ ) stand for other forms of energy, such as nuclear or electric, that also might be present. We'll treat these and others in later chapters.

**FIGURE 10.1** A system and its energies.



### Some important forms of energy

#### Kinetic energy $K$



Kinetic energy is the energy of *motion*. All moving objects have kinetic energy. The heavier an object and the faster it moves, the more kinetic energy it has. The wrecking ball in this picture is effective in part because of its large kinetic energy.

#### Gravitational potential energy $U_g$



Gravitational potential energy is *stored* energy associated with an object's *height above the ground*. As this coaster ascends, energy is stored as gravitational potential energy. As it descends, this stored energy is converted into kinetic energy.

#### Elastic or spring potential energy $U_s$



Elastic potential energy is energy stored when a spring or other elastic object, such as this archer's bow, is *stretched*. This energy can later be transformed into the kinetic energy of the arrow.

*Continued*

**Thermal energy  $E_{\text{th}}$** 

Hot objects have more *thermal energy* than cold ones because the molecules in a hot object jiggle around more than those in a cold object. Thermal energy is the sum of the microscopic kinetic and potential energies of all the molecules in an object.

**Chemical energy  $E_{\text{chem}}$** 

Electric forces cause atoms to bind together to make molecules. Energy can be stored in these bonds, energy that can later be released as the bonds are rearranged during chemical reactions. All animals eat, taking in chemical energy to provide energy to move muscles and fuel processes of the body.

**Nuclear energy  $E_{\text{nuclear}}$** 

The forces that hold together the particles in the nucleus of the atom are much stronger than the electric forces that hold together molecules, so they store a great deal more energy. Certain nuclei break apart into smaller fragments, releasing some of this *nuclear energy*. The energy is transformed into the kinetic energy of the fragments and then into thermal energy.

**Energy Transformations**

If the amounts of each form of energy never changed, the world would be a very dull place. What makes the world interesting is that **energy of one kind can be transformed into energy of another kind**. The following table illustrates a few common energy transformations. In this table, we use an arrow  $\rightarrow$  as a shorthand way of representing an energy transformation.

**Some energy transformations****A weightlifter lifts a barbell over her head**

The barbell has much more gravitational potential energy when high above her head than when on the floor. To lift the barbell, she transforms chemical energy in her body into gravitational potential energy of the barbell.

$$E_{\text{chem}} \rightarrow U_{\text{g}}$$

**A base runner slides into the base**

When running, he has lots of kinetic energy. After sliding, he has none. His kinetic energy is transformed mainly into thermal energy: The ground and his legs are slightly warmer.

$$K \rightarrow E_{\text{th}}$$

**A burning campfire**

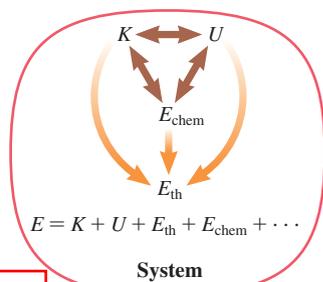
The wood contains considerable chemical energy. When the carbon in the wood combines chemically with oxygen in the air, this chemical energy is transformed largely into thermal energy of the hot gases and embers.

$$E_{\text{chem}} \rightarrow E_{\text{th}}$$

**A springboard diver**

Here's a two-step energy transformation. At the instant shown, the board is flexed to its maximum extent, so that elastic potential energy is stored in the board. Soon this energy will begin to be transformed into kinetic energy; then, as the diver rises into the air and slows, this kinetic energy will be transformed into gravitational potential energy.

$$U_{\text{s}} \rightarrow K \rightarrow U_{\text{g}}$$

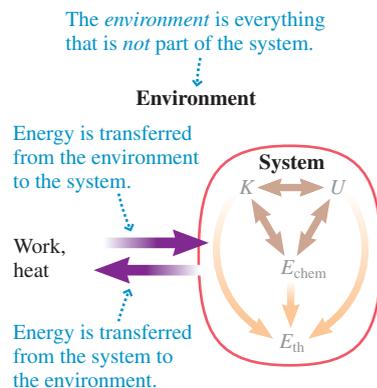
**FIGURE 10.2** Energy transformations within the system.

Videos featured in eText called out prominently with logo/info



A video to support a section's topic is embedded in the eText.

**Video Demo** The Basic Energy Model

**FIGURE 10.3** Work and heat are energy transfers into and out of the system.

**FIGURE 10.2** reinforces the idea that **energy transformations are changes of energy *within* the system from one form to another.** (The  $U$  in this figure is a generic potential energy; it could be gravitational potential energy  $U_g$ , spring potential energy  $U_s$ , or some other form of potential energy.) There are two types of arrows in the figure. The arrow between  $K$  and  $U$  is a two-way arrow; it's easy to transform energy back and forth between these forms. When the springboard diver goes up in the air, his kinetic energy is transformed into gravitational potential energy; when he comes back down, this process is reversed. But the arrow between  $K$  and  $E_{th}$  is a one-way arrow pointing toward  $E_{th}$ . When the runner slides into the base, his kinetic energy is transformed into thermal energy. This process doesn't spontaneously reverse, although this would certainly make baseball a more exciting game. In Chapter 11, we'll see that it is possible to transform thermal energy into other forms, but it's not easy, and there are real limitations.

### Energy Transfers and Work

We've just seen that energy *transformations* occur between forms of energy *within* a system. But every physical system also interacts with the world around it—that is, with its *environment*. In the course of these interactions, the system can exchange energy with the environment. **An exchange of energy between system and environment is called an energy transfer.** There are two primary energy-transfer processes: **work**, the *mechanical* transfer of energy to or from a system by pushing or pulling on it, and **heat**, the *nonmechanical* transfer of energy from the environment to the system (or vice versa) because of a temperature difference between the two.

**FIGURE 10.3**, which we call the **basic energy model**, shows how our energy model is modified to include energy transfers into and out of the system as well as energy transformations within the system. In this chapter we'll consider energy transfers by means of work; the concept of heat will be developed in Chapters 11 and 12.

“Work” is a common word in the English language, with many meanings. When you first think of work, you probably think of physical effort or the job you do to make a living. In physics, “work” is the process of *transferring* energy from the environment to a system, or from a system to the environment, by the application of mechanical forces—pushes and pulls—to the system. Once the energy has been transferred to the system, it can appear in many forms. Exactly what form it takes depends on the details of the system and how the forces are applied. The table below gives three examples of energy transfers due to work. We use  $W$  as the symbol for work.

#### Energy transfers: work



##### Putting a shot

**The system:** The shot

**The environment:** The athlete

As the athlete pushes on the shot to get it moving, he is doing work on the system; that is, he is transferring energy from himself to the shot. The energy transferred to the system appears as kinetic energy.

**The transfer:**  $W \rightarrow K$



##### Striking a match

**The system:** The match and matchbox

**The environment:** The hand

As the hand quickly pulls the match across the box, the hand does work on the system, increasing its thermal energy. The match head becomes hot enough to ignite.

**The transfer:**  $W \rightarrow E_{th}$



##### Firing a slingshot

**The system:** The slingshot

**The environment:** The boy

As the boy pulls back on the elastic bands, he does work on the system, increasing its elastic potential energy.

**The transfer:**  $W \rightarrow U_s$

Notice that in each example on the preceding page, the environment applies a force while the system undergoes a *displacement*. Energy is transferred as work only when the system *moves* while the force acts. A force applied to a stationary object, such as when you push against a wall, transfers no energy to the object and thus does no work.

**NOTE** ▶ In the table on the preceding page, energy is being transferred *from* the athlete *to* the shot by the force of his hand. We say he “does work” on the shot. We speak similarly for the other examples. The hand does work on the match and matchbox, and the boy does work on the slingshot. ◀

## The Law of Conservation of Energy

Work done on a system represents energy that is transferred into or out of the system. This transferred energy *changes* the system’s energy by exactly the amount of work  $W$  that was done. Writing the change in the system’s energy as  $\Delta E$ , we can represent this idea mathematically as

$$\Delta E = W \quad (10.2)$$

Now the total energy  $E$  of a system is, according to Equation 10.1, the sum of the different energies present in the system. Thus the change in  $E$  is the sum of the *changes* in the different energies present. Then Equation 10.2 gives what is called the *work-energy equation*:

**The work-energy equation** The total energy of a system changes by the amount of work done on it:

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{\text{th}} + \Delta E_{\text{chem}} + \cdots = W \quad (10.3)$$

**NOTE** ▶ Equation 10.3, the work-energy equation, is the mathematical representation of the basic energy model of Figure 10.3. Together, they are the heart of what the subject of energy is all about. ◀

Suppose we have an **isolated system**, one that is separated from its surrounding environment in such a way that no energy is transferred into or out of the system. This means that *no work is done on the system*. The energy within the system may be transformed from one form into another, but it is a deep and remarkable fact of nature that, during these transformations, the total energy of an isolated system—the *sum* of all the individual kinds of energy—remains *constant*, as shown in **FIGURE 10.4**. We say that **the total energy of an isolated system is conserved**.

For an isolated system, we must set  $W = 0$  in Equation 10.3, leading to the following statement of the *law of conservation of energy*:

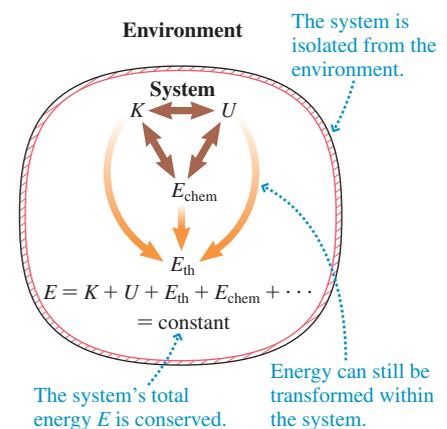
**Law of conservation of energy** The total energy of an isolated system remains constant:

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{\text{th}} + \Delta E_{\text{chem}} + \cdots = 0 \quad (10.4)$$

The law of conservation of energy is similar to the law of conservation of momentum. A system’s momentum changes when an external force acts on it, but the total momentum of an *isolated* system doesn’t change. Similarly, a system’s energy changes when external forces do work on it, but the total energy of an *isolated* system doesn’t change.

In solving momentum problems, we adopted a new before-and-after perspective: The momentum *after* an interaction was the same as the momentum *before* the

**FIGURE 10.4** An isolated system.



interaction. We will introduce a similar before-and-after perspective for energy that will lead to an extremely powerful problem-solving strategy.

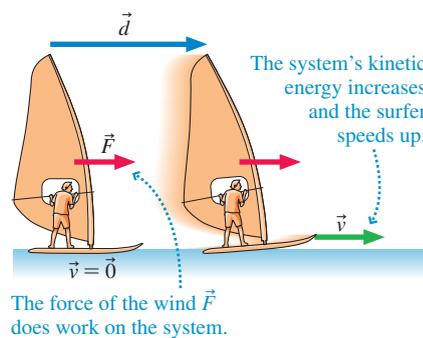
**STOP TO THINK 10.1** A roller coaster slows as it goes up a hill. The energy transformation is

- A.  $U_g \rightarrow K$     B.  $U_g \rightarrow E_{th}$     C.  $K \rightarrow U_g$     D.  $K \rightarrow E_{th}$

## 10.2 Work

We've seen that work is the transfer of energy to or from a system by the application of forces exerted on the system by the environment. Thus work is done on a system by forces *outside* the system; we call such forces *external forces*. Only external forces can change the energy of a system. *Internal forces*—forces between objects *within* the system—cause energy transformations within the system but don't change the system's total energy. In order for energy to be transferred as work, the system must undergo a displacement—it must *move*—during the time that the force is applied.

**FIGURE 10.5** The force of the wind does work on the system, increasing its kinetic energy  $K$ .



Consider a system consisting of a windsurfer at rest, as shown on the left in **FIGURE 10.5**. Let's assume that there is no friction or drag force acting on the board. Initially the system has no kinetic energy. But if a force from outside the system, such as the force due to the wind, begins to act on the system, the surfer will begin to speed up, and his kinetic energy will increase. In terms of energy transfers, we would say that the energy of the system has increased because of the work done on the system by the force of the wind.

What determines how much work is done by the force of the wind? First, we note that the greater the distance over which the wind pushes the surfer, the faster the surfer goes, and the more his kinetic energy increases. This implies a greater transfer of energy. So, **the larger the displacement, the greater the work done.** Second, if the wind pushes with a stronger force, the surfer speeds up more rapidly, and the change in his kinetic energy is greater than with a weaker force. **The stronger the force, the greater the work done.**

This suggests that the amount of energy transferred to a system by a force  $\vec{F}$ —that is, the amount of work done by  $\vec{F}$ —depends on both the magnitude  $F$  of the force *and* the displacement  $d$  of the system. Many experiments of this kind have established that the amount of work done by  $\vec{F}$  is *proportional* to both  $F$  and  $d$ . For the simplest case described above, where the force  $\vec{F}$  is constant and points in the direction of the object's displacement, the expression for the work done is found to be

$$W = Fd \quad (10.5)$$

Work done by a constant force  $\vec{F}$  in the direction of a displacement  $\vec{d}$

The unit of work, that of force multiplied by distance, is  $\text{N} \cdot \text{m}$ . This unit is so important that it has been given its own name, the **joule** (rhymes with *cool*). We define:

$$1 \text{ joule} = 1 \text{ J} = 1 \text{ N} \cdot \text{m}$$

Because work is simply energy being transferred, **the joule is the unit of all forms of energy.** Note that work, unlike momentum, is a *scalar* quantity—it has a magnitude but not a direction.

All of the chapter examples now use real data for real physical situations.

### EXAMPLE 10.1 Working like a dog

A dog in a weight-pulling competition tugs a sled 4.9 m across a snowy track at a constant speed. The force needed to keep the sled moving is 350 N. How much work does the dog do? Where does this energy go?



**STRATEGIZE** Let's take the system to be the sled + snow. The friction force between the runners and the snow is thus an internal force, so it won't change the total energy of the system, just the form of the energy. But the rope extends outside the system; this is an external interaction, so the tension force of the rope does work on the sled as it moves. Since the dog pulls on the end of the rope, we can say, informally, that the dog does work on the system.

**PREPARE** We'll continue, as we did with momentum problems in Chapter 9, with a before-and-after visual overview, shown in **FIGURE 10.6**. The tension force is in the direction of the sled's motion, so we can use Equation 10.5 to calculate the work that the dog does on the sled.

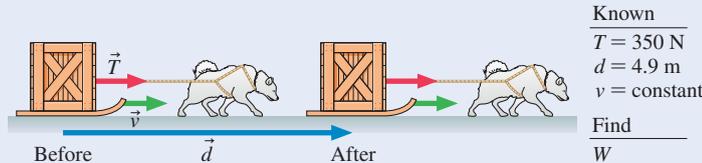
**SOLVE** The work done is

$$W = Fd = (350 \text{ N})(4.9 \text{ m}) = 1700 \text{ J}$$

The dog does work on the system, but the kinetic energy doesn't increase (the sled doesn't speed up) and the gravitational potential energy doesn't increase (the track is level). The energy the dog puts into the system goes to increasing the system's thermal energy as friction warms up the runners and the snow.

**ASSESS** 1700 J is a decent amount of energy, as we'll see, but pulling with a 350 N force (about 80 pounds) for a distance of 4.9 m (about 16 feet) sounds like a lot of work, so our result makes sense.

**FIGURE 10.6** A dog pulling a loaded sled.



## Work by Forces at an Angle to the Displacement

A force does the greatest possible amount of work on an object when the force points in the same direction as the object's displacement. Less work is done when the force acts at an angle to the displacement. To see this, consider the kite buggy of **FIGURE 10.7a**, pulled along a horizontal path by the angled force of the kite string  $\vec{F}$ . As shown in **FIGURE 10.7b**, we can divide  $\vec{F}$  into a component  $F_{\perp}$  perpendicular to the motion, and a component  $F_{\parallel}$  parallel to the motion. Only the parallel component acts to accelerate the rider and increase her kinetic energy, so only the parallel component does work on the rider. From Figure 10.7b, we see that if the angle between  $\vec{F}$  and the displacement is  $\theta$ , then the parallel component is  $F_{\parallel} = F \cos \theta$ . So, when the force acts at an angle  $\theta$  to the direction of the displacement, we have

$$W = F_{\parallel}d = Fd \cos \theta \quad (10.6)$$

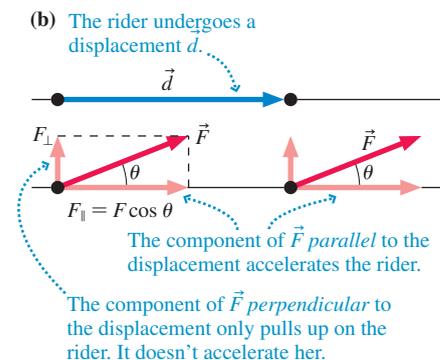
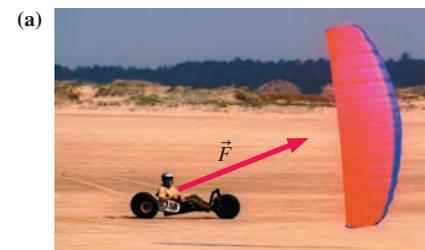
Work done by a constant force  $\vec{F}$  at an angle  $\theta$  to the displacement  $\vec{d}$

Notice that this more general definition of work agrees with Equation 10.5 if  $\theta = 0^\circ$ .

Tactics Box 10.1 shows how to calculate the work done by a force at any angle to the direction of motion. The system illustrated is a block sliding on a frictionless, horizontal surface, so that only the kinetic energy is changing. However, the same relationships hold for any object undergoing a displacement.

The quantities  $F$  and  $d$  are always positive, so the sign of  $W$  is determined entirely by the angle  $\theta$  between the force and the displacement. Note that Equation 10.6,  $W = Fd \cos \theta$ , is valid for any angle  $\theta$ . In three special cases,  $\theta = 0^\circ$ ,  $\theta = 90^\circ$ , and  $\theta = 180^\circ$ , however, there are simple versions of Equation 10.6 that you can use. These are noted in Tactics Box 10.1.

**FIGURE 10.7** The force on the kite buggy is at an angle to the displacement.



**TACTICS BOX 10.1** Calculating the work done by a constant force

Direction of force relative to displacement	Angles and work done	Sign of $W$	Energy transfer
<p>Before: <math>\vec{v}_i</math> After: <math>\vec{v}_f</math>  <math>\theta = 0^\circ</math>  <math>\vec{d}</math>  <math>\vec{F}</math></p>	$\theta = 0^\circ$ $\cos \theta = 1$ $W = Fd$	+	The force is in the direction of motion. The block has its greatest positive acceleration. $K$ increases the most: <b>Maximum energy transfer into the system.</b>
<p><math>\theta &lt; 90^\circ</math>  <math>\vec{d}</math>  <math>\vec{F}</math></p>	$\theta < 90^\circ$ $W = Fd \cos \theta$	+	The component of force parallel to the displacement is less than $F$ . The block has a smaller positive acceleration. $K$ increases less: <b>Decreased energy transfer into the system.</b>
<p><math>\theta = 90^\circ</math>  <math>\vec{d}</math>  <math>\vec{F}</math></p>	$\theta = 90^\circ$ $\cos \theta = 0$ $W = 0$	0	There is no component of force in the direction of motion. The block moves at constant speed. No change in $K$ : <b>No energy transferred.</b>
<p><math>\theta &gt; 90^\circ</math>  <math>\vec{d}</math>  <math>\vec{F}</math></p>	$\theta > 90^\circ$ $W = Fd \cos \theta$	-	The component of force parallel to the displacement is opposite the motion. The block slows down, and $K$ decreases: <b>Decreased energy transfer out of the system.</b>
<p><math>\theta = 180^\circ</math>  <math>\vec{d}</math>  <math>\vec{F}</math></p>	$\theta = 180^\circ$ $\cos \theta = -1$ $W = -Fd$	-	The force is directly opposite the motion. The block has its greatest deceleration. $K$ decreases the most: <b>Maximum energy transfer out of the system.</b>

Exercises 5–6

**EXAMPLE 10.2** Work done in pulling a suitcase

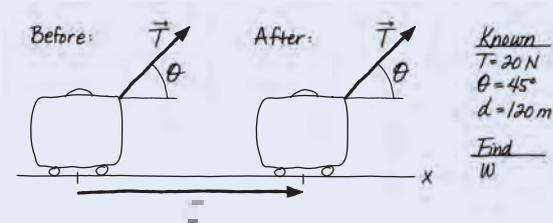
It's 120 m from one gate to another in the airport. You use a strap inclined upward at a  $45^\circ$  angle to pull your suitcase through the airport. The tension in the strap is 20 N. How much work do you do?

**STRATEGIZE** Let's take the system to be the suitcase + floor. As with the dog sled, friction forces (in the wheels or between the wheels and the floor) are internal forces. Both the strap and you are forces outside the system. The tension force of the strap does work on the suitcase as it rolls. Since you are the one pulling the strap, this is, ultimately, energy provided by you.

**PREPARE** **FIGURE 10.8** is a before-and-after visual overview showing the suitcase and the strap. The force is at an angle to the displacement, so we must use Equation 10.6 to calculate the work.

**SOLVE** The tension force does work

$$W = Td \cos \theta = (20 \text{ N})(120 \text{ m})\cos(45^\circ) = 1700 \text{ J}$$

**FIGURE 10.8** A suitcase pulled by a strap.


**ASSESS** This is the same amount of work that the dog did pulling the sled. The force is much less, but the distance is much greater, so this result makes sense.

## CONCEPTUAL EXAMPLE 10.3

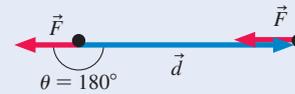
## Work done by a parachute

A drag racer is slowed by a parachute. What is the sign of the work done?

**REASON** The drag force on the drag racer is shown in **FIGURE 10.9**, along with the dragster's displacement as it slows. The force points in the direction opposite the displacement, so the angle  $\theta$  in Equation 10.6 is  $180^\circ$ . Then  $\cos\theta = \cos(180^\circ) = -1$ . Because  $F$  and  $d$  in Equation 10.6 are magnitudes, and hence positive, the work  $W = Fd \cos\theta = -Fd$  done by the drag force is *negative*.



**FIGURE 10.9** The force acting on a drag racer.



**ASSESS** Applying Equation 10.3 to this situation, we have

$$\Delta K = W$$

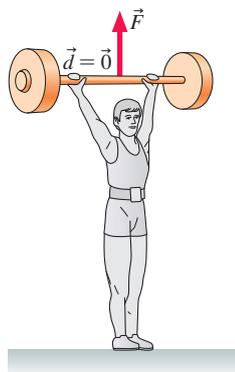
because the only system energy that changes is the racer's kinetic energy  $K$ . Because the kinetic energy is decreasing, its change  $\Delta K$  is negative. This agrees with the sign of  $W$ . This example illustrates the general principle that **negative work represents a transfer of energy out of the system**.

If several forces act on an object that undergoes a displacement, each does work on the object. The **total** (or **net**) work  $W_{\text{total}}$  is the sum of the work done by each force. The total work represents the total energy transfer *to* the system from the environment (if  $W_{\text{total}} > 0$ ) or *from* the system to the environment (if  $W_{\text{total}} < 0$ ).

### Forces That Do No Work

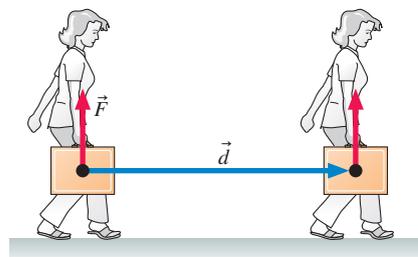
The fact that a force acts on an object doesn't mean that the force will do work on the object. The table below shows three common cases where a force does no work.

#### Forces that do no work



**If the object undergoes no displacement while the force acts, no work is done.**

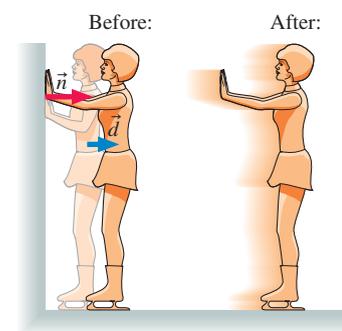
This can sometimes seem counterintuitive. The weightlifter struggles mightily to hold the barbell over his head. But during the time the barbell remains stationary, he does no work on it because its displacement is zero. Why then is it so hard for him to hold it there? Your muscles use energy to apply a force even if there is no displacement and thus no work. We'll talk about the energy that you use to perform a task in Chapter 11.



**A force perpendicular to the displacement does no work.**

The woman exerts only a vertical force on the briefcase she's carrying. This force has no component in the direction of the displacement, so the briefcase moves at a constant velocity and its kinetic energy remains constant. Since the energy of the briefcase doesn't change, it must be that no energy is being transferred to it as work.

(This is the case where  $\theta = 90^\circ$  in Tactics Box 10.1.)

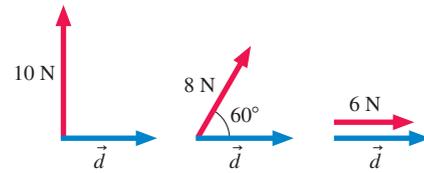


**If the part of the object on which the force acts undergoes no displacement, no work is done.**

Even though the wall pushes on the skater with a normal force  $\vec{n}$  and she undergoes a displacement  $\vec{d}$ , the wall does no work on her, because the point of her body on which  $\vec{n}$  acts—her hands—undergoes no displacement. This makes sense: How could energy be transferred as work from an inert, stationary object? The energy to get the skater moving comes, as you know, from her muscles. This is an internal transformation; chemical energy in her muscles is converted to kinetic energy of her motion.

**STOP TO THINK 10.2** Which force does the most work?

- A. The 10 N force
- B. The 8 N force
- C. The 6 N force
- D. They all do the same amount of work.



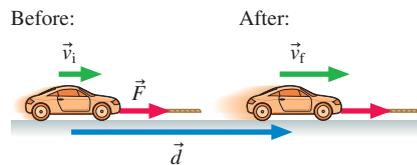
## 10.3 Kinetic Energy

Kinetic energy is an object's energy of motion. We can use what we've learned about work, and some simple kinematics, to find quantitative expressions for kinetic energy.

We'll start with the case of an object in motion along a line. Such an object has **translational kinetic energy**. In Chapter 7, we introduced the idea of rotational motion: Objects can be in motion even if they aren't going anywhere. An object, like the blade of a wind turbine, rotating about a fixed axis has **rotational kinetic energy**, the kinetic energy of the rotational motion.

### Translational Kinetic Energy

**FIGURE 10.10** The work done by the tow rope increases the car's kinetic energy.



Consider a car being pulled by a tow rope, as in **FIGURE 10.10**. The rope pulls with a constant force  $\vec{F}$  while the car undergoes a displacement  $\vec{d}$ , so the force does work  $W = Fd$  on the car. If we ignore friction and drag, the work done by  $\vec{F}$  is transferred entirely into the car's energy of motion—its kinetic energy. In this case, the change in the car's kinetic energy is given by the work-energy equation, Equation 10.3, as

$$W = \Delta K = K_f - K_i \quad (10.7)$$

Using kinematics, we can find another expression for the work done, in terms of the car's initial and final speeds. Recall from **SECTION 2.5** the kinematic equation

$$v_f^2 = v_i^2 + 2a \Delta x$$

Applied to the motion of our car,  $\Delta x = d$  is the car's displacement and, from Newton's second law, the acceleration is  $a = F/m$ . Thus we can write

$$v_f^2 = v_i^2 + \frac{2Fd}{m} = v_i^2 + \frac{2W}{m}$$

where we have replaced  $Fd$  with the work  $W$ . If we now solve for the work, we find

$$W = \frac{1}{2} m(v_f^2 - v_i^2) = \frac{1}{2} m v_f^2 - \frac{1}{2} m v_i^2$$

If we compare this result with Equation 10.7, we see that

$$K_f = \frac{1}{2} m v_f^2 \quad \text{and} \quad K_i = \frac{1}{2} m v_i^2$$

In general, then, an object of mass  $m$  moving with speed  $v$  has kinetic energy

$$K = \frac{1}{2}mv^2 \quad (10.8)$$

Kinetic energy of an object of mass  $m$  moving with speed  $v$



From Equation 10.8, the units of kinetic energy are those of mass times speed squared, or  $\text{kg} \cdot (\text{m/s})^2$ . But

$$1 \text{ kg} \cdot (\text{m/s})^2 = 1 \text{ kg} \cdot \underbrace{(\text{m/s}^2)}_{1 \text{ N}} \cdot \text{m} = 1 \text{ N} \cdot \text{m} = 1 \text{ J}$$

We see that the units of kinetic energy are the same as those of work, as they must be. TABLE 10.1 gives some approximate kinetic energies.

TABLE 10.1 Some approximate kinetic energies

Object	Kinetic energy
Ant walking	$1 \times 10^{-8} \text{ J}$
Coin dropped 1 m	$5 \times 10^{-3} \text{ J}$
Person walking	70 J
Fastball, 100 mph	150 J
Bullet	5000 J
Car, 60 mph	$5 \times 10^5 \text{ J}$
Supertanker, 20 mph	$2 \times 10^{10} \text{ J}$

#### EXAMPLE 10.4 Finding the work to set a boat in motion

At a history center, an old canal boat is pulled by two draft horses. It doesn't take much force to keep the boat moving; the drag force is quite small. But it takes some work to get the 55,000 kg boat up to speed! The horses can pull with a steady force and put a 1400 N tension in the rope that connects to the boat. The rope is straight and level. The boat starts from rest, and the horses pull steadily as they begin their walk down the towpath. How much distance do the horses cover as they bring the boat up to its final speed of 0.70 m/s?

**STRATEGIZE** Let's take the system to be the boat. We could include the water, but since we can ignore the drag force (we're told that it's small), it's not important to do so. The rope is not part of the system, so the tension force does work on the boat. It's this work, which comes from energy provided by the horses, that increases the kinetic energy, and thus the speed, of the boat. We'll consider the initial state to be the boat at rest, the final state to be the boat in motion at its final speed.

**PREPARE** FIGURE 10.11 is a before-and-after visual overview of the situation. The work that is done by the rope will change the energy of the system, so we can use Equation 10.3, the work-energy equation. Because the only thing that changes is the speed, the only form of energy that changes is the kinetic energy, so we can simplify the equation to

$$\Delta K = W$$

This makes sense—the work done changes the kinetic energy of the boat. The tension force is in the direction of the motion, so

the work done is  $W = Td$ . The boat starts at rest, with kinetic energy equal to zero, so the change in kinetic energy is just the final kinetic energy:  $\Delta K = \frac{1}{2}mv_f^2$ .

**SOLVE** With the details noted, the work-energy equation reduces to

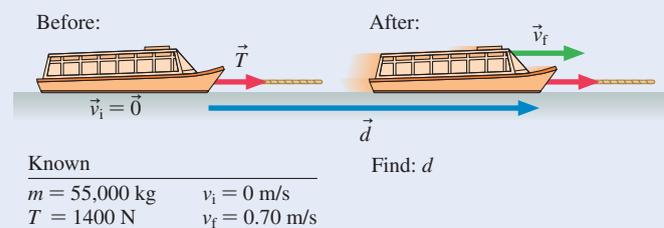
$$\frac{1}{2}mv_f^2 = Td$$

We are looking for the distance the horses pull the boat:

$$d = \frac{mv_f^2}{2T} = \frac{(55,000 \text{ kg})(0.70 \text{ m/s})^2}{2(1400 \text{ N})} = 9.6 \text{ m}$$

**ASSESS** This distance is about 30 feet. This seems a reasonable distance; the horses would be pulling for several strides as they get the boat up to speed.

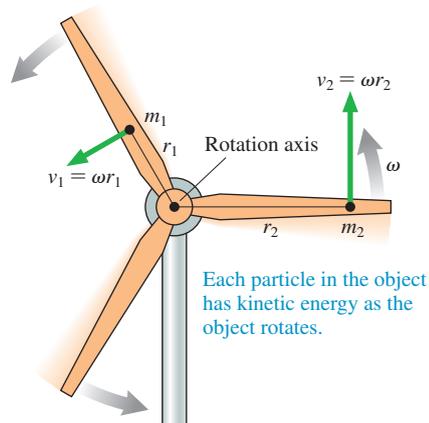
FIGURE 10.11 Getting the canal boat up to speed.



**STOP TO THINK 10.3** Rank in order, from greatest to least, the kinetic energies of the sliding pucks.



**FIGURE 10.12** Rotational kinetic energy of a spinning wind turbine.



## Rotational Kinetic Energy

**FIGURE 10.12** shows the rotating blades of a wind turbine. Although the blades have no overall translational motion, each particle in the blades is moving and hence has kinetic energy. Adding up the kinetic energy of all the particles that make up the blades, we find that the blades have rotational kinetic energy, the kinetic energy due to rotation.

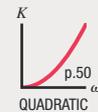
In Figure 10.12, we focus on the motion of two particles in the wind turbine blades. The blade assembly rotates with angular velocity  $\omega$ . Recall from **SECTION 7.1** that a particle moving with angular velocity  $\omega$  in a circle of radius  $r$  has a speed  $v = \omega r$ . Thus particle 1, which rotates in a circle of radius  $r_1$ , moves with speed  $v_1 = r_1\omega$  and so has kinetic energy  $\frac{1}{2}m_1v_1^2 = \frac{1}{2}m_1r_1^2\omega^2$ . Similarly, particle 2, which rotates in a circle with a larger radius  $r_2$ , has kinetic energy  $\frac{1}{2}m_2r_2^2\omega^2$ . The object's rotational kinetic energy is the sum of the kinetic energies of *all* the particles:

$$K_{\text{rot}} = \frac{1}{2}m_1r_1^2\omega^2 + \frac{1}{2}m_2r_2^2\omega^2 + \cdots = \frac{1}{2}\left(\sum mr^2\right)\omega^2$$

You will recognize the term in parentheses as our old friend, the moment of inertia  $I$ . Thus the rotational kinetic energy is

$$K_{\text{rot}} = \frac{1}{2}I\omega^2 \quad (10.9)$$

Rotational kinetic energy of an object with moment of inertia  $I$  and angular velocity  $\omega$



**Video Demo** Canned Food Race



**NOTE** ▶ Rotational kinetic energy is *not* a new form of energy. It is the ordinary kinetic energy of motion, only now expressed in a form that is especially convenient for rotational motion. Comparison with the familiar  $\frac{1}{2}mv^2$  shows again that the moment of inertia  $I$  is the rotational equivalent of mass. ◀

A rolling object, such as a wheel, is undergoing both rotational *and* translational motions. Consequently, its total kinetic energy is the sum of its rotational and translational kinetic energies:

$$K = K_{\text{trans}} + K_{\text{rot}} = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \quad (10.10)$$

This illustrates an important fact: **The kinetic energy of a rolling object is always greater than that of a nonrotating object moving at the same speed.**

◀ **Rotational recharge** A promising new technology would replace spacecraft batteries that need periodic and costly replacement with a *flywheel*—a cylinder rotating at a very high angular speed. Energy from solar panels is used to speed up the flywheel, which stores energy as rotational kinetic energy that can then be converted back into electric energy as needed.

### EXAMPLE 10.5 Where should you trim the weight?

Any time a cyclist stops, it will take energy to get moving again. Using less energy to get going means more energy is available to go farther or go faster, so racing cyclists want their bikes to be as light as possible. It's particularly important to have light-weight wheels, as this example will show. Consider two bikes that have the same total mass but different mass wheels. Bike 1

has a 10.0 kg frame and two 1.00 kg wheels; bike 2 has a 9.00 kg frame and two 1.50 kg wheels. Both bikes thus have the same 12.0 kg total mass. What is the kinetic energy of each bike when they are moving at 12.0 m/s? Most of the weight of the tire and wheel is at the rim, so we can model each wheel as a hoop.



**STRATEGIZE** As the bike moves, the wheels rotate. The bike has translational kinetic energy, but the wheels have both translational and rotational kinetic energy. If the bike is moving at speed  $v$ , we know from Chapter 7 that the wheels rotate at  $\omega = v/R$ , where  $R$  is the radius of a wheel.

**PREPARE** Each bike's frame has only translational kinetic energy  $K_{\text{frame}} = \frac{1}{2}mv^2$ , where  $m$  is the mass of the frame. The kinetic energy of each rolling wheel is given by Equation 10.10. From Table 7.1, we find that  $I$  for a hoop is  $MR^2$ , where  $M$  is the mass of one wheel.

**SOLVE** From Equation 10.10 the kinetic energy of each rolling wheel is

$$K_{\text{wheel}} = \frac{1}{2}Mv^2 + \frac{1}{2}I\omega^2 = \frac{1}{2}Mv^2 + \frac{1}{2} \underbrace{(MR^2)}_I \underbrace{\left(\frac{v}{R}\right)^2}_{\omega^2} = Mv^2$$

Then the total kinetic energy of a bike is

$$K = K_{\text{frame}} + 2K_{\text{wheel}} = \frac{1}{2}mv^2 + 2Mv^2$$

The factor of 2 in the second term occurs because each bike has two wheels. Thus the kinetic energies of the two bikes are

$$K_1 = \frac{1}{2}(10.0 \text{ kg})(12.0 \text{ m/s})^2 + 2(1.00 \text{ kg})(12.0 \text{ m/s})^2 = 1010 \text{ J}$$

$$K_2 = \frac{1}{2}(9.00 \text{ kg})(12.0 \text{ m/s})^2 + 2(1.50 \text{ kg})(12.0 \text{ m/s})^2 = 1080 \text{ J}$$

The kinetic energy of bike 2 is about 7% higher than that of bike 1. Note that the radius of the wheels was not needed in this calculation.

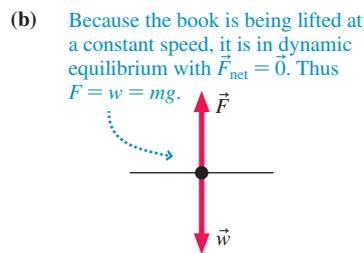
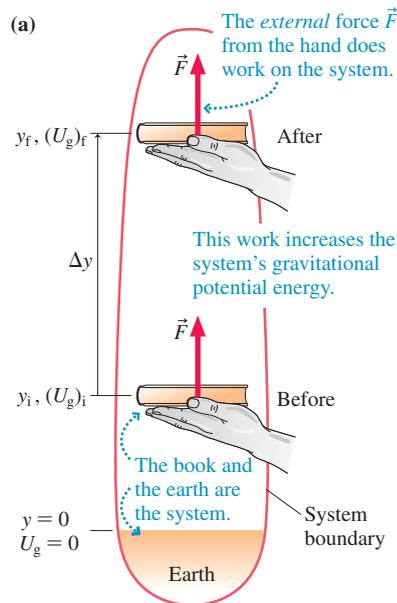
**ASSESS** We were told that it's particularly important for cyclists to have lightweight wheels, so this result makes sense. Both of the bikes in the example have the same total mass, but the one with lighter wheels takes less energy to get moving. Shaving a little extra weight off your bike's wheels is more useful than taking that same weight off the bike's frame.

## 10.4 Potential Energy

When two or more objects in a system interact, it is sometimes possible to *store* energy in the system in a way that the energy can be easily recovered. For instance, the earth and a ball interact by the gravitational force between them. If the ball is lifted up into the air, energy is stored in the ball + earth system, energy that can later be recovered as kinetic energy when the ball is released and falls. Similarly, a spring is a system made up of countless atoms that interact via their atomic “springs.” If we push a box against a spring, energy is stored that can be recovered when the spring later pushes the box across the table. This sort of stored energy is called **potential energy**, since it has the *potential* to be converted into other forms of energy, such as kinetic or thermal energy.

**NOTE** ► Potential energy is really a property of a *system*, but we often speak informally of the potential energy of an *object*. We might say, for instance, that raising a ball increases its potential energy. This is fine as long as we remember that this energy is really stored in the ball + earth system. ◀

The forces due to gravity and springs are special in that they allow for the storage of energy. Other interaction forces do not. When a dog pulls a sled, the sled interacts with the ground via the force of friction, and the work that the dog does on the sled is converted into thermal energy. The energy is *not* stored up for later recovery—it slowly diffuses into the environment and cannot be recovered.

**FIGURE 10.13** Lifting a book increases the system's gravitational potential energy.

## Gravitational Potential Energy

To find an expression for **gravitational potential energy**  $U_g$ , let's consider the system of the book and the earth shown in **FIGURE 10.13a**. The book is lifted at a constant speed from its initial position at  $y_i$  to a final height  $y_f$ . The lifting force of the hand is external to the system and so does work  $W$  on the system, increasing its energy. The book is lifted at a constant speed, so its kinetic energy doesn't change. Because there's no friction, the book's thermal energy doesn't change either. Thus the work done goes entirely into increasing the gravitational potential energy of the system. According to Equation 10.3, the work-energy equation, this can be written as  $\Delta U_g = W$ . Because  $\Delta U_g = (U_g)_f - (U_g)_i$ , Equation 10.3 can be written

$$(U_g)_f = (U_g)_i + W \quad (10.11)$$

The work done is  $W = Fd$ , where  $d = \Delta y = y_f - y_i$  is the vertical distance that the book is lifted. From the free-body diagram of **FIGURE 10.13b**, we see that  $F = mg$ . Thus  $W = mg \Delta y$ , and so

$$(U_g)_f = (U_g)_i + mg \Delta y \quad (10.12)$$

Because our final height was greater than our initial height,  $\Delta y$  is positive and  $(U_g)_f > (U_g)_i$ . **The higher the object is lifted, the greater the gravitational potential energy in the object + earth system.**

We can express Equation 10.12 in terms of the change in potential energy,  $\Delta U_g = (U_g)_f - (U_g)_i$ :

$$\Delta U_g = mg \Delta y \quad (10.13)$$

If we lift a 1.5 kg book up by  $\Delta y = 2.0$  m, we increase the system's gravitational potential energy by  $\Delta U_g = (1.5 \text{ kg})(9.8 \text{ m/s}^2)(2.0 \text{ m}) = 29.4 \text{ J}$ . This increase is *independent* of the book's starting height: The gravitational potential energy increases by 29.4 J whether we lift the book 2.0 m starting at sea level or starting at the top of the Washington Monument. This illustrates an important general fact about *every* form of potential energy: **Only changes in potential energy are significant.**

Because of this fact, we are free to choose a *reference level* where we define  $U_g$  to be zero. Our expression for  $U_g$  is particularly simple if we choose this reference level to be at  $y = 0$ . We then have

$$U_g = mgy \quad (10.14)$$

Gravitational potential energy of an object of mass  $m$  at height  $y$   
(assuming  $U_g = 0$  when the object is at  $y = 0$ )

### EXAMPLE 10.6 Racing up a skyscraper

In the Empire State Building Run-Up, competitors race up the 1576 steps of the Empire State Building, climbing a total vertical distance of 320 m. How much gravitational potential energy does a 70 kg racer gain during this race?



Racers head up the staircase in the Empire State Building Run-Up.

**STRATEGIZE** We'll take the system to be the racer + earth so that we can consider gravitational potential energy.

**PREPARE** We are asked for the change in gravitational potential energy as the racer goes up the stairs, so we need only consider the change in height, which is given. We can use Equation 10.13 to compute the change in potential energy during the run.

**SOLVE** As the racer goes up the stairs, her change in gravitational potential energy is

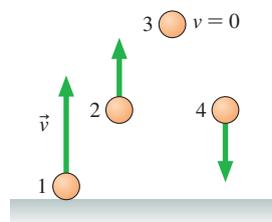
$$\Delta U_g = mg \Delta y = (70 \text{ kg})(9.8 \text{ m/s}^2)(320 \text{ m}) = 2.2 \times 10^5 \text{ J}$$

**ASSESS** This is a lot of energy. According to Table 10.1, it's comparable to the energy of a speeding car. But the difference in height is pretty great, so this seems reasonable. In Chapter 11, we'll consider how much food energy you'd need to consume to fuel this climb.

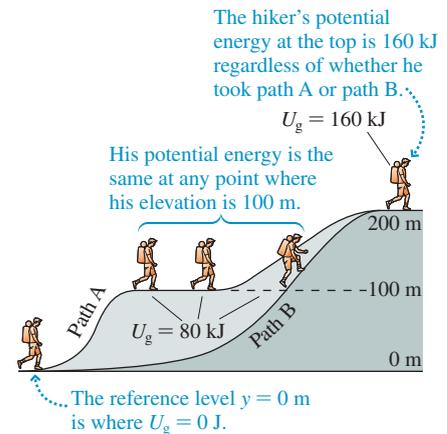
An important conclusion from Equation 10.14 is that gravitational potential energy depends only on the height of the object above the reference level  $y = 0$ , not on the object's horizontal position. To understand why, consider carrying a briefcase while walking on level ground at a constant speed. As shown in the table on page 325, the vertical force of your hand on the briefcase is *perpendicular* to the displacement. No work is done on the briefcase, so its gravitational potential energy remains constant as long as its height above the ground doesn't change.

This idea can be applied to more complicated cases, such as the 82 kg hiker in **FIGURE 10.14**. His gravitational potential energy depends *only* on his height  $y$  above the reference level. Along path A, it's the same value  $U_g = mgy = 80$  kJ at any point where he is at height  $y = 100$  m above the reference level. If he had instead taken path B, his gravitational potential energy at  $y = 100$  m would be the same 80 kJ. It doesn't matter *how* he gets to the 100 m elevation; his potential energy at that height is always the same. **Gravitational potential energy depends only on the height of an object and not on the path the object took to get to that position.** This fact will allow us to use the law of conservation of energy to easily solve a variety of problems that would be very difficult to solve using Newton's laws alone.

**STOP TO THINK 10.4** Rank in order, from largest to smallest, the gravitational potential energies of identical balls 1 through 4.



**FIGURE 10.14** The hiker's gravitational potential energy depends only on his height above the  $y = 0$  m reference level.



## Elastic Potential Energy

Energy can also be stored in a compressed or extended spring as **elastic** (or **spring**) **potential energy**  $U_s$ . We can find out how much energy is stored in a spring by using an external force to slowly compress the spring. This external force does work on the spring, transferring energy to the spring. Since only the elastic potential energy of the spring is changing, Equation 10.3 becomes

$$\Delta U_s = W \quad (10.15)$$

That is, we can find out how much elastic potential energy is stored in the spring by calculating the amount of work needed to compress the spring.

**FIGURE 10.15** shows a spring being compressed by a hand. In **SECTION 8.3** we found that the force the spring exerts on the hand is  $F_s = -k\Delta x$  (Hooke's law), where  $\Delta x$  is the displacement of the end of the spring from its equilibrium position and  $k$  is the spring constant. In Figure 10.15 we have set the origin of our coordinate system at the equilibrium position. The displacement from equilibrium  $\Delta x$  is therefore equal to  $x$ , and the spring force is then  $-kx$ . By Newton's third law, the force that the hand exerts on the spring is thus  $F = +kx$ .

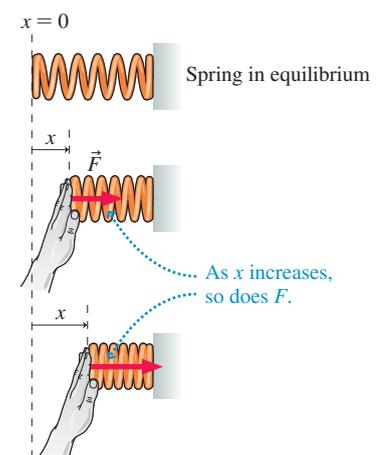
As the hand pushes the end of the spring from its equilibrium position to a final position  $x$ , the applied force increases from 0 to  $kx$ . This is not a constant force, so we can't use Equation 10.5,  $W = Fd$ , to find the work done. However, it seems reasonable to calculate the work by using the *average* force in Equation 10.5. Because the force varies from  $F_i = 0$  to  $F_f = kx$ , the average force used to compress the spring is  $F_{\text{avg}} = \frac{1}{2}kx$ . Thus the work done by the hand is

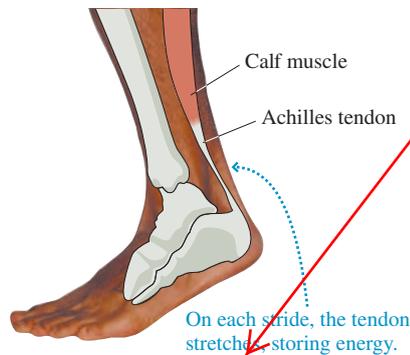
$$W = F_{\text{avg}}d = F_{\text{avg}}x = \left(\frac{1}{2}kx\right)x = \frac{1}{2}kx^2$$

This work is stored as potential energy in the spring, so we can use Equation 10.15 to find that as the spring is compressed, the elastic potential energy increases by

$$\Delta U_s = \frac{1}{2}kx^2$$

**FIGURE 10.15** The force required to compress a spring is not constant.





**Spring in your step** **BIO** When you run, your feet repeatedly stop and start; when your foot strikes the ground, it comes to rest, losing kinetic energy. About 35% of this decrease in kinetic energy is stored as elastic potential energy in the stretchable Achilles tendon of the lower leg. On each plant of the foot, the tendon is stretched, storing some energy. The tendon springs back as you push off the ground again, helping to propel you forward and returning the stored elastic potential energy back to kinetic energy. Recovering this energy that would otherwise be lost and thus increases your efficiency.

Just as in the case of gravitational potential energy, we have found an expression for the *change* in  $U_s$ , not  $U_s$  itself. Again, we are free to set  $U_s = 0$  at any convenient spring extension. An obvious choice is to set  $U_s = 0$  at the point where the spring is in equilibrium, neither compressed nor stretched—that is, at  $x = 0$ . With this choice we have

$$U_s = \frac{1}{2}kx^2 \quad (10.16)$$

Elastic potential energy of a spring displaced a distance  $x$  from equilibrium (assuming  $U_s = 0$  when the end of the spring is at  $x = 0$ )



**NOTE** ▶ Because  $U_s$  depends on the *square* of the displacement  $x$ ,  $U_s$  is the same whether  $x$  is positive (the spring is compressed as in Figure 10.15) or negative (the spring is stretched). ◀

#### EXAMPLE 10.7 Finding the energy stored in a stretched tendon **BIO**

We noted that your Achilles tendon stretches when you run, and this stores some energy—energy that is returned to you when you push off the ground with your foot. **FIGURE 10.16** shows smoothed data for restoring force versus extension for the Achilles tendon and attached muscle in a female subject. When she runs, at one point in her stride the stretch reaches a maximum of 0.50 cm. What energy is stored for this stretch?

**STRATEGIZE** The force increases linearly with extension, so we can model the tendon as a spring. If we find the spring constant, we can compute the stored energy using Equation 10.16.

**PREPARE** The spring constant  $k$  is the slope of the graph in Figure 10.16. At the top right, the line goes through a point that is easy to read off the axes. Using this point, we determine the slope to be

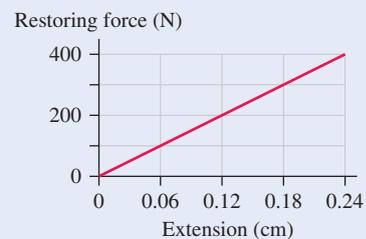
$$k = \text{slope} = \frac{400 \text{ N}}{0.0024 \text{ m}} = 1.67 \times 10^5 \text{ N/m}$$

**SOLVE** With this spring constant, the energy stored for a 0.50 cm (0.0050 m) stretch is

$$U_s = \frac{1}{2}kx^2 = \frac{1}{2}(1.67 \times 10^5 \text{ N/m})(0.0050 \text{ m})^2 = 2.1 \text{ J}$$

**ASSESS** Table 10.1 gives 70 J as the kinetic energy for a person walking; 2.1 J is a few percent of that value. This is reasonable: When you run, the only part of your body that stops and starts is your feet; it's a fraction of this energy that is recovered, and we expect this to be a small fraction of the kinetic energy of your body. However, even this small amount of energy is useful; over a long run of many steps, it will add saving up!

**FIGURE 10.16** Force data for the stretch of the Achilles tendon.



**STOP TO THINK 10.5** When a spring is stretched by 5 cm, its elastic potential energy is 1 J. What will its elastic potential energy be if it is *compressed* by 10 cm?

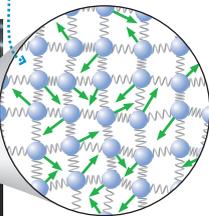
- A. -4 J      B. -2 J      C. 2 J      D. 4 J

## 10.5 Thermal Energy

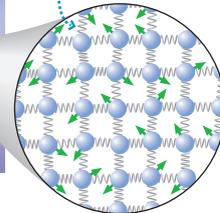
We noted earlier that thermal energy is related to the microscopic motion of the atoms of an object. As **FIGURE 10.17** shows, the atoms in a hot object jiggle around their average positions more than the atoms in a cold object. This has two consequences. First, each atom is on average moving faster in the hot object. This means that each atom has a higher *kinetic energy*. Second, each atom in the hot object tends to stray farther from its equilibrium position, leading to a greater stretching or compressing of the spring-like molecular bonds. This means that each atom has on average a higher *potential energy*. The potential energy stored in any one bond and the kinetic energy of any one atom are both exceedingly small, but there are incredibly many bonds and atoms. The sum of all these microscopic potential and kinetic energies is what we call **thermal energy**  $E_{\text{th}}$ . Increasing an object's thermal energy corresponds to increasing its temperature.

**FIGURE 10.17** An atomic view of thermal energy.

Hot object: Fast-moving atoms have lots of kinetic and elastic potential energy.



Cold object: Slow-moving atoms have little kinetic and elastic potential energy.



**FIGURE 10.18** shows a thermograph of a heavy box and the floor across which it has just been dragged. In this image, cool areas appear in shades of blue and green, warm areas in shades of red. You can clearly see that the patch of floor that the box has been dragged across is much warmer than the box or the rest of the floor. Dragging the box across the floor caused the thermal energy of the system to increase.

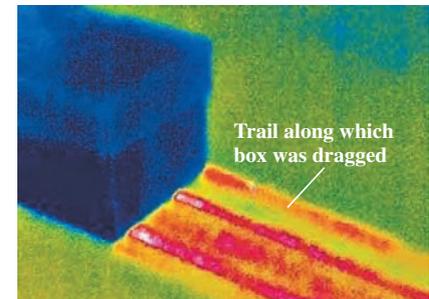
This increase in thermal energy is a general feature of any system in which there is friction between sliding objects. An atomic-level explanation is illustrated in **FIGURE 10.19**. The interaction between the surfaces that leads to the force of friction also leads to increased thermal energy of the sliding surfaces.

We can find a quantitative expression for the change in thermal energy by considering the case of the box pulled by a rope at a constant speed. Let's consider the system to be the box + floor. As the box is pulled across the floor, the rope exerts a constant forward force  $\vec{F}$  on the box, while the friction force  $\vec{f}_k$  exerts a constant force on the box that is directed backward. Because the box moves at a constant speed, the magnitudes of these two forces are equal:  $F = f_k$ . As the box moves through a displacement  $d = \Delta x$ , the rope does work  $W = F\Delta x = f_k\Delta x$  on the box. This work represents energy transferred into the system, so the system's energy must increase. The box's kinetic energy and gravitational potential energy don't change, so the increased energy must be in the form of thermal energy  $E_{\text{th}}$ . Because all of the work into the system shows up as increased thermal energy, we can say that

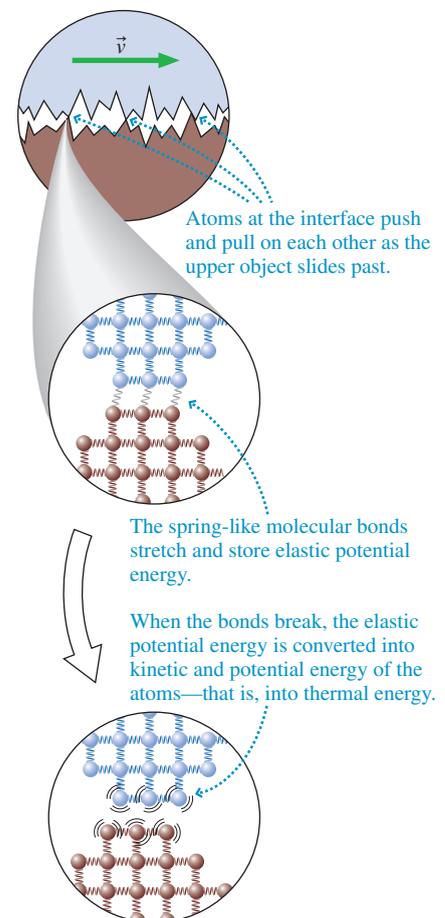
$$\Delta E_{\text{th}} = f_k \Delta x \quad (10.17)$$

The increased thermal energy is distributed between the two surfaces, the box and the floor, the two elements of the system. Although we arrived at Equation 10.17 by considering energy transferred into the system via work done by an external force, the equation is equally valid for the transformation of energy into thermal energy when, for instance, an object slides to a halt on a rough surface.

**FIGURE 10.18** A thermograph of a box that's been dragged across the floor.



**FIGURE 10.19** How friction causes an increase in thermal energy.



PEARSON  
eText  
2.0

Video Demo Figure 10.19

We can do a similar analysis for the drag force. For the case of an object moving through air, water, or another fluid that exerts a drag force, we'll consider the object + fluid to be the system. As the object moves, the drag force  $D$  transforms energy into thermal energy:

$$\Delta E_{\text{th}} = D\Delta x \quad (10.18)$$

The change in thermal energy is mostly a change in the air or the water: Collisions between the object and particles of the fluid cause the particles to move more quickly, thus increasing thermal energy.

The work-energy equation, Equation 10.3, states that the change in the total energy of a system equals the energy transferred to or from the system as work. If we consider only those forms of energy that are typically transformed during the motion of ordinary objects—kinetic energy  $K$ , gravitational and elastic potential energies  $U_g$  and  $U_s$ , and thermal energy  $E_{\text{th}}$ —then the work-energy equation can be written as

$$\Delta K + \Delta U + \Delta E_{\text{th}} = W \quad (10.19)$$

**NOTE** ▶ We've written the change in potential energy as a single potential energy change  $\Delta U$ . Depending on the situation, we can interpret this as a change in gravitational potential energy, a change in elastic potential energy, or a combination of the two. In later chapters, we'll add additional forms of potential energy, and this equation can be adapted accordingly. ◀

#### EXAMPLE 10.8 How much energy does it take to swim a kilometer?

How much energy is required for a 70 kg swimmer to complete a 1.0 km swim at a steady 1.4 m/s? We can assume typical data for a swimmer moving through the water: frontal area  $0.080 \text{ m}^2$ , drag coefficient 0.45, density of water  $1000 \text{ kg/m}^3$ .

**STRATEGIZE** Moving through the water at a constant speed means continuously replacing the energy that drag transforms into thermal energy. We can compute the change in thermal energy during the swim to find energy that the swimmer must supply. We can find the change in thermal energy using Equation 10.18.

**PREPARE** We'll need to compute the drag force before we can find the necessary energy. A swimmer moving through the water has a very large Reynold's number, so we can use Equation 5.b to compute the drag force, as shown in the next column:

$$\begin{aligned} D &= \frac{1}{2}C_D\rho Av^2 \\ &= \frac{1}{2}(0.45)(1000 \text{ kg/m}^3)(0.080 \text{ m}^2)(1.4 \text{ m/s})^2 = 35 \text{ N} \end{aligned}$$

**SOLVE** With the drag force in hand, we can find the energy converted to thermal energy:

$$\Delta E_{\text{th}} = D\Delta x = (35 \text{ N})(1000 \text{ m}) = 3.5 \times 10^4 \text{ J}$$

This is the energy that the swimmer must supply, which is all converted to thermal energy. The net effect of swimming laps is to warm up the water in the pool!

**ASSESS** This is a lot of energy, about one-sixth of the energy needed to climb the Empire State Building, which seems reasonable.

We've done a few calculations of the energy required for certain tasks. But there's another factor to consider—efficiency. How much energy would your body actually *use* in completing these tasks? The swimmer needs to supply  $3.5 \times 10^4 \text{ J}$  to move through the water. But how much metabolic energy will it cost the swimmer to provide this energy? Swimming is, for humans, a reasonably inefficient form of locomotion, so the energy used by the swimmer is quite a bit greater than the value we found. We'll return to this issue in Chapter 11.

**STOP TO THINK 10.6** A block with an initial kinetic energy of 4.0 J comes to rest after sliding 1.0 m. How far would the block slide if it had 8.0 J of initial kinetic energy?

- A. 1.4 m      B. 2.0 m      C. 3.0 m      D. 4.0 m

## 10.6 Conservation of Energy

Just as for momentum conservation, we will develop a before-and-after perspective for energy conservation. We'll limit our consideration for now to kinetic energy, potential energy (both gravitational and elastic), thermal energy, and work. We then note that  $\Delta K = K_f - K_i$  and  $\Delta U = U_f - U_i$ . Now we can rewrite Equation 10.19 as a rule that we can use to solve problems:

$$K_f + U_f + \Delta E_{\text{th}} = K_i + U_i + W \quad (10.20)$$

Before-and-after work-energy equation

Equation 10.20 states that a system's final energy, including any change in the system's thermal energy, equals its initial energy plus any energy added to the system as work. This equation is the basis for a powerful problem-solving approach.

**NOTE** ▶ We don't write  $\Delta E_{\text{th}}$  as  $(E_{\text{th}})_f - (E_{\text{th}})_i$  in Equation 10.20 because the initial and final values of the thermal energy are typically unknown; only their difference  $\Delta E_{\text{th}}$  can be measured. ◀

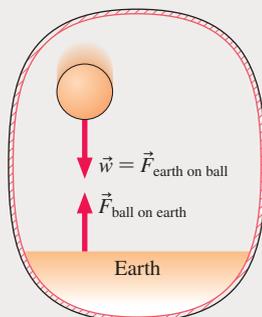
In Section 10.1 we introduced the idea of an isolated system—one in which no work is done on the system and no energy is transferred into or out of the system. In that case,  $W = 0$  in Equation 10.20, so the final energy, including any change in thermal energy, equals the initial energy:

$$K_f + U_f + \Delta E_{\text{th}} = K_i + U_i$$

The following table shows how to choose an isolated system for common situations.

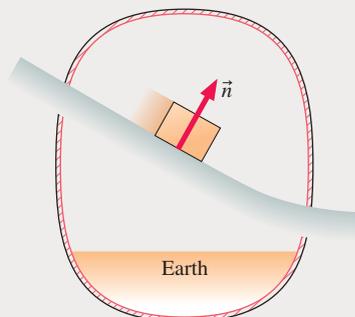
### KEY CONCEPT Choosing an isolated system

An object in free fall



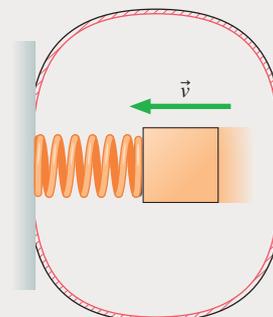
We choose the ball *and* the earth as the system, so that the forces between them are *internal* forces. There are no external forces to do work, so the system is isolated.

An object sliding down a frictionless ramp



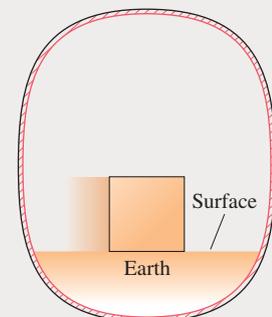
The external force the ramp exerts on the object is perpendicular to the motion, and so does no work. The object and the earth together form an isolated system.

An object compressing a spring



We choose the object and the spring to be the system. The forces between them are internal forces, so no work is done.

An object sliding along a surface with friction



The block and the surface interact via kinetic friction forces, but these forces are internal to the system. There are no external forces to do work, so the system is isolated.

**STOP TO THINK 10.7** A student is sliding down a rope, using friction to keep her moving at a constant speed. How do you choose the system so that it is isolated?

### Using the Law of Conservation of Energy

Now that we have mathematical expressions for different forms of energy and a general before-and-after equation expressing the law of conservation of energy, we have all the tools we need to formulate a problem-solving approach. We'll sketch out the details and then use it to solve a range of problems.



Video Demo Breaking Boards



Video Demo Chin Basher?

Key Concept figures encourage students to actively engage with key or complex figures by asking them to reason with a related Stop To Think question.



**Spring into action** **BIO** A locust can jump as far as 1 meter, an impressive distance for such a small animal. To make such a jump, its legs must extend much more rapidly than muscles can ordinarily contract. Thus, instead of using its muscles to make the jump directly, the locust uses them to more slowly stretch an internal “spring” near its knee joint. This stores elastic potential energy in the spring. When the muscles relax, the spring is suddenly released, and its energy is rapidly converted into kinetic energy of the insect.

**Bio Example with real data**

### PROBLEM-SOLVING APPROACH 10.1 Conservation of energy problems

The work-energy equation and the law of conservation of energy relate a system’s *final* energy to its *initial* energy. We can solve for initial and final heights, speeds, and displacements from these energies.

**STRATEGIZE** The first step in a conservation of energy problem is to choose the system. This means thinking about the forces and the energies involved. We’ll consider the situation before and after a process or an interaction, so we must also decide on the initial and final states.

**PREPARE** As we did for momentum problems, we’ll start with a before-and-after visual overview, as outlined in Tactics Box 9.1. Note the known quantities, and identify what you’re trying to find.

**SOLVE** Apply Equation 10.20:

$$K_f + U_f + \Delta E_{\text{th}} = K_i + U_i + W$$

Start with this general equation, then specialize to the case at hand:

- Use the appropriate form or forms of potential energy.
- If the system is isolated, no work is done. Set  $W = 0$ .
- If there is no friction, drag, or similar force, set  $\Delta E_{\text{th}} = 0$ .

Depending on the problem, you’ll need to calculate the initial and/or final values of these energies. You can then solve for the unknown energies, and from these any unknown speeds (from  $K$ ), heights and distances (from  $U_g$  and  $U_s$ ), or displacements, friction, or drag forces.

**ASSESS** Check the signs of your energies. Kinetic energy is always positive, as is the change in thermal energy. Check that your result has the correct units, is reasonable, and answers the question.

Exercise 23

### EXAMPLE 10.9 How high can the locust jump? **BIO**

As we noted, a desert locust is an excellent jumper. Suppose a 2.0 g locust leaps straight up, leaving the ground at 3.1 m/s, a speed that a desert locust can easily reach.

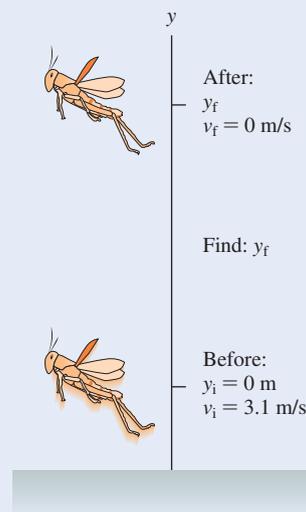
- a. If we ignore the drag force, how high will the locust jump?
- b. If 20% of the initial kinetic energy is lost to drag, how high will the locust jump?

**STRATEGIZE** We don’t know how much the locust extends its legs as it pushes off the ground, or other details of this phase of the motion. For us, the problem starts when the locust is leaving the ground at its maximum speed. We’ll then consider the locust’s motion through the air, and take our final point to be when the locust is at its highest point. Once the locust leaves the ground, the locust + earth + air form an isolated system.

**PREPARE** The before-and-after visual overview is shown in **FIGURE 10.20**. We’ll describe the situation using Equation 10.20 with  $W = 0$ , because we’ve identified an isolated system. For the initial and final points we chose our working equation becomes

$$K_f + (U_g)_f + \Delta E_{\text{th}} = K_i + (U_g)_i$$

**FIGURE 10.20** Visual overview of the locust’s jump.



**SOLVE** a. For this part, we ignore drag, so  $\Delta E_{\text{th}} = 0$ . We then substitute expressions for the various forms of energy to find

$$\frac{1}{2}mv_f^2 + mgy_f = \frac{1}{2}mv_i^2 + mgy_i$$

The mass appears in every term, so we can cancel out this factor. We'll take our starting position to be  $y_i = 0$  and note that the final velocity  $v_f = 0$  to simplify further:

$$gy_f = \frac{1}{2}v_i^2$$

$$y_f = \frac{v_i^2}{2g} = \frac{(3.1 \text{ m/s})^2}{2(9.8 \text{ m/s}^2)} = 0.49 \text{ m}$$

b. For this part of the problem, we assume that 20% of the initial kinetic energy is lost to drag. The "lost" energy is transformed

into thermal energy, so  $\Delta E_{\text{th}} = (0.20)K_i$ . Our working equation then becomes

$$K_f + (U_g)_f + (0.20)K_i = K_i + (U_g)_i$$

$$K_f + (U_g)_f = (0.80)K_i + (U_g)_i$$

Simplifying as we did before, we find

$$gy_f = (0.80)\frac{1}{2}v_i^2$$

$$y_f = (0.80)\frac{v_i^2}{2g} = (0.80)\frac{(3.1 \text{ m/s})^2}{2(9.8 \text{ m/s}^2)} = 0.39 \text{ m}$$

**ASSESS** We noted that the desert locust can jump a horizontal distance of 1 m, so a vertical leap of half a meter seems reasonable. Notice that the locust's mass didn't enter into our calculation; this isn't a surprise, given that the motion is free fall. This also gives us confidence in our solution.

### EXAMPLE 10.10 To push or not to push?

The Summit Plummet is an extreme water slide—one of the steepest and fastest in the world. Riders drop 36 m from the start until they hit a run-out at the bottom. If you give yourself a good push at the start, so that you begin your plunge moving at 2.0 m/s, how fast are you moving when you get to the bottom? How fast would you be moving if you skipped the push? The slide is steep and slippery, so assume that you can ignore friction and drag forces.

**STRATEGIZE** We'll take the system to be the rider + earth. The initial state has the rider moving at 2.0 m/s at a height of 36 m above the bottom of the slide; the final state is at the bottom.

**PREPARE** The visual overview in **FIGURE 10.21** shows the initial and final states and the slide in between. The exact shape of the slide doesn't matter; we care only about the difference in height. We'll describe the situation using Equation 10.20 with  $W = 0$ , because this is an isolated system—once you start the ride, no

one is giving you a push! There is no elastic potential energy, only gravitational, and we can ignore friction, so our working equation becomes

$$K_f + (U_g)_f = K_i + (U_g)_i$$

**SOLVE** If we write our working equation in terms of the change in potential energy, we can express this in terms of the change in height using Equation 10.13:

$$K_f = K_i + ((U_g)_i - (U_g)_f) = K_i + \Delta U_g = K_i + mg\Delta y$$

We rewrite the kinetic energy in terms of speed and then solve for the final speed:

$$\frac{1}{2}mv_f^2 = \frac{1}{2}mv_i^2 + mg\Delta y$$

$$v_f = \sqrt{v_i^2 + 2g\Delta y} = \sqrt{(2.0 \text{ m/s})^2 + 2(9.8 \text{ m/s}^2)(36 \text{ m})}$$

$$= 27 \text{ m/s}$$

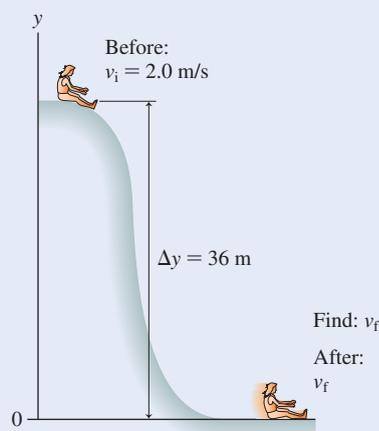
This is pretty speedy! Now, suppose you skip the initial push. How much does this change the final result? The calculation is the same but with  $v_i = 0$ :

$$v_f = \sqrt{2g\Delta y} = \sqrt{2(9.8 \text{ m/s}^2)(36 \text{ m})} = 27 \text{ m/s}$$

We get exactly the same result to 2 significant figures: greater precision is not warranted given the approximations we've made. Push or not—the final result is about the same! Most of your energy at the end of the ride comes from the change in potential energy, not your initial push.

**ASSESS** We weren't given the mass of the rider, but the mass canceled along the way, which gives us confidence in the process. The final result, 27 m/s (about 60 mph), is pretty fast. But this is an extreme slide, and a website for this slide claims that you can expect to reach 60 mph, so the result of the calculation is reasonable, even if actually riding the slide isn't.

**FIGURE 10.21** Visual overview of the trip down the water slide.



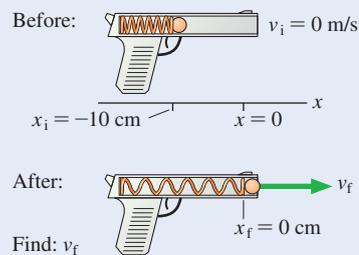
**EXAMPLE 10.11** Speed of a spring-launched ball

A spring-loaded toy gun is used to launch a 10 g plastic ball. The spring, which has a spring constant of 10 N/m, is compressed by 10 cm as the ball is pushed into the barrel. When the trigger is pulled, the spring is released and shoots the ball back out horizontally. What is the ball's speed as it leaves the barrel? Assume that friction is negligible.

**STRATEGIZE** Let's take the system to be the ball + spring. The initial state has the compressed spring touching the stationary ball; the final state is the expanded spring and the ball in motion.

**PREPARE** The visual overview is shown in **FIGURE 10.22**. We have chosen the origin of the coordinate system to be the

**FIGURE 10.22** Before-and-after visual overview of a ball being shot out of a spring-loaded toy gun.



equilibrium position of the free end of the spring, making  $x_i = -10$  cm and  $x_f = 0$  cm. Work is done on the spring during the compression, but during the time the spring is expanding, the ball + spring is an isolated system, so  $W = 0$ . We are ignoring friction, so  $\Delta E_{\text{th}} = 0$ . Because the launch is horizontal, we can ignore changes in gravitational potential energy. With these assumptions, the work-energy equation becomes

$$K_f + (U_s)_f = K_i + (U_s)_i$$

**SOLVE** We can use expressions for kinetic energy and elastic potential energy to rewrite this equation as

$$\frac{1}{2}mv_f^2 + \frac{1}{2}kx_f^2 = \frac{1}{2}mv_i^2 + \frac{1}{2}kx_i^2$$

We know that  $x_f = 0$  m and  $v_i = 0$  m/s, so this simplifies to

$$\frac{1}{2}mv_f^2 = \frac{1}{2}kx_i^2$$

It is now straightforward to solve for the ball's speed:

$$v_f = \sqrt{\frac{kx_i^2}{m}} = \sqrt{\frac{(10 \text{ N/m})(-0.10 \text{ m})^2}{0.010 \text{ kg}}} = 3.2 \text{ m/s}$$

**ASSESS** The ball moves pretty slowly, which we expect for a toy gun. Our result seems reasonable.

This is not a problem that we could have easily solved with Newton's laws. The acceleration is not constant, and we have not learned how to handle the kinematics of variable acceleration. But with conservation of energy, this was a straightforward problem.

**EXAMPLE 10.12** The thermal energy of a trip down a slide

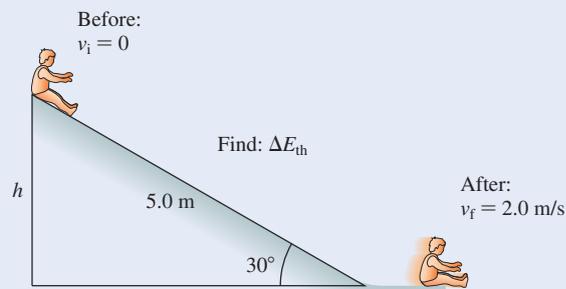
Quinn is at rest at the top of a playground slide. The main part of the slide is 5.0 m long, and it is tipped at a  $30^\circ$  angle. Quinn starts sliding, moving down the tipped section, and then the slide levels out so that he leaves the slide at 2.0 m/s, moving horizontally. If Quinn's mass is 24 kg, how much thermal energy is deposited in his trousers and in the slide?

**STRATEGIZE** We'll choose Quinn + earth + slide to be the system. The initial point will be when Quinn is motionless at the top of the slide; the final point will be when Quinn has descended the slide and is moving off the end. As Quinn goes down the slide, potential energy decreases and kinetic energy increases. But there is clearly friction, so that his speed is slower than it would be otherwise. Some of the energy is transformed into thermal energy of his trousers and the slide, internal to the system. It's this change in thermal energy that we'll solve for.

**PREPARE** The visual overview in **FIGURE 10.23** shows the initial and final points of the motion. We've chosen an isolated system, so  $W = 0$ . The only form of potential energy is gravitational potential energy, so the work-energy equation reduces to

$$K_f + (U_g)_f + \Delta E_{\text{th}} = K_i + (U_g)_i$$

**FIGURE 10.23** Visual overview for motion down the slide.



We can find the difference in the vertical position  $h$  from the geometry of the slide:

$$h = (5.0 \text{ m})\sin 30^\circ = 2.5 \text{ m}$$

We'll take the initial height as  $y_i = h$ , the final height as  $y_f = 0$ , so  $(U_g)_f = 0$ . Quinn starts at rest, so  $K_i = 0$ .

**SOLVE** With all of these parts in hand we can simplify the work-energy equation further and then solve for  $\Delta E_{\text{th}}$ :

$$\begin{aligned}\Delta E_{\text{th}} &= (U_{\text{g}})_i - K_f \\ &= mgy - \frac{1}{2}mv_f^2 \\ &= 588 \text{ J} - 48 \text{ J} = 540 \text{ J}\end{aligned}$$

We've found values for the change in potential energy and the final kinetic energy so that you can see the relative magnitudes.

The values in the problem are typical values for a slide—about an 8 foot drop, kids launched off the end at a slow jogging pace. During the slide, the most important energy transformation that takes place is the increase in thermal energy. The slide is mostly about warming things up rather than getting kids up to speed!

**ASSESS** If you remember going down the slide as a child, you no doubt remember the appreciable warming during the motion, so our result makes sense.

### SYNTHESIS 10.1 Energy and its conservation

The energies present in an isolated system can transform from one kind into another, but the total energy is *conserved*. The unit of all types of energy is the **joule (J)**.

**Kinetic energy** is the energy of motion.

$$K = \frac{1}{2}mv^2$$

Mass (kg)  
Velocity (m/s)

**Gravitational potential energy** is stored energy associated with an object's height above the ground.

$$U_{\text{g}} = mgy$$

Free-fall acceleration  
Mass (kg)  
Height (m) above a reference level  $y = 0$

**Elastic potential energy** is stored energy associated with a stretched or compressed spring.

$$U_{\text{s}} = \frac{1}{2}kx^2$$

Spring constant (N/m)  
Displacement of end of spring from equilibrium (m)

**Work** is the transfer of energy into or out of a system by an external force:

$$W = F_{\parallel}d$$

Work into (+) or out of (-) a system  
Force parallel to motion  
Displacement

The before-and-after work-energy equation captures the **law of conservation of energy**:

$$K_f + U_f + \Delta E_{\text{th}} = K_i + U_i + W$$

Final kinetic and potential energy plus change in thermal energy  
Initial kinetic and potential energy plus energy transferred by work

**STOP TO THINK 10.8** At the water park, Katie slides down each of the frictionless slides shown. At the top, she is given a push so that she has the same initial speed each time. At the bottom of which slide is she moving the fastest?



- A. Slide A      B. Slide B  
C. Slide C      D. Her speed is the same at the bottom of all three slides.



**Video Demo** Rotational Motion: Loop-the-Loop

## 10.7 Energy Diagrams

Energy is a central concept in physics, but it's also crucial for understanding chemistry, biology, and other sciences. In this section and the following one, we'll develop different means of describing energy that connect to these other subjects that you are likely studying or have studied. It's not that energy is different in chemistry, but the way it is treated, the language used to describe it, may be.

### • 10.7: Energy Diagrams • 10.8: Molecular Bonds and Chemical Energy

There is now a greater emphasis on the connections between Physics and the other sciences (namely life sciences but this is an example of Chemistry).

In this section, we'll consider isolated systems for which there is no friction or drag. In this case, there is no work and there is no change in thermal energy, so the work-energy equation becomes

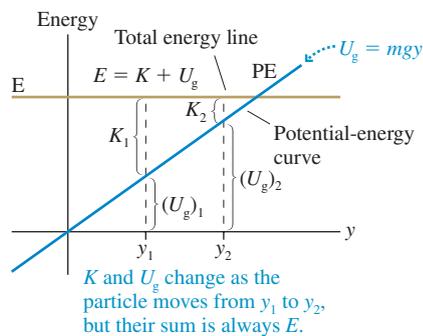
$$K_f + U_f = K_i + U_i$$

In other words, the sum of the kinetic and potential energy is constant. We'll define the total energy  $E$  as the sum of these two quantities. For the systems we consider in this section,

$$E = K + U = \text{constant}$$

Kinetic energy depends on an object's speed, but potential energy depends on its *position*. A tossed ball's gravitational potential energy depends on its height  $y$ , while the elastic potential energy of a compressed spring depends on the displacement  $x$ . Other potential energies also depend in some way on position. A graph showing a system's potential energy and total energy as a function of position is called an **energy diagram**. We'll spend some time learning about energy diagrams so that we can use them to think about bonds and chemical reactions in the next section.

**FIGURE 10.24** The energy diagram of a ball in free fall.

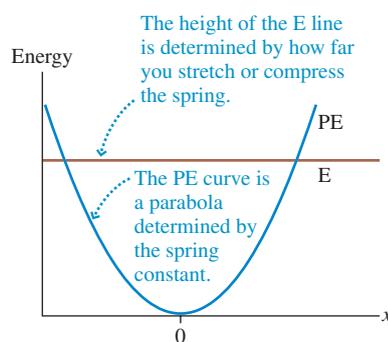


**FIGURE 10.24** is the energy diagram of a ball in free fall. This is a bit different from most graphs we've seen. It doesn't include time; the horizontal axis is the vertical position  $y$ , and the vertical axis represents energy. The lines on the graph show different energies as a function of the vertical position. The gravitational potential energy increases with the vertical position; the mathematical relationship is  $U_g = mgy$ , and a graph of  $mgy$  versus  $y$  is a straight line through the origin with slope  $mg$ . The resulting blue *potential-energy curve* is labeled PE. The tan line labeled E is the system's total energy. This line is always horizontal because the sum of kinetic and potential energy is the same at every point.

Suppose we consider a ball that is at a vertical position  $y_1$  and is moving upward. When the ball is at height  $y_1$ , the distance from the axis up to the potential-energy curve is the potential energy  $(U_g)_1$  at that position. Because  $K_1 = E - (U_g)_1$ , the kinetic energy is represented graphically as the distance between the potential-energy curve and the total energy line. Now, the ball continues to rise. Some time later it is at height  $y_2$ . The energy diagram shows that the potential energy  $(U_g)_2$  has increased while the ball's kinetic energy  $K_2$  has decreased, as we know must be the case. Kinetic energy has been transformed into potential energy, but their sum has not changed.

**NOTE** ▶ In graphs like this, the potential-energy curve PE is determined by the physical properties of the system—for example, the mass or the spring constant. But the total energy line E is under your control. If you change the *initial conditions*, such as throwing the ball upward with a different speed or compressing a spring by a different amount, the total energy line will appear at a different position. We can thus use an energy diagram to see how changing the initial conditions affects the subsequent motion. ◀

**FIGURE 10.25** The energy diagram of a mass on a horizontal spring.

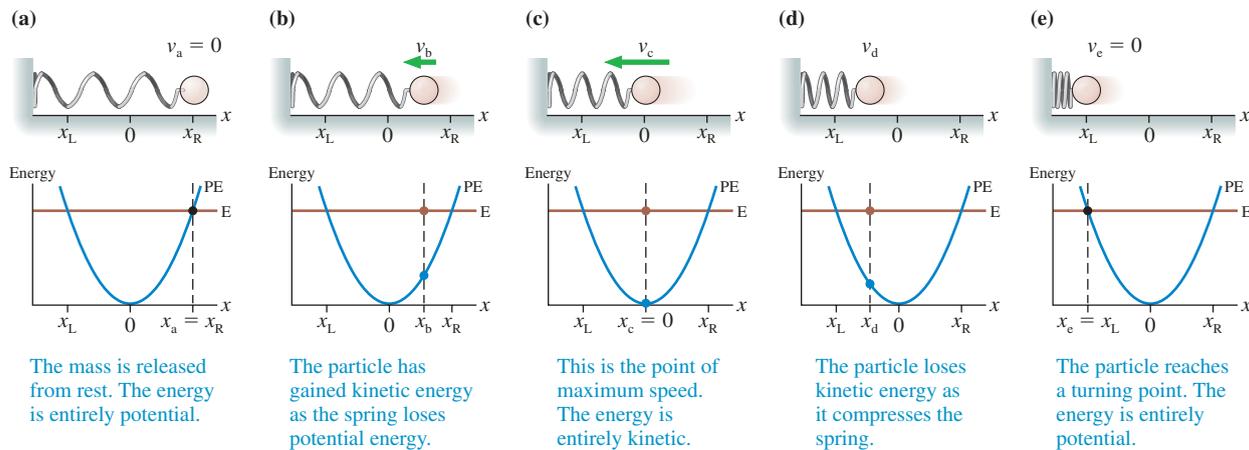


**FIGURE 10.25** is the energy diagram of a mass on a horizontal spring. In this case, the blue potential-energy curve  $U_s = \frac{1}{2}kx^2$  is a parabola centered at  $x = 0$ , the equilibrium position of the end of the spring. The blue PE curve is determined by the spring constant; we can't change it. But we can set the tan E line to any height we wish by stretching or compressing the spring to different lengths. The figure shows one possible E line.

Suppose you pull the mass out to position  $x_R$  and release it from rest. **FIGURE 10.26** shows a five-frame “movie” of the subsequent motion. Initially, in frame a, the energy is entirely potential—the energy of a stretched spring—so the E line has been drawn to cross the PE line at  $x_a = x_R$ . This is the graphical statement that initially  $E = U_s$  and  $K = 0$ .

The restoring force pulls the mass toward the origin. In frame b, where the mass has reached  $x_b$ , the potential energy has decreased while the kinetic energy—the

FIGURE 10.26 A five-frame movie of a mass oscillating on a spring.



distance *above* the PE curve—has increased. Notice that the total energy—the brown dot—hasn't changed. The mass continues to speed up until it reaches maximum speed at  $x_c = 0$ , where the PE curve is at a minimum and the distance above the PE curve is maximum. At position  $x_d$ , the mass has started to slow down as it begins to transform kinetic energy back into elastic potential energy.

The mass continues moving to the left until, in frame e, it reaches position  $x_L$ , where the total energy line crosses the potential-energy curve. This point, where  $K = 0$  and the energy is entirely potential, is a *turning point* where the mass reverses direction. A mass would need negative kinetic energy to be to the left of  $x_L$ , and that's not physically possible. You should be able to see, from the energy diagram, that the mass will *oscillate* back and forth between positions  $x_L$  and  $x_R$ , having maximum kinetic energy (and thus maximum speed) each time it passes through  $x = 0$ .

Now, let's consider a different initial condition. Suppose you pull the mass out to a greater initial distance. You've increased the potential energy in the system, and thus the total energy. The tan E line is now at a greater height, and it will intersect the PE graph at two points that are farther from the equilibrium point. With this new initial condition, the mass will oscillate back and forth between two points at a greater distance from equilibrium.

## Interpreting Energy Diagrams

The lessons we learn from Figure 10.26 are true for any energy diagram:

- At any position, the distance from the axis to the PE curve is the object's potential energy. The distance from the PE curve to the E line is its kinetic energy.
- The object cannot be at a position where the PE curve is above the E line.
- A position where the E line crosses the PE curve is a turning point where the object reverses direction.
- If the E line crosses the PE curve at two positions, the object will oscillate between those two positions. Its speed will be maximum at the position where the PE curve is a minimum.

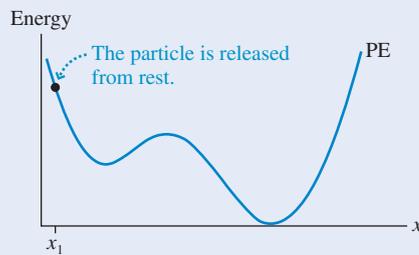
### CONCEPTUAL EXAMPLE 10.13 Interpreting an energy diagram

FIGURE 10.27 is a more general energy diagram. We don't know how this potential energy was created, but we can still use the energy diagram to understand how a particle with this potential energy will move. Suppose a particle begins at rest at the position shown in the figure and is then released. Describe its subsequent motion.

**REASON** We've added details to the graph and sketched out details of the motion in FIGURE 10.28. The particle is at rest at the starting point, so  $K = 0$  and the total energy is equal to the potential energy. We can draw the E line through this point. The PE curve tells us the particle's potential energy at each position.

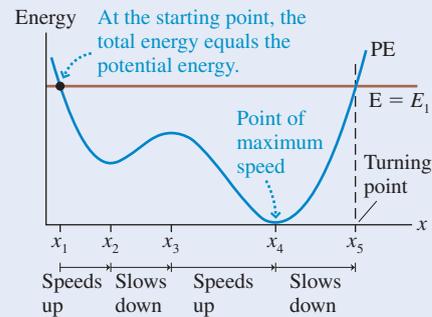
*Continued*

FIGURE 10.27 A more general energy diagram.



The distance between the PE curve and the E line is the particle's kinetic energy. The particle cannot move to the left because that would require the PE curve to go above the E line, so it begins moving to the right. The particle speeds up from  $x_1$  to  $x_2$  because  $U$  decreases and thus  $K$  must increase. It then slows down (but doesn't stop) from  $x_2$  to  $x_3$  as it goes over the "potential-energy hill." It speeds up after  $x_3$  until it reaches maximum speed at  $x_4$ , where the PE curve is a minimum. The particle then steadily slows from  $x_4$  to  $x_5$  as kinetic energy is transformed into an increasing potential energy. Position  $x_5$  is a turning point, a position where the E line crosses the PE curve. The particle is

FIGURE 10.28 The motion of the particle in the potential of Figure 10.27.



instantaneously at rest and then reverses direction. Because the E line crosses the PE curve at both  $x_1$  and  $x_5$  the particle will oscillate back and forth between these two points, speeding up and slowing down as described.

**ASSESS** Our results make sense. The particle is moving fastest where the PE line is lowest, as it must, and it turns around where the E and PE lines cross, meaning  $K = 0$  and the particle is at rest.

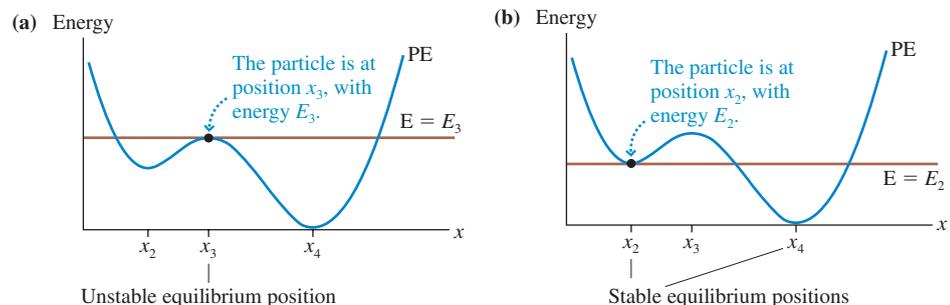
### Equilibrium Positions

Positions  $x_2$ ,  $x_3$ , and  $x_4$  in Figure 10.28, where the potential energy has a local minimum or maximum, are special positions. Consider the particle at position  $x_3$  with energy  $E_3$  in FIGURE 10.29a. Its energy is entirely potential energy and its kinetic energy is zero. It must be *at rest*—in equilibrium.

But suppose this particle is slightly disturbed—a tiny push to the right or left—giving it a very small amount of kinetic energy. The particle will begin to move away from  $x_3$ , moving away faster and faster because the potential energy decreases—and thus kinetic energy increases—on both sides of  $x_3$ . The situation is analogous to trying to balance a marble on the top of a hill; we can do so if the positioning is absolutely perfect, but any small displacement or disturbance will cause the marble to roll down the hill. An equilibrium position for which any small disturbance drives the particle away from equilibrium is called a point of **unstable equilibrium**. **Any local maximum in the PE curve is a point of unstable equilibrium.**

In contrast, consider a particle at position  $x_2$  with energy  $E_2$  in FIGURE 10.29b. Its kinetic energy is zero and, as we just discussed, the particle must be at rest. Position  $x_2$  is also an equilibrium position, this time for a particle with energy  $E_2$ . What happens if this particle is slightly disturbed, raising the E line by a very small amount? Now the E line will intersect the PE curve just slightly to either side of  $x_2$ . These

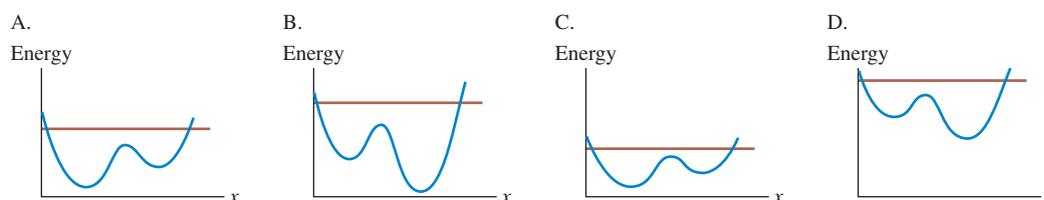
FIGURE 10.29 Positions of (a) unstable and (b) stable equilibrium.



intersections are turning points, so the particle will undergo a very small oscillation centered on  $x_2$ , rather like a marble in the bottom of a bowl. An equilibrium for which a small disturbance causes only a small oscillation around the equilibrium position is called a point of **stable equilibrium**. You should recognize that **any local minimum in the PE curve is a point of stable equilibrium**. Position  $x_4$  is also a point of stable equilibrium—in this case for a particle with  $E_4 = 0$ .

In the next section, we'll see how ideas about stable and unstable equilibrium help us understand molecular bonds and chemical reactions.

**STOP TO THINK 10.9** The figures below show blue PE curves and tan E lines for four identical particles. Which particle has the highest maximum speed?



## 10.8 Molecular Bonds and Chemical Energy

With few exceptions, the materials of everyday life are made of atoms bound together into larger molecules. The *molecular bond* that holds two atoms together is an electric interaction between the atoms' negative electrons and positive nuclei. The electric force, like the gravitational force, is a force that can store energy. Fortunately, we don't need to know any details about electric potential energy—a topic we'll take up in Chapter 21—to deduce the energy diagram of a molecular bond.

We've noted that molecular bonds are somewhat analogous to springs: The normal force when an object rests on a table arises from the compression of spring-like bonds, and thermal energy is due, in part, to spring-like vibrations of atoms around an equilibrium position. This suggests that the energy diagram of two atoms connected by a molecular bond should look similar to the Figure 10.25 energy diagram of a mass on a spring.

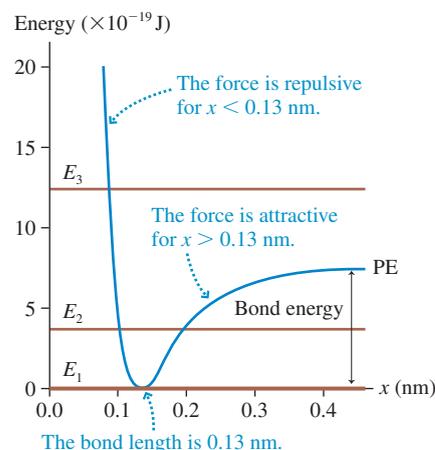
**FIGURE 10.30** shows the experimentally determined energy diagram of the diatomic molecule HCl (hydrogen chloride). Distance  $x$  is the *atomic separation*, the distance between the hydrogen and chlorine atoms. Note the very small distances:  $1 \text{ nm} = 10^{-9} \text{ m}$ . The left side of the PE curve looks very much like the PE curve of a spring; the right side starts out similar to the PE curve of a spring and then levels off. We can interpret and understand this potential-energy diagram by using what we learned in Section 10.7.

There is a clear minimum of the potential energy curve, a position of stable equilibrium. We've set the potential energy equal to zero at this position. If the total energy is zero as well, as is the case for the total energy line  $E_1$ , the atoms will rest at this separation. They will have no kinetic energy—no molecular vibration—and will form a molecule with an atomic separation of  $0.13 \text{ nm}$ . This is the **bond length** of HCl.

If we try to push the atoms closer together, the potential energy rises very rapidly. Physically, this is an electric repulsion between the negative electrons orbiting each atom, but it's analogous to the increasingly strong repulsive force we get when we compress a spring. Thus the PE curve to the left of the equilibrium position looks very much like the PE curve of a spring.

There are also attractive forces between two atoms. These can be the attractive force between two oppositely charged ions, as is the case for HCl; the attractive forces of covalent bonds when electrons are shared; or even weak *polarization forces* that are related to the static electricity force by which a comb that has been

**FIGURE 10.30** The energy diagram of the diatomic molecule HCl.



brushed through your hair attracts small pieces of paper. For any of these, the attractive force resists if we try to pull the atoms apart—analogue to stretching a spring—and thus potential energy increases to the right. The equilibrium position, with minimum potential energy, is the separation at which the repulsive force between electrons and the attractive force are exactly balanced.

The repulsive force gets stronger as we push the atoms closer together, but the attractive force gets *weaker* as we pull them farther apart. If we pull too hard, the bond breaks and the atoms come apart. Consequently, the PE curve becomes *less steep* as  $x$  increases, eventually leveling off when the atoms are so far apart that they cease interacting with each other. This difference between the attractive and repulsive forces explains the asymmetric PE curve in Figure 10.30.

It turns out, for quantum physics reasons, that a molecule cannot have  $E = 0$  and thus cannot simply rest at the equilibrium position. By requiring the molecule to have some energy, as for the total energy line  $E_2$  in Figure 10.30, we see that the atoms will oscillate back and forth between two turning points where the total energy line crosses the PE curve. This is a *molecular vibration*, and atoms held together by a molecular bond are constantly vibrating. For an HCl molecule with energy as  $E_2 = 3.5 \times 10^{-19}$  J, illustrated, the distance between the atoms oscillates between roughly 0.10 nm and 0.18 nm.

As we've seen, an object's thermal energy is the sum of the energies of all the moving and vibrating atoms and molecules. Increasing a system's thermal energy increases the energy of each molecule. If we imagine the line  $E_2$  in Figure 10.30 being raised, we can see that increased thermal energy, and thus increased temperature, corresponds to molecules vibrating more vigorously, with larger amplitude and more kinetic energy.

Suppose the molecule's energy is increased to  $E_3 = 12.5 \times 10^{-19}$  J. This could happen, for example, if the molecule absorbs some light. We can see from the energy diagram that the molecules will keep moving apart. By raising the molecule's energy to  $E_3$ , we've broken the molecular bond. The breaking of molecular bonds by the absorption of light is called **photodissociation**. Light-mediated reactions, from sun tanning to photosynthesis to vision, are very similar to photodissociation but involve conformational changes in macromolecules—which require energy—rather than the actual breaking of bonds.

The **bond energy** is the minimum energy required to break a bond when the molecule's energy corresponds to a “room temperature” of 25°C. Bond energy is shown on an energy diagram as the vertical distance from the total energy line to the potential-energy “plateau” on the right side of the diagram. HCl molecules at room temperature have energy  $E \approx 0.04 \times 10^{-19}$  J, barely distinguishable from zero energy. We can see in Figure 10.30 that the bond energy of HCl is approximately  $7.5 \times 10^{-19}$  J.

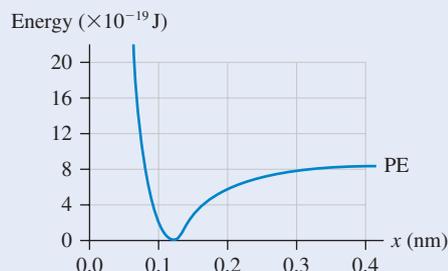
**NOTE** ▶ Chemists and biologists usually quote molecular energies in kJ/mol or kcal/mol. Physicists prefer to work directly with the energy per molecule or energy per bond in J. To find energies in kJ/mol, simply multiply the bond energy by Avogadro's number. For example, the  $7.5 \times 10^{-19}$  J bond energy of HCl becomes 450 kJ/mol. ◀

#### EXAMPLE 10.14 Does the photon have enough energy?

An energy diagram for molecular oxygen,  $O_2$ , is shown in **FIGURE 10.31**. A germicidal lamp for sterilizing equipment uses short-wavelength ultraviolet radiation at 185 nm. At this wavelength, each photon, or quantum, of ultraviolet light has

$10.7 \times 10^{-19}$  J of energy. If a molecule of  $O_2$  at room temperature absorbs one photon of light from the lamp, does this provide enough energy to split the molecule? If so, what will be the kinetic energy of the atoms after they have separated?

**FIGURE 10.31** The energy diagram for molecular oxygen,  $O_2$ .

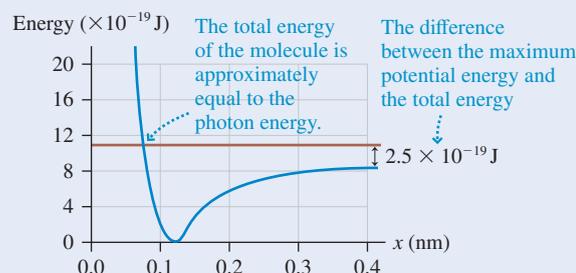


**STRATEGIZE** We can use the molecular energy diagram in Figure 10.31 to determine what happens at different energies.

**PREPARE** We'll assume that the room-temperature energy is similar to that for HCl, very close to zero. After the molecule absorbs the photon, the energy of the molecule will be nearly equal to the photon energy.

**SOLVE** **FIGURE 10.32** is the  $O_2$  energy diagram with a total energy line added that corresponds to the photon energy. The total energy is much greater than the maximum of the potential energy on the right side of the graph. After absorbing the photon,

**FIGURE 10.32** Comparing the photon energy to the potential energy for  $O_2$ .



the two oxygen molecules will separate. The residual kinetic energy will be equal to the difference between the total energy and the maximum of the potential energy, which we estimate to be  $2.5 \times 10^{-19}$  J.

**ASSESS** Germicidal lamps at this wavelength are known to produce  $O_3$ , ozone, a very reactive form of oxygen—so it's clear that the photons have enough energy to break apart the normally stable  $O_2$  molecules. Therefore, our answer makes sense.

## Chemical Reactions

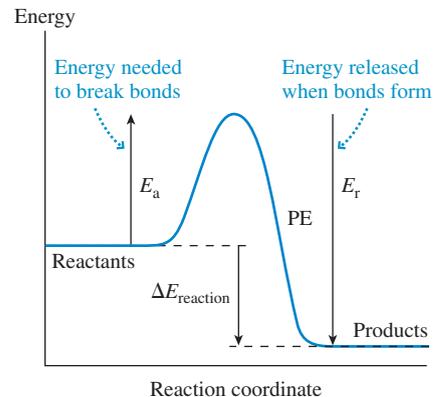
Energy ideas are key to understanding what happens during a chemical reaction. The basic idea of any chemical reaction—involving simple diatomic molecules or large biological macromolecules—is that some molecular bonds are broken and new molecular bonds are formed. For example, a simple reaction that we can symbolize as  $AB + CD \rightarrow AC + BD$  requires the bonds of molecules AB and CD to be broken and then new bonds to form between atoms A and C and between atoms B and D. And, as we've just seen, it takes energy to break molecular bonds.

**FIGURE 10.33** is the energy diagram of a chemical reaction. It's very much like the energy diagrams we've been using, but with one important difference: The position coordinate of the horizontal axis has been replaced with an abstract **reaction coordinate**. The reaction coordinate is not a physical quantity that could be measured; instead, it shows in a general sense the progress of bond breaking and bond formation as a reaction moves from reactants, on the left, to products, on the right.

All reaction energy diagrams have a large hump, or **energy barrier**, in the middle. This represents the energy required to break the bonds of the reactant molecules. For the reaction to take place, the reactants must increase their potential energy by the amount  $E_a$ , called the **activation energy**. Graphically, the activation energy is the height of the energy barrier above the initial potential energy of the reactants.

How does this happen? The reactant molecules have thermal energy, which means that the individual molecules are moving around and vibrating. When molecules collide, this energy can be transformed into the increased potential energy of stretched bonds. If the thermal energy is too low, the increased potential energy is less than the activation energy, meaning that the bonds don't break and the reaction doesn't occur. Wood and oxygen don't react at room temperature, even though the reaction—combustion—is energetically favorable, because the reactants don't have enough thermal energy to allow bond breaking during collisions. In essence, the total energy line is lower than the energy barrier, so there's a turning point in the reaction coordinate.

**FIGURE 10.33** A reaction energy diagram.



To burn wood, you must substantially increase the thermal energy of at least a portion of the fuel. You can do this with the high-temperature flame from a match. Some of the reactant molecules can then, via collisions, transform their large kinetic energy into potential energy that reaches or exceeds the activation energy—the molecules collide with enough kinetic energy to break molecular bonds. The reaction begins, and the energy subsequently released can trigger further reactions. Once you light a wood splint, the flame will work its way along the wood.

For combustion, the potential energy of the products is lower than that of the reactants, as is the case in Figure 10.33. More energy is released in the formation of new bonds than was required to initiate the reaction. The increase in thermal energy causes the final temperature of the products to be higher than the initial temperature of the reactants. Such reactions are called **exothermic reactions**. In contrast, an **endothermic reaction** releases less energy than was required to initiate it. Such reactions require a continuous input of energy to keep going.

**NOTE** ▶ Chemists and biologists often describe reactions in terms of what is called *free energy*. Free energy is a more appropriate description when some or all of the energy released in a reaction is used to do work rather than increasing the thermal energy. This is often the case in biology, where the energy released by a reaction does work by moving molecules around or changing the configuration of macromolecules instead of simply heating up the cell. We'll leave the definition and use of free energy to your chemistry and biology classes, simply noting that the analysis of a reaction in terms of free energy is exactly the same as the analysis presented here. ◀

## Reaction Rates and Catalysts

The reaction energy diagram tells us nothing about the *rate of reaction*—how fast a reaction proceeds. A more detailed theory, which you will study in chemistry, finds that the rate of reaction increases *exponentially* as the activation energy decreases. An exponential change means that even a small decrease in activation energy can produce a large increase in the rate of reaction.

The role of a catalyst is to provide an alternate reaction pathway with a lower activation energy, thus dramatically speeding up the rate of reaction. **FIGURE 10.34** shows an exothermic reaction, one that is energetically favorable but where the energy barrier is so high that this reaction will not happen at room temperature because the reaction rate is essentially zero. In Figure 10.34, we see that a catalyst offers an alternate pathway whose activation energy is easily exceeded by room-temperature molecules. A catalyst can dramatically increase reaction rates.

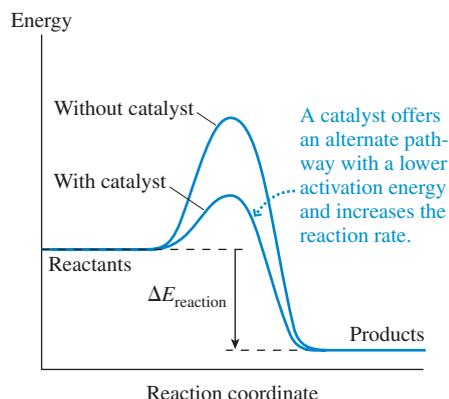
Most of biochemistry is mediated by catalysts in the form of *enzymes*. Processes such as respiration, photosynthesis, and protein synthesis involve energetically favorable exothermic (also called *exergonic*) reactions, but the activation energy is so high that the reactants, on their own, would react barely, if at all, at normal temperatures. Enzymes catalyze these reactions, allowing them to proceed at a rate sufficient for cellular functions.

## Chemical Energy

The law of conservation of energy includes the term  $\Delta E_{\text{chem}}$ , the change in chemical energy. Physics usually focuses on systems in which chemical energy is not important, but energy conservation also has to apply to chemistry and biology. Chemical energy is simply a name for the total electric potential energy stored in all the molecular bonds of a system. If there are no reactions, the chemical energy doesn't change and we can ignore it, because only energy *changes* enter into the law of energy conservation.

If there are chemical reactions, then the breaking and creation of molecular bonds change the system's chemical energy. In Figure 10.33 the energy of the products is

**FIGURE 10.34** A reaction energy diagram for a chemical reaction with and without a catalyst.



lower than the energy of the reactants. To make the reaction go, potential energy must be increased by the activation energy  $E_a$ —the energy of breaking bonds. Once the reaction is over the energy barrier, the formation of new bonds releases energy  $E_r$ ; that is, potential energy is transformed into thermal energy. The difference,  $\Delta E_{\text{reaction}} = E_r - E_a$ , is the net energy released in *one* reaction due to the change in bonds.

Any realistic system has a vast number of chemical reactions taking place. The change in chemical energy is simply the total energy released by all these reactions. If  $N$  reactions take place, then

$$\Delta E_{\text{chem}} = N\Delta E_{\text{reaction}} \quad (10.21)$$

In biological systems, the production of chemical energy via the catalyzed reactions of respiration powers the cellular machinery and maintains body temperature. This change in energy will be an important part of the story in Chapter 11.

## 10.9 Energy in Collisions

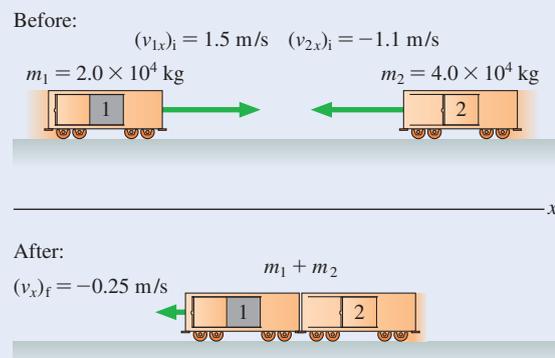
In Chapter 9 we studied collisions between two objects. We found that if no external forces are acting on the objects, the total *momentum* of the objects will be conserved. Now we wish to study what happens to *energy* in collisions.

Let's first re-examine a perfectly inelastic collision. We studied just such a collision in Example 9.8. Recall that in such a collision the two objects stick together and then move with a common final velocity. What happens to the energy?

### EXAMPLE 10.15 How much energy is transformed in a collision between railroad cars?

**FIGURE 10.35** shows two train cars that move toward each other, collide, and couple together. In Example 9.8, we used conservation of momentum to find the final velocity shown in Figure 10.35 from the given initial velocities. How much thermal energy is created in this collision?

**FIGURE 10.35** Before-and-after visual overview of a collision between two train cars.



**STRATEGIZE** We'll choose our system to be the two cars. The initial state is the instant before the collision; the final state is the instant just after.

**PREPARE** This is an isolated system, so  $W = 0$ . Because the track is horizontal, there is no change in potential energy. Thus the work-energy equation reduces to

$$K_f + \Delta E_{\text{th}} = K_i$$

Energy is conserved, but *kinetic* energy is not; it will be lower after the collision than before.

**SOLVE** The initial kinetic energy is

$$\begin{aligned} K_i &= \frac{1}{2}m_1(v_{1x})_i^2 + \frac{1}{2}m_2(v_{2x})_i^2 \\ &= \frac{1}{2}(2.0 \times 10^4 \text{ kg})(1.5 \text{ m/s})^2 + \frac{1}{2}(4.0 \times 10^4 \text{ kg})(-1.1 \text{ m/s})^2 \\ &= 4.7 \times 10^4 \text{ J} \end{aligned}$$

Because the cars stick together and move as a single object with mass  $m_1 + m_2$ , the final kinetic energy is

$$\begin{aligned} K_f &= \frac{1}{2}(m_1 + m_2)(v_x)_f^2 \\ &= \frac{1}{2}(6.0 \times 10^4 \text{ kg})(-0.25 \text{ m/s})^2 = 1900 \text{ J} \end{aligned}$$

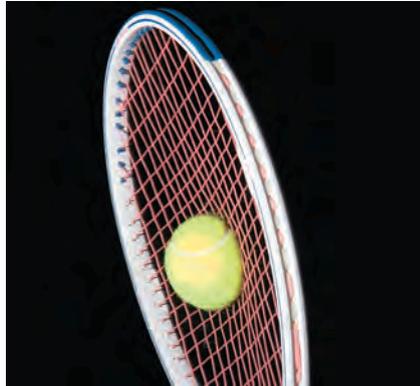
From the conservation of energy equation above, we find that the thermal energy increases by

$$\Delta E_{\text{th}} = K_i - K_f = 4.7 \times 10^4 \text{ J} - 1900 \text{ J} = 4.5 \times 10^4 \text{ J}$$

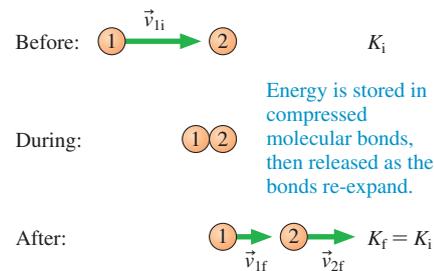
This amount of the initial kinetic energy is transformed into thermal energy during the impact of the collision.

**ASSESS** The cars are moving much more slowly after the collision than before, so we expect that most of the kinetic energy is transformed into thermal energy, just as we observed.

**FIGURE 10.36** A tennis ball collides with a racket. Notice that the ball is compressed and the strings are stretched.



**FIGURE 10.37** A perfectly elastic collision.



**Video Demo** Happy/Sad Pendulums

## Elastic Collisions

**FIGURE 10.36** shows a collision of a tennis ball with a racket. The ball is compressed and the racket strings stretch as the two collide, then the ball expands and the strings rebound as the two are pushed apart. In the language of energy, the kinetic energy of the objects is transformed into the elastic potential energy of the ball and strings, then back into kinetic energy as the two objects spring apart. If *all* of the kinetic energy is stored as elastic potential energy, and *all* of the elastic potential energy is transformed back into the post-collision kinetic energy of the objects, then mechanical energy is conserved. A collision in which mechanical energy is conserved is called a **perfectly elastic collision**.

Needless to say, most real collisions fall somewhere between perfectly elastic and perfectly inelastic. A rubber ball bouncing on the floor might “lose” 20% of its kinetic energy on each bounce and return to only 80% of the height of the preceding bounce. But collisions between two very hard objects, such as two pool balls or two steel balls, come close to being perfectly elastic. And collisions between microscopic particles, such as atoms or electrons, can be perfectly elastic.

**FIGURE 10.37** shows a head-on, perfectly elastic collision of a ball of mass  $m_1$ , having initial velocity  $(v_{1x})_i$ , with a ball of mass  $m_2$  that is initially at rest. The balls’ velocities after the collision are  $(v_{1x})_f$  and  $(v_{2x})_f$ . These are velocities, not speeds, and have signs. Ball 1, in particular, might bounce backward and have a negative value for  $(v_{1x})_f$ .

The collision must obey two conservation laws: conservation of momentum (obeyed in any collision) and conservation of mechanical energy (because the collision is perfectly elastic). Although the energy is transformed into potential energy during the collision, the mechanical energy before and after the collision is purely kinetic energy. Thus,

$$\text{momentum conservation: } m_1(v_{1x})_i = m_1(v_{1x})_f + m_2(v_{2x})_f$$

$$\text{energy conservation: } \frac{1}{2} m_1(v_{1x})_i^2 = \frac{1}{2} m_1(v_{1x})_f^2 + \frac{1}{2} m_2(v_{2x})_f^2$$

Momentum conservation alone is not sufficient to analyze the collision because there are two unknowns: the two final velocities. That is why we did not consider perfectly elastic collisions in Chapter 9. Energy conservation gives us another condition. The complete solution of these two equations involves straightforward but rather lengthy algebra. We’ll just give the solution here:

$$(v_{1x})_f = \frac{m_1 - m_2}{m_1 + m_2} (v_{1x})_i \quad (v_{2x})_f = \frac{2m_1}{m_1 + m_2} (v_{1x})_i \quad (10.22)$$

Perfectly elastic collision with object 2 initially at rest

Equations 10.22 allow us to compute the final velocity of each object. Let’s look at a common and important example: a perfectly elastic collision between two objects of equal mass.

### EXAMPLE 10.16 Finding the aftermath of a collision between air hockey pucks

On an air hockey table, a moving puck, traveling to the right at 2.3 m/s, makes a head-on collision with an identical puck at rest. What is the final velocity of each puck?

**PREPARE** The before-and-after visual overview is shown in **FIGURE 10.38**. We’ve shown the final velocities in the picture, but we don’t really know yet which way the pucks will move. Because one puck was initially at rest, we can use Equations 10.22 to find

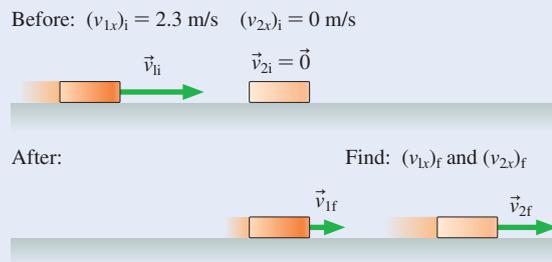
the final velocities of the pucks. The pucks are identical, so we have  $m_1 = m_2 = m$ .

**SOLVE** We use Equations 10.22 with  $m_1 = m_2 = m$  to get

$$(v_{1x})_f = \frac{m - m}{m + m} (v_{1x})_i = 0 \text{ m/s}$$

$$(v_{2x})_f = \frac{2m}{m + m} (v_{1x})_i = (v_{1x})_i = 2.3 \text{ m/s}$$

**FIGURE 10.38** A moving puck collides with a stationary puck.

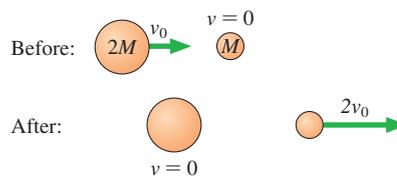


The incoming puck stops dead, and the initially stationary puck goes off with the same velocity that the incoming one had.

**ASSESS** You can see that momentum and energy are conserved: The incoming puck's momentum and energy are completely transferred to the outgoing puck. If you've ever played pool, you've probably seen this sort of collision when you hit a ball head-on with the cue ball. The cue ball stops and the other ball picks up the cue ball's velocity.

**STOP TO THINK 10.10** A small ball with mass  $M$  is at rest. It is then struck by a ball with twice the mass, moving at speed  $v_0$ . The situation after the collision is shown in the figure. Is this possible?

- A. Yes  
 B. No, because momentum is not conserved  
 C. No, because energy is not conserved  
 D. No, because neither momentum nor energy is conserved



## 10.10 Power

We've now studied how energy can be transformed from one kind into another and how it can be transferred between the environment and the system as work. In many situations we would like to know *how quickly* the energy is transformed or transferred. Is a transfer of energy very rapid, or does it take place over a long time? In passing a truck, your car needs to transform a certain amount of the chemical energy in its fuel into kinetic energy. It makes a *big* difference whether your engine can do this in 20 s or 60 s!

The question *How quickly?* implies that we are talking about a *rate*. For example, the velocity of an object—how fast it is going—is the *rate of change* of position. So, when we raise the issue of how fast the energy is transformed, we are talking about the *rate of transformation* of energy. Suppose in a time interval  $\Delta t$  an amount of energy  $\Delta E$  is transformed from one form into another. The rate at which this energy is transformed is called the **power**  $P$  and is defined as

$$P = \frac{\Delta E}{\Delta t} \quad (10.23)$$

Power when an amount of energy  $\Delta E$  is transformed in a time interval  $\Delta t$

The unit of power is the **watt**, which is defined as  $1 \text{ watt} = 1 \text{ W} = 1 \text{ J/s}$ .

Power also measures the rate at which energy is transferred into or out of a system as work  $W$ . If work  $W$  is done in time interval  $\Delta t$ , the rate of energy *transfer* is

$$P = \frac{W}{\Delta t} \quad (10.24)$$

Power when an amount of work  $W$  is done in a time interval  $\Delta t$

If a person, animal, vehicle, or device is transforming or transferring energy at a rate of 3 J/s, we say that it has an **output power** of 3 W.



Both these cars take about the same energy to reach 60 mph, but the race car gets there in a much shorter time, so its *power* is much greater.

The English unit of power is the *horsepower*. The conversion factor to watts is

$$1 \text{ horsepower} = 1 \text{ hp} = 746 \text{ W}$$

Many common appliances, such as motors, are rated in hp.

We can express Equation 10.24 in a different form. If in the time interval  $\Delta t$  an object undergoes a displacement  $\Delta x$ , the work done by a force acting on the object is  $W = F\Delta x$ . Then Equation 10.24 can be written as

$$P = \frac{W}{\Delta t} = \frac{F\Delta x}{\Delta t} = F \frac{\Delta x}{\Delta t} = Fv$$

The rate at which energy is transferred to an object as work—the power—is the product of the force that does the work and the velocity of the object:

$$P = Fv \quad (10.25)$$

Rate of energy transfer due to a force  $F$  acting on an object moving at velocity  $v$

#### EXAMPLE 10.17 Finding the output power for a weightlifter **BIO**

A 100 kg weightlifter performs a lift called a clean and jerk, raising a 190 kg bar from the ground to a height of 1.9 m in a time of 1.8 s. What is his output power?

**STRATEGIZE** We'll take the system to be the weightlifter + bar + earth. We'll assume that the bar is stationary before and after the lift, so the relevant energy change is the increase in gravitational potential energy of the bar. This is an isolated system, so the change is an internal transformation. We'll use Equation 10.23 to compute the power.

**PREPARE** The change in potential energy depends on the change in height:

$$\Delta U_g = mg\Delta y = (190 \text{ kg})(9.8 \text{ m/s}^2)(1.9 \text{ m}) = 3540 \text{ J}$$

**SOLVE** The power of the transformation is

$$P = \frac{\Delta E}{\Delta t} = \frac{3540 \text{ J}}{1.8 \text{ s}} = 2000 \text{ W}$$

**ASSESS** This is a lot of power—about 2.7 horsepower! But we'd expect such a large output power for a large weightlifter.

The 100 kg weightlifter has a very large output power, which isn't surprising. How about someone smaller?

#### EXAMPLE 10.18 Finding the output power for a sprinter **BIO**

A 50 kg sprinter accelerates from 0 to 11 m/s in 3.0 s. What is the output power for this rapid start?

**STRATEGIZE** We can take the system to be the runner + earth. Let's assume that the track is level, so there is no change in potential energy, only a change in kinetic energy. We can safely ignore drag and other forces, so this is isolated system and the change is an internal transformation.

**PREPARE** The initial kinetic energy is zero, so the change in kinetic energy is equal to the final kinetic energy:

$$\Delta K = K_f = \frac{1}{2}mv_f^2 = \frac{1}{2}(50 \text{ kg})(11 \text{ m/s})^2 = 3000 \text{ J}$$

**SOLVE** The power of the transformation is

$$P = \frac{\Delta E}{\Delta t} = \frac{3000 \text{ J}}{3.0 \text{ s}} = 1000 \text{ W}$$

**ASSESS** This is a lot of power—about 1.3 horsepower—but less than for the weightlifter, which makes sense. In this case, as for the weightlifter, the power came from the athlete's muscles.

A 100 kg weightlifter can produce more output power than a 50 kg sprinter, which makes sense. It's worthwhile to consider what we'll call the **specific power**—the output power divided by the mass of the person (or animal, device, or machine) doing the transformation or the work:

$$\text{specific power} = \frac{\text{power of a transformation or a transfer}}{\text{mass of agent causing the transformation or transfer}}$$

Let's compute the specific power for the weightlifter and the sprinter:

$$\text{sprinter:} \quad \text{specific power} = \frac{1000 \text{ W}}{50 \text{ kg}} = 20 \text{ W/kg}$$

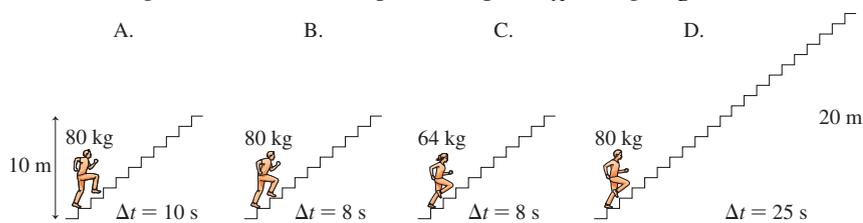
$$\text{weightlifter:} \quad \text{specific power} = \frac{2000 \text{ W}}{100 \text{ kg}} = 20 \text{ W/kg}$$

The numbers for the sprinter and the weightlifter are at the extreme end of what humans are capable of; these are numbers typical of world-class athletes. It's interesting to note that the specific power for both cases is about the same. Humans in peak condition who are skilled at athletic pursuits are capable of short bursts of about 20 W/kg. Larger athletes can produce more output power, but the power per kilogram is about the same. As we'll see in the next chapter, humans can't sustain this level of power output; this number applies for only short bursts that use the large muscles of the body. Sustained activities such as cycling or swimming correspond to specific powers of perhaps 5 W/kg for elite athletes.

Smaller animals are generally capable of higher specific powers. A bushbaby, a 200 g primate that gets around by executing rapid leaps in the trees it calls home, is able to push off with its legs with sufficient force to accelerate to 6.7 m/s in 0.16 s, corresponding to a specific power of 140 W/kg. This is the upper end of what can be accomplished with muscle power alone. The leap of the 2.0 g desert locust that we considered earlier has an even higher specific power, but this power comes from springs in the legs; muscles alone could not get the locust to such a high speed in such a short time. Many of the impressive jumpers of the insect world, from fleas to springtails, use energy storage systems corresponding to springs to power their leaps.

Of course, the notion of specific power can be applied to other systems as well. We can do a similar calculation for a passenger car, either starting from rest or climbing a hill, to find a specific power in the range of 90 W/kg. This is an interesting measure of a vehicle.

**STOP TO THINK 10.11** Four students run up the stairs in the times shown. Rank in order, from largest to smallest, their power outputs  $P_A$  through  $P_D$ .



**INTEGRATED EXAMPLE 10.19 Stopping a runaway truck**

A truck's brakes can overheat and fail while descending mountain highways, leading to an extremely dangerous runaway truck. Some highways have *runaway-truck ramps* to safely bring out-of-control trucks to a stop. These uphill ramps are covered with a deep bed of gravel. The uphill slope and the large coefficient of rolling friction as the tires sink into the gravel bring the truck to a safe halt.



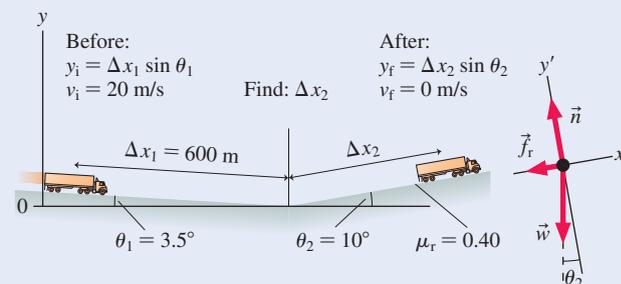
A 22,000 kg truck heading down a  $3.5^\circ$  slope at 20 m/s ( $\approx 45$  mph) suddenly has its brakes fail. Fortunately, there's a runaway-truck ramp 600 m ahead. The ramp slopes upward at an angle of  $10^\circ$ , and the coefficient of rolling friction between the truck's tires and the loose gravel is  $\mu_r = 0.40$ . Ignore air resistance and rolling friction as the truck rolls down the highway.

- Use conservation of energy to find how far along the ramp the truck travels before stopping.
- By how much does the thermal energy of the truck and ramp increase as the truck stops?

**STRATEGIZE** We'll follow the steps of Problem-Solving Approach 10.1. We start by defining the system as the truck + ramp + earth. Gravitational potential energy will be part of the solution, and the change in thermal energy will be an internal transformation.

**PREPARE** FIGURE 10.39 shows a before-and-after visual overview. Because we're going to need to determine friction forces to calculate the increase in thermal energy, we've also drawn a free-body diagram for the truck as it moves up the ramp. One slight complication is that the  $y$ -axis of free-body diagrams is drawn perpendicular to the slope, whereas the calculation of gravitational potential energy needs a vertical  $y$ -axis to measure height.

FIGURE 10.39 Visual overview of the runaway truck.



We've dealt with this by labeling the free-body diagram axis the  $y'$ -axis.

**SOLVE** a. The work-energy equation for the motion of the truck, from the moment its brakes fail to when it finally stops, is

$$K_f + (U_g)_f + \Delta E_{\text{th}} = K_i + (U_g)_i$$

Because friction is present only along the ramp, thermal energy will increase only as the truck moves up the ramp. This thermal energy is then given by  $\Delta E_{\text{th}} = f_r \Delta x_2$ , because  $\Delta x_2$  is the length of the ramp. The conservation of energy equation then is

$$\frac{1}{2}mv_f^2 + mgy_f + f_r \Delta x_2 = \frac{1}{2}mv_i^2 + mgy_i$$

From Figure 10.39 we have  $y_i = \Delta x_1 \sin \theta_1$ ,  $y_f = \Delta x_2 \sin \theta_2$ , and  $v_f = 0$ , so the equation becomes

$$mg \Delta x_2 \sin \theta_2 + f_r \Delta x_2 = \frac{1}{2}mv_i^2 + mg \Delta x_1 \sin \theta_1$$

To find  $f_r = \mu_r n$  we need to find the normal force  $n$ . The free-body diagram shows that

$$\sum F_{y'} = n - mg \cos \theta_2 = a_{y'} = 0$$

from which  $f_r = \mu_r n = \mu_r mg \cos \theta_2$ . With this result for  $f_r$ , our conservation of energy equation is

$$mg \Delta x_2 \sin \theta_2 + \mu_r mg \cos \theta_2 \Delta x_2 = \frac{1}{2}mv_i^2 + mg \Delta x_1 \sin \theta_1$$

which, after we divide both sides by  $mg$ , simplifies to

$$\Delta x_2 \sin \theta_2 + \mu_r \cos \theta_2 \Delta x_2 = \frac{v_i^2}{2g} + \Delta x_1 \sin \theta_1$$

Solving this for  $\Delta x_2$  gives

$$\begin{aligned} \Delta x_2 &= \frac{\frac{v_i^2}{2g} + \Delta x_1 \sin \theta_1}{\sin \theta_2 + \mu_r \cos \theta_2} \\ &= \frac{\frac{(20 \text{ m/s})^2}{2(9.8 \text{ m/s}^2)} + (600 \text{ m})(\sin 3.5^\circ)}{\sin 10^\circ + 0.40(\cos 10^\circ)} = 100 \text{ m} \end{aligned}$$

b. We know that  $\Delta E_{\text{th}} = f_r \Delta x_2 = (\mu_r mg \cos \theta_2) \Delta x_2$ , so that

$$\begin{aligned} \Delta E_{\text{th}} &= (0.40)(22,000 \text{ kg})(9.8 \text{ m/s}^2)(\cos 10^\circ)(100 \text{ m}) \\ &= 8.5 \times 10^6 \text{ J} \end{aligned}$$

**ASSESS** It seems reasonable that a truck that speeds up as it rolls 600 m downhill takes only 100 m to stop on a steeper, high-friction ramp. At the top of the hill the truck's kinetic energy is  $K_i = \frac{1}{2}mv_i^2 = \frac{1}{2}(22,000 \text{ kg})(20 \text{ m/s})^2 = 4.4 \times 10^6 \text{ J}$ , which is of the same order of magnitude as  $\Delta E_{\text{th}}$ . Our answer is reasonable.

# SUMMARY

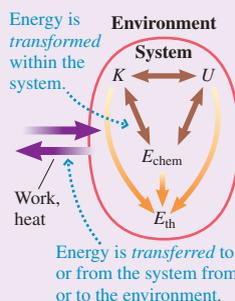
**GOAL** To introduce the concept of energy and to learn a new problem-solving strategy based on conservation of energy.

## GENERAL PRINCIPLES

### Basic Energy Model

Within a system, energy can be **transformed** between various forms. Energy can be **transferred** into or out of a system in two basic ways:

- **Work:** The transfer of energy by mechanical forces
- **Heat:** The nonmechanical transfer of energy from a hotter to a colder object



### Solving Energy Transfer and Energy Conservation Problems

**STRATEGIZE** Choose the system. Determine the initial and final states.

**PREPARE** Draw a before-and-after visual overview.

**SOLVE** Use the before-and-after version of the work-energy equation:

$$K_f + U_f + \Delta E_{th} = K_i + U_i + W$$

Start with this general equation, then specialize to the case at hand:

- Use the appropriate form or forms of potential energy.
- If the system is isolated, set  $W = 0$ .
- If there is no friction or drag, set  $\Delta E_{th} = 0$ .

**ASSESS** See if the numbers make sense—and if the numbers add up. Energy is conserved, and kinetic energy and the change in thermal energy are always positive.

### Conservation of Energy

When work  $W$  is done on a system, the system's total energy changes by the amount of work done. In mathematical form, this is the **work-energy equation**:

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \dots = W$$

A system is isolated when no energy is transferred into or out of the system. This means the work is zero, giving the **law of conservation of energy**:

$$\Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \dots = 0$$

## IMPORTANT CONCEPTS

**Kinetic energy** is an energy of motion:

$$K = \underbrace{\frac{1}{2}mv^2}_{\text{Translational}} + \underbrace{\frac{1}{2}I\omega^2}_{\text{Rotational}}$$

**Potential energy** is energy stored in a system of interacting objects.

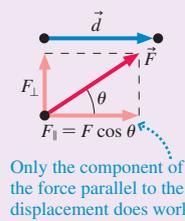
- **Gravitational potential energy:**  $U_g = mgy$
- **Elastic potential energy:**  $U_s = \frac{1}{2}kx^2$

**Thermal energy** is the sum of the microscopic kinetic and potential energies of all the molecules in an object. The hotter an object, the more thermal energy it has. When kinetic (sliding) friction is present, the increase in the thermal energy is  $\Delta E_{th} = f_k \Delta x$ . When the drag force is present, the increase in the thermal energy is  $\Delta E_{th} = D\Delta x$ .

**Work** is the process by which energy is transferred to or from a system by the application of mechanical forces.

If a particle moves through a displacement  $\vec{d}$  while acted upon by a constant force  $\vec{F}$ , the force does work

$$W = F_{\parallel}d = Fd \cos \theta$$

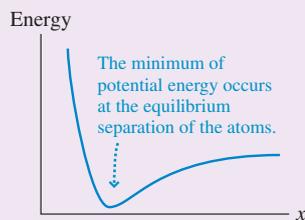


Only the component of the force parallel to the displacement does work.

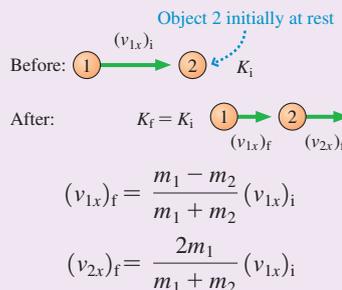
## APPLICATIONS

**Energy diagrams** are a useful way to analyze physical systems.

This curve shows the potential energy of a two-atom molecule as a function of the atomic separation.



**Perfectly elastic collisions** Both mechanical energy and momentum are conserved.



**Power** is the rate at which energy is transformed . . .

$$P = \frac{\Delta E}{\Delta t} \left\{ \begin{array}{l} \leftarrow \text{Amount of energy transformed} \\ \leftarrow \text{Time required to transform it} \end{array} \right.$$

. . . or at which work is done.

$$P = \frac{W}{\Delta t} \left\{ \begin{array}{l} \leftarrow \text{Amount of work done} \\ \leftarrow \text{Time required to do work} \end{array} \right.$$

We now provide **Learning Objectives** keyed to relevant end of chapter problems to help students check their understanding and guide them in choosing appropriate problems to optimize their study time.

**Learning Objectives** After studying this chapter, you should be able to:

- Calculate the work done on an object. *Problems 10.1, 10.2, 10.3, 10.4, 10.5, 10.6, 10.7*
- Calculate an object's kinetic and potential energy. *Conceptual Questions 10.17, 10.18; Problems 10.14, 10.17, 10.20, 10.23, 10.25*
- Understand and calculate the change in thermal energy. *Conceptual Question 10.12; Problems 10.29, 10.30, 10.31, 10.32, 10.34*
- Use the problem-solving approach to solve conservation of energy problems. *Conceptual Questions 10.20, 10.22; Problems 10.36, 10.37, 10.39, 10.41, 10.48*
- Draw and interpret energy diagrams. *Conceptual Question 10.24; Problems 10.51, 10.52*
- Interpret and use molecular bond energies. *Problems 10.53, 10.54*
- Apply energy and momentum conservation to elastic collisions. *Problems 10.55, 10.56, 10.58*
- Understand and calculate power. *Problems 10.60, 10.61, 10.62, 10.65, 10.68*

### STOP TO THINK ANSWERS

**Chapter Preview Stop to Think: A.** Because the car starts from rest,  $v_i = 0$  and the kinematic equation is  $(v_x)_f^2 = 2a_x \Delta x$ , so that  $(v_x)_f = \sqrt{2a_x \Delta x}$ . Thus the speed is proportional to the square root of the displacement. If, as in this question, the displacement increases by a factor of 4, the speed only doubles. So the speed will increase from 5 m/s to 10 m/s.

**Stop to Think 10.1: C.** The coaster slows. Its kinetic energy is decreasing because kinetic energy is transformed into gravitational potential energy as the coaster climbs the hill.

**Stop to Think 10.2: C.**  $W = Fd \cos \theta$ . The 10 N force at  $90^\circ$  does no work at all.  $\cos 60^\circ = \frac{1}{2}$ , so the 8 N force does less work than the 6 N force.

**Stop to Think 10.3: B > D > A = C.**  $K = \frac{1}{2}mv^2$ . Using the given masses and velocities, we find  $K_A = 2.0$  J,  $K_B = 4.5$  J,  $K_C = 2.0$  J,  $K_D = 4.0$  J.

**Stop to Think 10.4:  $(U_g)_3 > (U_g)_2 = (U_g)_4 > (U_g)_1$ .** Gravitational potential energy depends only on height, not speed.

**Stop to Think 10.5: D.** The potential energy of a spring depends on the *square* of the displacement  $x$ , so the energy is positive whether the spring is compressed or extended. If the spring is compressed by twice the amount it had been stretched, the energy will increase by a factor of  $2^2 = 4$ . So the energy will be  $4 \times 1$  J = 4 J.

**Stop to Think 10.6: B.** We can use conservation of energy to write  $\Delta K + \Delta E_{th} = 0$ . Now if the initial kinetic energy doubles, so does  $\Delta K$ , so  $\Delta E_{th}$  must double as well. But  $\Delta E_{th} = f_k \Delta x$ , so if  $\Delta E_{th}$  doubles, then  $\Delta x$  doubles to 2.0 m.

**Stop to Think 10.7:** We define the system as the student, the rope, and the earth. The friction force and the weight force are internal to the system, so it is an isolated system.

**Stop to Think 10.8: D.** In all three cases, Katie has the same initial kinetic energy and potential energy. Thus her energy must be the same at the bottom of the slide in all three cases. Because she has only kinetic energy at the bottom, her speed there must be the same in all three cases as well.

**Stop to Think 10.9: B.** The kinetic energy is the difference between the total energy and the potential energy. This is highest at the bottom of the right well in B.

**Stop to Think 10.10: C.** The initial momentum is  $(2M)v_0 + 0$ , and the final momentum is  $0 + M(2v_0)$ . These are equal, so momentum is conserved. The initial kinetic energy is  $\frac{1}{2}(2M)v_0^2 = Mv_0^2$ , and the final kinetic energy is  $\frac{1}{2}M(2v_0)^2 = 2Mv_0^2$ . The final kinetic energy is *greater* than the initial kinetic energy, so this collision is not possible. (If the final kinetic energy had been less than the initial kinetic energy, the collision could be possible because the difference in energy could be converted into thermal energy.)

**Stop to Think 10.11:  $P_B > P_A = P_C > P_D$ .** The power here is the rate at which each runner's internal chemical energy is converted into gravitational potential energy. The change in gravitational potential energy is  $mg\Delta y$ , so the power is  $mg\Delta y/\Delta t$ . For runner A, the ratio  $m\Delta y/\Delta t$  equals  $(80 \text{ kg})(10 \text{ m})/(10 \text{ s}) = 80 \text{ kg} \cdot \text{m/s}$ . For C, the ratio is also  $80 \text{ kg} \cdot \text{m/s}$ . For B, it's  $100 \text{ kg} \cdot \text{m/s}$ , while for D the ratio is  $64 \text{ kg} \cdot \text{m/s}$ .

**Additional Stop To Think questions** provide students with more crucial practice and concept checks as they go through the chapters. The solutions to these questions have been moved to a more prominent location.



Video Tutor Solution Chapter 10

## QUESTIONS

### Conceptual Questions

- The brake shoes of your car are made of a material that can tolerate very high temperatures without being damaged. Why is this so?

For Questions 2 through 9, give a specific example of a system with the energy transformation shown. In these questions,  $W$  is the work done on the system, and  $K$ ,  $U$ , and  $E_{th}$  are the kinetic, potential, and thermal energies of the system, respectively. Any energy not

mentioned in the transformation is assumed to remain constant; if work is not mentioned, it is assumed to be zero.

- $W \rightarrow K$
- $W \rightarrow U$
- $K \rightarrow U$
- $K \rightarrow W$
- $U \rightarrow K$
- $W \rightarrow \Delta E_{th}$
- $U \rightarrow \Delta E_{th}$
- $K \rightarrow \Delta E_{th}$

- A ball of putty is dropped from a height of 2 m onto a hard floor, where it sticks. What object or objects need to be included within the system if the system is to be isolated during this process?

11. A diver leaps from a high platform, speeds up as she falls, and then slows to a stop in the water. How do you define the system so that the energy changes are all transformations internal to an isolated system?
12. When your hands are cold, you can rub them together to warm them. Explain the energy transformations that make this possible.
13. Puck B has twice the mass of puck A. Starting from rest, both pucks are pulled the same distance across frictionless ice by strings with the same tension.
  - a. Compare the final kinetic energies of pucks A and B.
  - b. Compare the final speeds of pucks A and B.
14. To change a tire, you need to use a jack to raise one corner of your car. While doing so, you happen to notice that pushing the jack handle down 20 cm raises the car only 0.2 cm. Use energy concepts to explain why the handle must be moved so far to raise the car by such a small amount.
15. You drop two balls from a tower, one of mass  $m$  and the other of mass  $2m$ . Just before they hit the ground, which ball, if either, has the larger kinetic energy? Explain.
16. If you fall and skid to a stop on a carpeted floor, you can get a rug burn. Much of this discomfort comes from abrasion, but there can also be a real burn where the skin was too hot. How does this happen?
17. A roller coaster car rolls down a frictionless track, reaching speed  $v$  at the bottom.
  - a. If you want the car to go twice as fast at the bottom, by what factor must you increase the height of the track?
  - b. Does your answer to part a depend on whether the track is straight or not? Explain.
18. A spring gun shoots out a plastic ball at speed  $v$ . The spring is then compressed twice the distance it was on the first shot.
  - a. By what factor is the spring's potential energy increased?
  - b. By what factor is the ball's speed increased? Explain.
19. A baseball pitcher can throw a baseball (mass 0.14 kg) much faster than a football quarterback can throw a football (mass 0.42 kg). Use energy concepts to explain why you would expect this to be true.
20. Sandy and Chris stand on the edge of a cliff and throw identical mass rocks at the same speed. Sandy throws her rock horizontally while Chris throws his upward at an angle of  $45^\circ$  to the horizontal. Are the rocks moving at the same speed when they hit the ground, or is one moving faster than the other? If one is moving faster, which one? Explain.

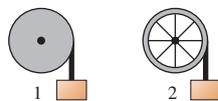


FIGURE Q10.21

21. A solid cylinder and a hollow cylinder have the same mass, same radius, and turn on frictionless, horizontal axes. (The hollow cylinder has lightweight spokes connecting it to the axle.) A rope is wrapped around each cylinder and tied to a block. The blocks have the same mass and are held the same height above the ground as shown in Figure Q10.21. Both blocks are released simultaneously. The ropes do not slip. Which block hits the ground first? Or is it a tie? Explain.

22. A bowler tosses a ball without spin. The ball slides down the alley. At some point, friction with the alley makes the ball start to roll; eventually, it rolls without sliding. When the ball reaches this point, it is moving at a lower speed than the original toss. Use energy concepts to give two reasons for this change.
23. Ferns that eject spores generally do so in pairs, with two spores flying off in opposite directions. The structure from which the spores are launched is quite lightweight. If it takes a certain amount of energy to eject each spore, explain how launching the spores in pairs provides for the greatest initial launch speed for each spore.
24. Figure Q10.24 shows a potential-energy diagram for a particle. The particle is at rest at point A and is then given a slight nudge to the right. Describe the subsequent motion.

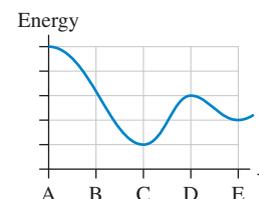


FIGURE Q10.24

### Multiple-Choice Questions

25. || A roller coaster starts from rest at its highest point and then descends on its (frictionless) track. Its speed is 30 m/s when it reaches ground level. What was its speed when its height was half that of its starting point?
  - A. 11 m/s
  - B. 15 m/s
  - C. 21 m/s
  - D. 25 m/s
26. | A woman uses a pulley and a rope to raise a 20 kg weight to a height of 2 m. If it takes 4 s to do this, about how much power is she supplying?
  - A. 100 W
  - B. 200 W
  - C. 300 W
  - D. 400 W
27. | A hockey puck sliding along frictionless ice with speed  $v$  to the right collides with a horizontal spring and compresses it by 2.0 cm before coming to a momentary stop. What will be the spring's maximum compression if the same puck hits it at a speed of  $2v$ ?
  - A. 2.0 cm
  - B. 2.8 cm
  - C. 4.0 cm
  - D. 5.6 cm
  - E. 8.0 cm
28. || A block slides down a smooth ramp, starting from rest at a height  $h$ . When it reaches the bottom it's moving at speed  $v$ . It then continues to slide up a second smooth ramp. At what height is its speed equal to  $v/2$ ?
  - A.  $h/4$
  - B.  $h/2$
  - C.  $3h/4$
  - D.  $2h$
29. | A wrecking ball is suspended from a 5.0-m-long cable that makes a  $30^\circ$  angle with the vertical. The ball is released and swings down. What is the ball's speed at the lowest point?
  - A. 7.7 m/s
  - B. 4.4 m/s
  - C. 3.6 m/s
  - D. 3.1 m/s
30. || A dog can provide sufficient power to pull a sled with a 60 N force at a steady 2.0 m/s. Suppose the dog is hitched to a different sled that requires 120 N to move at a constant speed. How fast can the dog pull this second sled?
  - A. 0.50 m/s
  - B. 1.0 m/s
  - C. 1.5 m/s
  - D. 2.0 m/s
31. ||| Most of the energy you expend in cycling is dissipated by the drag force. If you double your speed, you increase the drag force by a factor of 4. This increases the power to cycle at this greater speed by what factor?
  - A. 2
  - B. 4
  - C. 8
  - D. 16

Problem difficulty is labeled as | (straightforward) to |||| (challenging).  
 INT Problems labeled integrate significant material from earlier chapters; BIO are of biological or medical interest.



The eText icon indicates when there is a video tutor solution available for the chapter or for a specific problem. To launch these videos, log into your eText through [MasteringPhysics](#) or log into the Study Area.

## PROBLEMS

## Section 10.2 Work

- || A 2.0 kg book is lying on a 0.75-m-high table. You pick it up and place it on a bookshelf 2.3 m above the floor. During this process,
  - How much work does gravity do on the book?
  - How much work does your hand do on the book?
- || The two ropes seen in Figure P10.2 are used to lower a 255 kg piano exactly 5 m from a second-story window to the ground. How much work is done by each of the three forces?

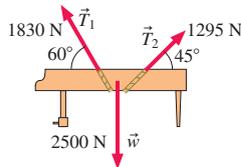


FIGURE P10.2

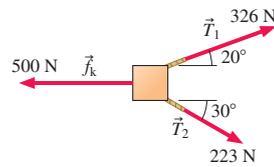


FIGURE P10.3

- | The two ropes shown in the bird's-eye view of Figure P10.3 are used to drag a crate exactly 3 m across the floor. How much work is done by each of the ropes on the crate?
- | You are pulling a child in a wagon. The rope handle is inclined upward at a 60° angle. The tension in the handle is 20 N. How much work do you do if you pull the wagon 100 m at a constant speed?
- | A boy flies a kite with the string at a 30° angle to the horizontal. The tension in the string is 4.5 N. How much work does the string do on the boy if the boy
  - Stands still?
  - Walks a horizontal distance of 11 m away from the kite?
  - Walks a horizontal distance of 11 m toward the kite?
- || A typical muscle fiber is 2.0 cm long and has a cross-section area of  $3.1 \times 10^{-9} \text{ m}^2$ . When the muscle fiber is stimulated, it pulls with a force of 1.2 mN. What is the work done by the muscle fiber as it contracts to a length of 1.6 cm?
- || A crate slides down a ramp that makes a 20° angle with the ground. To keep the crate moving at a steady speed, Paige pushes back on it with a 68 N horizontal force. How much work does Paige do on the crate as it slides 3.5 m down the ramp?

## Section 10.3 Kinetic Energy

- || A wind turbine works by slowing the air that passes its blades and converting much of the extracted kinetic energy to electric energy. A large wind turbine has 45-m-radius blades. In typical conditions, 92,000 kg of air moves past the blades every second. If the air is moving at 12 m/s before it passes the blades and the wind turbine extracts 40% of this kinetic energy, how much energy is extracted every second?
- || At what speed does a 1000 kg compact car have the same kinetic energy as a 20,000 kg truck going 25 km/h?
- | A 60 kg runner in a sprint moves at 11 m/s. A 60 kg cheetah in a sprint moves at 33 m/s. By what factor does the kinetic energy of the cheetah exceed that of the human runner?
- | A car is traveling at 10 m/s.
  - How fast would the car need to go to double its kinetic energy?
  - By what factor does the car's kinetic energy increase if its speed is doubled to 20 m/s?

- || The opposite of a wind turbine is an electric fan: The electric energy that powers the fan is converted to the kinetic energy of moving air. A fan is putting 1.0 J of kinetic energy into the air every second. Then the fan speed is increased by a factor of 2. Air moves through the fan faster, so the fan moves twice as much air at twice the speed. How much kinetic energy goes into the air every second?
- | How fast would an 80 kg man need to run in order to have the same kinetic energy as an 8.0 g bullet fired at 400 m/s?
- || A fielder tosses a 0.15 kg baseball at 32 m/s at a 30° angle to the horizontal. What is the ball's kinetic energy at the start of its motion? What is the kinetic energy at the highest point of its arc?
- || Sam's job at the amusement park is to slow down and bring to a stop the boats in the log ride. If a boat and its riders have a mass of 1200 kg and the boat drifts in at 1.2 m/s, how much work does Sam do to stop it?
- || A school has installed a modestly-sized wind turbine. The three blades are 4.6 m long; each blade has a mass of 45 kg. You can assume that the blades are uniform along their lengths. When the blades spin at 240 rpm, what is the kinetic energy of the blade assembly?
- || The turntable in a microwave oven has a moment of inertia of  $0.040 \text{ kg} \cdot \text{m}^2$  and rotates continuously, making a complete revolution every 4.0 s. What is its kinetic energy?
- || A typical meteor that hits the earth's upper atmosphere has a mass of only 2.5 g, about the same as a penny, but it is moving at an impressive 40 km/s. As the meteor slows, the resulting thermal energy makes a glowing streak across the sky, a shooting star. The small mass packs a surprising punch. At what speed would a 900 kg compact car need to move to have the same kinetic energy?
- || An energy storage system based on a flywheel (a rotating disk) can store a maximum of 4.0 MJ when the flywheel is rotating at 20,000 revolutions per minute. What is the moment of inertia of the flywheel?



## Section 10.4 Potential Energy

- || The lowest point in Death Valley is 85.0 m below sea level. The summit of nearby Mt. Whitney has an elevation of 4420 m. What is the change in gravitational potential energy of an energetic 65.0 kg hiker who makes it from the floor of Death Valley to the top of Mt. Whitney?
- | The world's fastest humans can reach speeds of about 11 m/s. In order to increase his gravitational potential energy by an amount equal to his kinetic energy at full speed, how high would such a sprinter need to climb?
- | A 72 kg bike racer climbs a 1200-m-long section of road that has a slope of 4.3°. By how much does his gravitational potential energy change during this climb?
- || A 1000 kg wrecking ball hangs from a 15-m-long cable. The ball is pulled back until the cable makes an angle of 25° with the vertical. By how much has the gravitational potential energy of the ball changed?

24. || How far must you stretch a spring with  $k = 1000 \text{ N/m}$  to store  $200 \text{ J}$  of energy?
25. || How much energy can be stored in a spring with a spring constant of  $500 \text{ N/m}$  if its maximum possible stretch is  $20 \text{ cm}$ ?
26. || The spring in a retractable ballpoint pen is  $1.8 \text{ cm}$  long, with a  $300 \text{ N/m}$  spring constant. When the pen is retracted, the spring is compressed by  $1.0 \text{ mm}$ . When you click the button to extend the pen, you compress the spring by an additional  $6.0 \text{ mm}$ . How much energy is required to extend the pen?
27. |||| The elastic energy stored in your tendons can contribute up to  $35\%$  of your energy needs when running. Sports scientists have studied the change in length of the knee extensor tendon in sprinters and nonathletes. They find (on average) that the sprinters' tendons stretch  $41 \text{ mm}$ , while nonathletes' stretch only  $33 \text{ mm}$ . The spring constant for the tendon is the same for both groups,  $33 \text{ N/mm}$ . What is the difference in maximum stored energy between the sprinters and the nonathletes?
28. || Scallops use muscles to close their shells. Opening the shell is another story—muscles can only pull, they can't push. Instead of muscles, the shell is opened by a spring, a pad of a very elastic biological material called abductin. When the shell closes, the pad compresses; a restoring force then pushes the shell back open. The energy to open the shell comes from the elastic energy that was stored when the shell was closed. Figure P10.28 shows smoothed data for the restoring force of an abductin pad versus the compression. When the shell closes, the pad compresses by  $0.15 \text{ mm}$ . How much elastic potential energy is stored?

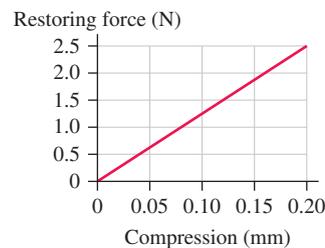


FIGURE P10.28

## Section 10.5 Thermal Energy

29. || Mark pushes his broken car  $150 \text{ m}$  down the block to his friend's house. He has to exert a  $110 \text{ N}$  horizontal force to push the car at a constant speed. How much thermal energy is created in the tires and road during this short trip?
30. || When you skid to a stop on your bike, you can significantly heat the small patch of tire that rubs against the road surface. Suppose a person skids to a stop by hitting the brake on his back tire, which supports half the  $80 \text{ kg}$  combined mass of the bike and rider, leaving a skid mark that is  $40 \text{ cm}$  long. Assume a coefficient of kinetic friction of  $0.80$ . How much thermal energy is deposited in the tire and the road surface?
31. || A  $900 \text{ N}$  crate slides  $12 \text{ m}$  down a ramp that makes an angle of  $35^\circ$  with the horizontal. If the crate slides at a constant speed, how much thermal energy is created?
32. || If you slide down a rope, it's possible to create enough thermal energy to burn your hands or your legs where they grip the rope. Suppose a  $40 \text{ kg}$  child slides down a rope at a playground, descending  $2.0 \text{ m}$  at a constant speed. How much thermal energy is created as she slides down the rope?
33. || A  $25 \text{ kg}$  child slides down a playground slide at a constant speed. The slide has a height of  $3.0 \text{ m}$  and is  $7.0 \text{ m}$  long. Using the law of conservation of energy, find the magnitude of the kinetic friction force acting on the child.
34. || Some runners train with parachutes that trail behind them to provide a large drag force. These parachutes are designed to have a large drag coefficient. One model expands to a square  $1.8 \text{ m}$  on a side, with a drag coefficient of  $1.4$ . A runner completes a  $200 \text{ m}$  run at  $5.0 \text{ m/s}$  with this chute trailing behind. How much thermal energy is added to the air by the drag force?

## Section 10.6 Conservation of Energy

35. || A boy reaches out of a window and tosses a ball straight up with a speed of  $10 \text{ m/s}$ . The ball is  $20 \text{ m}$  above the ground as he releases it. Use conservation of energy to find
- The ball's maximum height above the ground.
  - The ball's speed as it passes the window on its way down.
  - The speed of impact on the ground.
36. | The famous cliff divers of Acapulco leap from a perch  $35 \text{ m}$  above the ocean. How fast are they moving when they reach the water surface? What happens to their kinetic energy as they slow to a stop in the water?
37. || What minimum speed does a  $100 \text{ g}$  puck need to make it to the top of a frictionless ramp that is  $3.0 \text{ m}$  long and inclined at  $20^\circ$ ?
38. | You can, in an emergency, start a manual transmission car by putting it in neutral, letting the car roll down a hill to pick up speed, then putting it in gear and quickly letting out the clutch. If the car needs to be moving at  $3.5 \text{ m/s}$  for this to work, how high a hill do you need? (You can ignore friction and drag.)
39. || A  $1500 \text{ kg}$  car is approaching the hill shown in Figure P10.39 at  $10 \text{ m/s}$  when it suddenly runs out of gas.
- Can the car make it to the top of the hill by coasting?
  - If your answer to part a is yes, what is the car's speed after coasting down the other side?



FIGURE P10.39

40. | A  $480 \text{ g}$  peregrine falcon reaches a speed of  $75 \text{ m/s}$  in a vertical dive called a stoop. If we assume that the falcon speeds up under the influence of gravity only, what is the minimum height of the dive needed to achieve this speed?



41. || A fireman of mass  $80 \text{ kg}$  slides down a pole. When he reaches the bottom,  $4.2 \text{ m}$  below his starting point, his speed is  $2.2 \text{ m/s}$ . By how much has thermal energy increased during his slide?
42. || A  $20 \text{ kg}$  child slides down a  $3.0\text{-m}$ -high playground slide. She starts from rest, and her speed at the bottom is  $2.0 \text{ m/s}$ .
- What energy transfers and transformations occur during the slide?
  - What is the total change in the thermal energy of the slide and the seat of her pants?

43. || A hockey puck is given an initial speed of 5.0 m/s. If the coefficient of kinetic friction between the puck and the ice is 0.05, how far does the puck slide before coming to rest? Solve this problem using conservation of energy.
44. || Monica pulls her daughter Jessie in a bike trailer. The trailer and Jessie together have a mass of 25 kg. Monica starts up a 100-m-long slope that's 4.0 m high. On the slope, Monica's bike pulls on the trailer with a constant force of 8.0 N. They start out at the bottom of the slope with a speed of 5.3 m/s. What is their speed at the top of the slope?
45. || In the winter activity of tubing, riders slide down snow-covered slopes while sitting on large inflated rubber tubes. To get to the top of the slope, a rider and his tube, with a total mass of 80 kg, are pulled at a constant speed by a tow rope that maintains a constant tension of 340 N. How much thermal energy is created in the slope and the tube during the ascent of a 30-m-high, 120-m-long slope?
46. || Mosses don't spread by dispersing seeds; they disperse tiny spores. The spores are so small that they will stay aloft and move with the wind, but getting them to be windborne requires the moss to shoot the spores upward. Some species do this by using a spore-containing capsule that dries out and shrinks. The pressure of the air trapped inside the capsule increases. At a certain point, the capsule pops, and a stream of spores is ejected upward at 3.6 m/s, reaching an ultimate height of 20 cm. What fraction of the initial kinetic energy is converted to the final potential energy? What happens to the "lost" energy?
47. || A cyclist is coasting at 12 m/s when she starts down a 450-m-long slope that is 30 m high. The cyclist and her bicycle have a combined mass of 70 kg. A steady 12 N drag force due to air resistance acts on her as she coasts all the way to the bottom. What is her speed at the bottom of the slope?
48. || When you stand on a trampoline, the surface depresses below equilibrium, and the surface pushes up on you, as the data for a real trampoline in Figure P10.48 show. The linear variation of the force as a function of distance

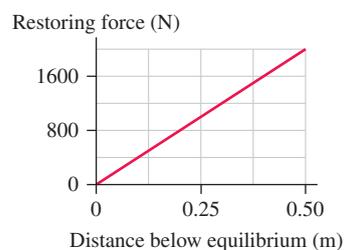


FIGURE P10.48

- means that we can model the restoring force as that of a spring. A 72 kg gymnast jumps on the trampoline. At the lowest point of his motion, he is 0.80 m below equilibrium. If we assume that all of the energy stored in the trampoline goes into his motion, how high above this lowest point will he rise?

49. || The 5.0-m-long rope in Figure P10.49 hangs vertically from a tree right at the edge of a ravine. A woman wants to use the rope to swing to the other side of the ravine. She runs as fast as she can, grabs the rope, and swings out over the ravine.

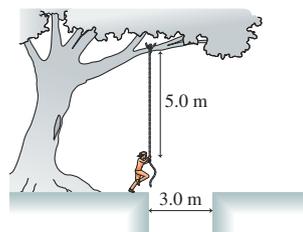


FIGURE P10.49

- a. As she swings, what energy conversion is taking place?  
 b. When she's directly over the far edge of the ravine, how much higher is she than when she started?

- c. Given your answers to parts a and b, how fast must she be running when she grabs the rope in order to swing all the way across the ravine?
50. || The Special Olympics raises money through "plane pull" events in which teams of 25 people compete to see who can pull a 74,000 kg airplane 3.7 m across the tarmac. The inertia of the plane is an issue—but so is the 14,000 N rolling friction force that works against the teams. If a team pulls with a constant force and moves the plane 3.7 m in 6.1 s (an excellent time), what fraction of the team's work goes to kinetic energy and what fraction goes to thermal energy?

### Section 10.7 Energy Diagrams

51. || Figure P10.51 is the potential-energy diagram for a 20 g particle that is released from rest at  $x = 1.0$  m.
- Will the particle move to the right or to the left? How can you tell?
  - What is the particle's maximum speed? At what position does it have this speed?
  - Where are the turning points of the motion?

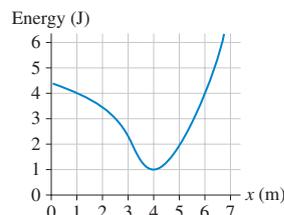


FIGURE P10.51

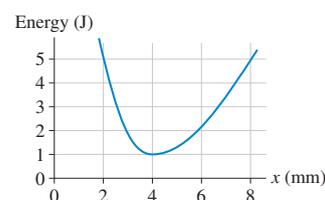


FIGURE P10.52

52. || For the potential-energy diagram in Figure P10.52, what is the maximum speed of a 2.0 g particle that oscillates between  $x = 2.0$  mm and  $x = 8.0$  mm?

### Section 10.8 Molecular Bonds and Chemical Energy

At normal temperatures and pressures, hydrogen gas is composed of  $H_2$  molecules. An energy diagram for a hydrogen molecule appears in Figure P10.53. Use this information to answer Problems 10.53 and 10.54.

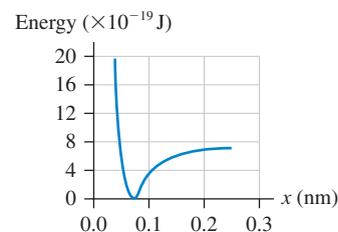


FIGURE P10.53

53. | How far apart are the individual atoms in a molecule of  $H_2$ ?  
 54. || What energy photon is needed to dissociate a molecule of  $H_2$ ?

### Section 10.9 Energy in Collisions

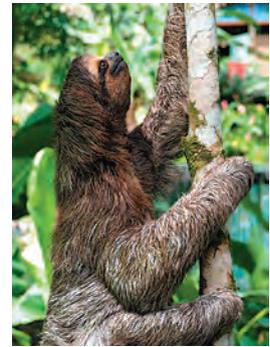
55. || A 50 g marble moving at 2.0 m/s strikes a 20 g marble at rest. What is the speed of each marble immediately after the collision? Assume the collision is perfectly elastic and the marbles collide head-on.
56. || Ball 1, with a mass of 100 g and traveling at 10 m/s, collides head-on with ball 2, which has a mass of 300 g and is initially at rest. What are the final velocities of each ball if the collision is (a) perfectly elastic? (b) perfectly inelastic?

57. I An air-track glider undergoes a perfectly inelastic collision with an identical glider that is initially at rest. What fraction of the first glider's initial kinetic energy is transformed into thermal energy in this collision?
58. I Two balls undergo a perfectly elastic head-on collision, with one ball initially at rest. If the incoming ball has a speed of 200 m/s, what are the final speed and direction of each ball if
- The incoming ball is *much* more massive than the stationary ball?
  - The stationary ball is *much* more massive than the incoming ball?

## Section 10.10 Power

59. II a. How much work must you do to push a 10 kg block of steel across a steel table at a steady speed of 1.0 m/s for 3.0 s? The coefficient of kinetic friction for steel on steel is 0.60.
- b. What is your power output while doing so?
60. II A shooting star is actually the track of a meteor, typically a small chunk of debris from a comet that has entered the earth's atmosphere. As the drag force slows the meteor down, its kinetic energy is converted to thermal energy, leaving a glowing trail across the sky. A typical meteor has a surprisingly small mass, but what it lacks in size it makes up for in speed. Assume that a meteor has a mass of 1.5 g and is moving at an impressive 50 km/s, both typical values. What power is generated if the meteor slows down over a typical 2.1 s? Can you see how this tiny object can make a glowing trail that can be seen hundreds of kilometers away?
61. I a. How much work does an elevator motor do to lift a 1000 kg elevator a height of 100 m at a constant speed?
- b. How much power must the motor supply to do this in 50 s at constant speed?
62. II A 500 kg horse can provide a steady output power of 750 W (that is, 1 horsepower) when pulling a load. How about a 38 kg sled dog? Data show that a 38 kg dog can pull a sled that requires a pulling force of 60 N at a steady 2.2 m/s. What are the specific power values for the dog and the horse? What is the minimum number of dogs needed to provide the same power as one horse?
63. III A 1000 kg sports car accelerates from 0 to 30 m/s in 10 s. What is the average power of the engine?
64. II A world-class sprinter running a 100 m dash was clocked at 5.4 m/s 1.0 s after starting running and at 9.8 m/s 1.5 s later. In which of these time intervals, 0 to 1.0 s or 1.0 s to 2.5 s, was his output power greater?
65. II An elite Tour de France cyclist can maintain an output power of 450 W during a sustained climb. At this output power, how long would it take an 85 kg cyclist (including the mass of his bike) to climb the famed 1100-m-high Alpe d'Huez mountain stage?
66. II A 70 kg human sprinter can accelerate from rest to 10 m/s in 3.0 s. During the same time interval, a 30 kg greyhound can accelerate from rest to 20 m/s. What is the specific power for each of these athletes?
67. II A 710 kg car drives at a constant speed of 23 m/s. It is subject to a drag force of 500 N. What power is required from the car's engine to drive the car
- On level ground?
  - Up a hill with a slope of  $2.0^\circ$ ?
68. II A 95 kg quarterback accelerates a 0.42 kg ball from rest to 24 m/s in 0.083 s. What is the specific power for this toss?

69. III An elevator weighing 2500 N ascends at a constant speed of 8.0 m/s. How much power must the motor supply to do this?
70. II Humans can produce an output power as great as 20 W/kg during extreme exercise. Sloths are not so energetic. At its maximum speed, a 4.0 kg sloth can climb a height of 6.0 m in 2.0 min. What's the specific power for this climb?



## General Problems

71. II A 550 kg elevator accelerates upward at  $1.2 \text{ m/s}^2$  for the first 15 m of its motion. How much work is done during this part of its motion by the cable that lifts the elevator?
72. II The energy yield of a nuclear weapon is often defined in terms of the equivalent mass of a conventional explosive. 1 ton of a conventional explosive releases 4.2 GJ. A typical nuclear warhead releases 250,000 times more, so the yield is expressed as 250 kilotons. That is a staggering explosion, but the asteroid impact that wiped out the dinosaurs was significantly greater. Assume that the asteroid was a sphere 10 km in diameter, with a density of  $2500 \text{ kg/m}^3$  and moving at 30 km/s. What energy was released at impact, in joules and in kilotons?
73. II A 2.3 kg box, starting from rest, is pushed up a ramp by a 10 N force parallel to the ramp. The ramp is 2.0 m long and tilted at  $17^\circ$ . The speed of the box at the top of the ramp is 0.80 m/s. Consider the system to be the box + ramp + earth.
- How much work  $W$  does the force do on the system?
  - What is the change  $\Delta K$  in the kinetic energy of the system?
  - What is the change  $\Delta U_g$  in the gravitational potential energy of the system?
  - What is the change  $\Delta E_{\text{th}}$  in the thermal energy of the system?
74. III A 55 kg skateboarder wants to just make it to the upper edge of a "half-pipe" with a radius of 3.0 m, as shown in Figure P10.74. What speed does he need at the bottom if he will coast all the way up? The skateboarder isn't a simple particle: Assume that his mass in a deep crouch is concentrated 0.75 m from the half-pipe. If he remains in that position all the way up, what initial speed does he need to reach the upper edge?

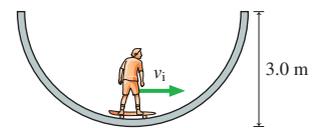


FIGURE P10.74

75. III Fleas have remarkable jumping ability. A 0.50 mg flea, jumping straight up, would reach a height of 40 cm if there were no air resistance. In reality, air resistance limits the height to 20 cm.
- What is the flea's kinetic energy as it leaves the ground?
  - At its highest point, what fraction of the initial kinetic energy has been converted to potential energy?
76. III You are driving your 1500 kg car at 20 m/s down a hill with a  $5.0^\circ$  slope when a deer suddenly jumps out onto the roadway. You slam on your brakes, skidding to a stop. How far do you skid before stopping if the kinetic friction force between your tires and the road is  $1.2 \times 10^4 \text{ N}$ ? Solve this problem using conservation of energy.
77. II A 20 kg child is on a swing that hangs from 3.0-m-long chains, as shown in Figure P10.77. What is her speed  $v_i$  at the

bottom of the arc if she swings out to a  $45^\circ$  angle before reversing direction?

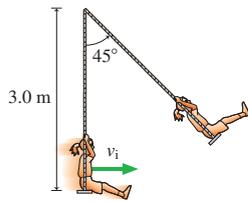


FIGURE P10.77

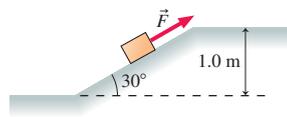


FIGURE P10.78

78. || Suppose you lift a 20 kg box by a height of 1.0 m.
- How much work do you do in lifting the box?  
Instead of lifting the box straight up, suppose you push it up a 1.0-m-high ramp that makes a  $30^\circ$  degree angle with the horizontal, as shown in Figure P10.78. Being clever, you choose a ramp with no friction.
  - How much force  $F$  is required to push the box straight up the slope at a constant speed?
  - How long is the ramp?
  - Use your force and distance results to calculate the work you do in pushing the box up the ramp. How does this compare to your answer to part a?
79. | The sledder shown in Figure P10.79 starts from the top of a frictionless hill and slides down into the valley. What initial speed  $v_i$  does the sledder need to just make it over the next hill?

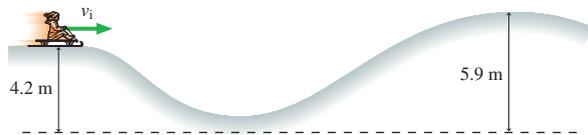


FIGURE P10.79

80. |||| In a physics lab experiment, a spring clamped to the table shoots a 20 g ball horizontally. When the spring is compressed 20 cm, the ball travels horizontally 5.0 m and lands on the floor 1.5 m below the point at which it left the spring. What is the spring constant?
81. |||| BIO The maximum energy a bone can absorb without breaking is surprisingly small. For a healthy human of mass 60 kg, experimental data show that the leg bones of both legs can absorb about 200 J.
- From what maximum height could a person jump and land rigidly upright on both feet without breaking his legs? Assume that all the energy is absorbed in the leg bones in a rigid landing.
  - People jump from much greater heights than this; explain how this is possible.
- Hint:** Think about how people land when they jump from greater heights.
82. || INT In an amusement park water slide, people slide down an essentially frictionless tube. The top of the slide is 3.0 m above the bottom where they exit the slide, moving horizontally, 1.2 m above a swimming pool. What horizontal distance do they travel from the exit point before hitting the water? Does the mass of the person make any difference?
83. || You have been asked to design a “ballistic spring system” to measure the speed of bullets. A bullet of mass  $m$  is fired into a block of mass  $M$ . The block, with the embedded bullet, then

slides across a frictionless table and collides with a horizontal spring whose spring constant is  $k$ . The opposite end of the spring is anchored to a wall. The spring’s maximum compression  $d$  is measured.

- Find an expression for the bullet’s initial speed  $v_B$  in terms of  $m$ ,  $M$ ,  $k$ , and  $d$ .

**Hint:** This is a two-part problem. The bullet’s collision with the block is an inelastic collision. What quantity is conserved in an inelastic collision? Subsequently the block hits a spring on a frictionless surface. What quantity is conserved in this collision?

- What was the speed of a 5.0 g bullet if the block’s mass is 2.0 kg and if the spring, with  $k = 50$  N/m, was compressed by 10 cm?
  - What fraction of the bullet’s initial kinetic energy is “lost”? Where did it go?
84. || Boxes A and B in Figure P10.84 have masses of 12.0 kg and 4.0 kg, respectively. The two boxes are released from rest. Use conservation of energy to find the boxes’ speed when box B has fallen a distance of 0.50 m. Assume a frictionless upper surface.

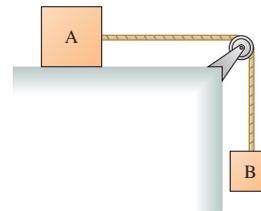
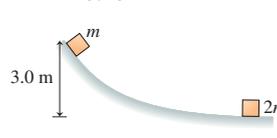


FIGURE P10.84

85. || INT Two coupled boxcars are rolling along at 2.5 m/s when they collide with and couple to a third, stationary boxcar.
- What is the final speed of the three coupled boxcars?
  - What fraction of the cars’ initial kinetic energy is transformed into thermal energy?
86. || INT A 50 g ball of clay traveling at 6.5 m/s hits and sticks to a 1.0 kg block sitting at rest on a frictionless surface.
- What is the speed of the block after the collision?
  - Show that the mechanical energy is *not* conserved in this collision. What percentage of the ball’s initial kinetic energy is “lost”? Where did this kinetic energy go?
87. || INT A package of mass  $m$  is released from rest at a warehouse loading dock and slides down a 3.0-m-high frictionless chute to a waiting truck. Unfortunately,
- 
- the truck driver went on a break without having removed the previous package, of mass  $2m$ , from the bottom of the chute as shown in Figure P10.87.
- Suppose the packages stick together. What is their common speed after the collision?
  - Suppose the collision between the packages is perfectly elastic. To what height does the package of mass  $m$  rebound?
88. |||| BIO Swordfish are capable of stunning output power for short bursts. A 650 kg swordfish has a cross-section area of  $0.92$  m<sup>2</sup> and a drag coefficient of 0.0091—exceptionally low due to a number of adaptations. Such a fish can sustain a speed of 30 m/s for a few seconds. Assume seawater has a density of  $1026$  kg/m<sup>3</sup>. What is the specific power for motion at this high speed?



89. || The mass of an elevator and its occupants is 1200 kg. The electric motor that lifts the elevator can provide a maximum power of 15 kW. What is the maximum constant speed at which this motor can lift the elevator?

### MCAT-Style Passage Problems

#### Tennis Ball Testing

A tennis ball bouncing on a hard surface compresses and then rebounds. The details of the rebound are specified in tennis regulations. Tennis balls, to be acceptable for tournament play, must have a mass of 57.5 g. When dropped from a height of 2.5 m onto a concrete surface, a ball must rebound to a height of 1.4 m. During impact, the ball compresses by approximately 6 mm.

90. | How fast is the ball moving when it hits the concrete surface? (Ignore air resistance.)  
 A. 5 m/s    B. 7 m/s    C. 25 m/s    D. 50 m/s
91. | If the ball accelerates uniformly when it hits the floor, what is its approximate acceleration as it comes to rest before rebounding?  
 A. 1000 m/s<sup>2</sup>    B. 2000 m/s<sup>2</sup>    C. 3000 m/s<sup>2</sup>    D. 4000 m/s<sup>2</sup>
92. | The ball's kinetic energy just after the bounce is less than just before the bounce. In what form does this lost energy end up?  
 A. Elastic potential energy  
 B. Gravitational potential energy  
 C. Thermal energy  
 D. Rotational kinetic energy

93. | By approximately what percent does the kinetic energy decrease?  
 A. 35%    B. 45%    C. 55%    D. 65%
94. | When a tennis ball bounces from a racket, the ball loses approximately 30% of its kinetic energy to thermal energy. A ball that hits a racket at a speed of 10 m/s will rebound with approximately what speed?  
 A. 8.5 m/s    B. 7.0 m/s    C. 4.5 m/s    D. 3.0 m/s

#### Work and Power in Cycling

When you ride a bicycle at constant speed, almost all of the energy you expend goes into the work you do against the drag force of the air. In this problem, assume that *all* of the energy expended goes into working against drag. As we saw in Section 5.6, the drag force on an object is approximately proportional to the square of its speed with respect to the air. For this problem, assume that  $F \propto v^2$  exactly and that the air is motionless with respect to the ground unless noted otherwise. Suppose a cyclist and her bicycle have a combined mass of 60 kg and she is cycling along at a speed of 5 m/s.

95. | If the drag force on the cyclist is 10 N, how much energy does she use in cycling 1 km?  
 A. 6 kJ    B. 10 kJ    C. 50 kJ    D. 100 kJ
96. | Under these conditions, how much power does she expend as she cycles?  
 A. 10 W    B. 50 W    C. 100 W    D. 200 W
97. | If she doubles her speed to 10 m/s, how much energy does she use in cycling 1 km?  
 A. 20 kJ    B. 40 kJ    C. 200 kJ    D. 400 kJ
98. | How much power does she expend when cycling at that speed?  
 A. 100 W    B. 200 W    C. 400 W    D. 1000 W
99. | Upon reducing her speed back down to 5 m/s, she hits a headwind of 5 m/s. How much power is she expending now?  
 A. 100 W    B. 200 W    C. 500 W    D. 1000 W