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A Strategic Approach

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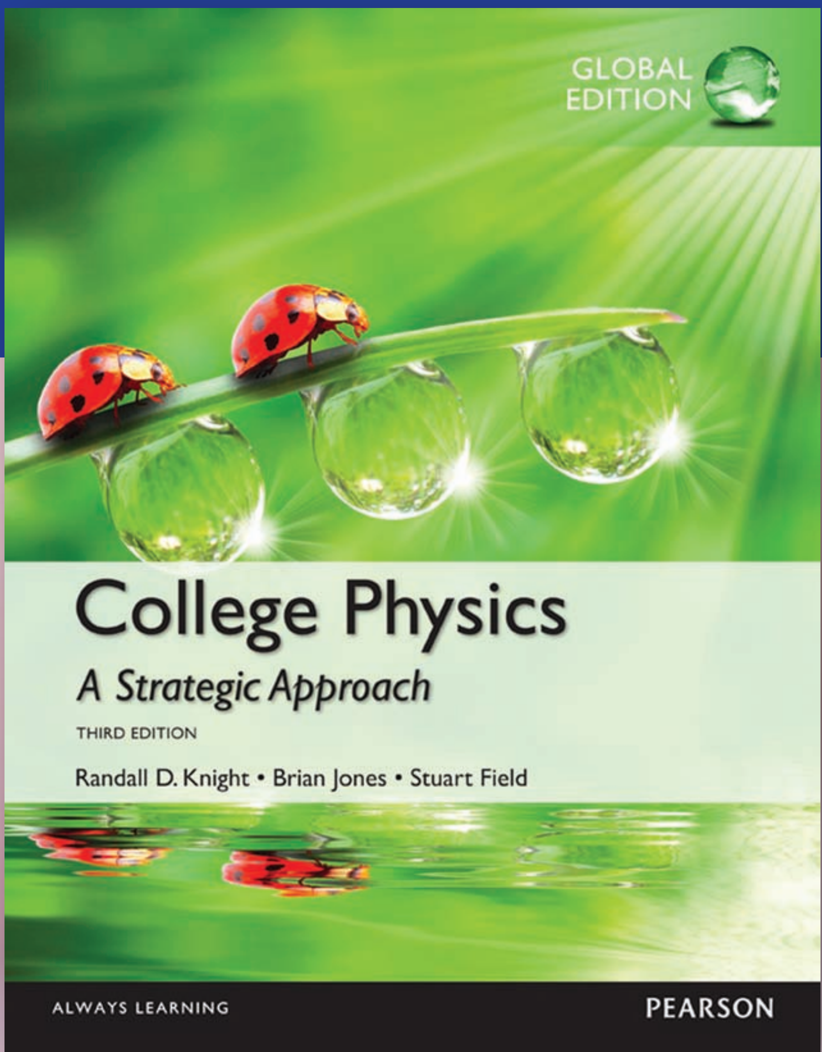

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CONCEPTUAL EXAMPLE 10.4 Kinetic energy changes for a car

Compare the increase in a 1000 kg car's kinetic energy as it speeds up by 5.0 m/s, starting from 5.0 m/s, to its increase in kinetic energy as it speeds up by 5.0 m/s, starting from 10 m/s.

REASON The change in the car's kinetic energy in going from 5.0 m/s to 10 m/s is

$$\Delta K_{5\to10} = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

This gives

$$\Delta K_{5\to10} = \frac{1}{2}(1000\text{ kg})(10\text{ m/s})^2 - \frac{1}{2}(1000\text{ kg})(5.0\text{ m/s})^2$$
$$= 3.8 \times 10^4\text{ J}$$

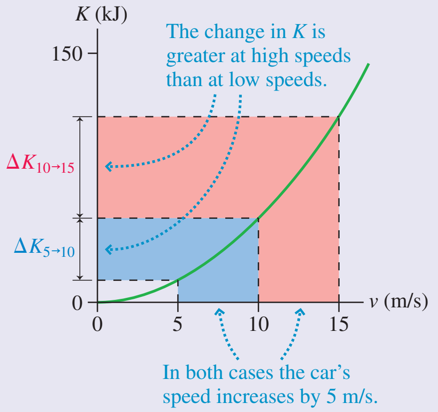
Similarly, increasing from 10 m/s to 15 m/s requires

$$\Delta K_{10\to15} = \frac{1}{2}(1000\text{ kg})(15\text{ m/s})^2 - \frac{1}{2}(1000\text{ kg})(10\text{ m/s})^2$$
$$= 6.3 \times 10^4\text{ J}$$

Even though the increase in the car's *speed* is the same in both cases, the increase in kinetic energy is substantially greater in the second case.

ASSESS Kinetic energy depends on the *square* of the speed v. In **FIGURE 10.11**, which plots kinetic energy versus speed, we see that the energy of the car increases rapidly with speed. We can also see graphically why the change in K for a 5 m/s change in v is greater at high speeds than at low speeds. In part this is why it's harder to accelerate your car at high speeds than at low speeds.

FIGURE 10.11 The kinetic energy increases as the *square* of the speed.

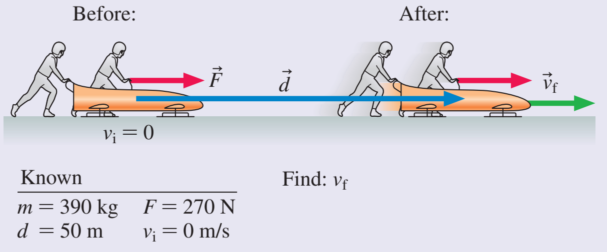


EXAMPLE 10.5 Speed of a bobsled after pushing

A two-man bobsled has a mass of 390 kg. Starting from rest, the two racers push the sled for the first 50 m with a net force of 270 N. Neglecting friction, what is the sled's speed at the end of the 50 m?

PREPARE Because friction is negligible, there is no change in the sled's thermal energy. And, because the sled's height is constant, its gravitational potential energy is unchanged as well. Thus the work-energy equation is simply $\Delta K = W$. We can therefore find the sled's final kinetic energy, and hence its speed, by finding the work done by the racers as they push on the sled. **FIGURE 10.12** lists the known quantities and the quantity v_f that we want to find.

FIGURE 10.12 The work done by the pushers increases the sled's kinetic energy.



SOLVE From the work-energy equation, Equation 10.3, the change in the sled's kinetic energy is $\Delta K = K_f - K_i = W$. The sled's final kinetic energy is thus

$$K_f = K_i + W$$

Using our expressions for kinetic energy and work, we get

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

Because $v_i = 0$, the work-energy equation reduces to

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

We can solve for the final speed to get

$$v_f = \sqrt{\frac{2Fd}{m}} = \sqrt{\frac{2(270\text{ N})(50\text{ m})}{390\text{ kg}}} = 8.3\text{ m/s}$$

ASSESS 8.3 m/s, about 18 mph, seems a reasonable speed for two fast pushers to attain.

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

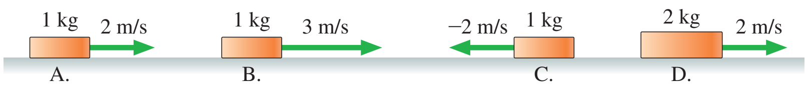
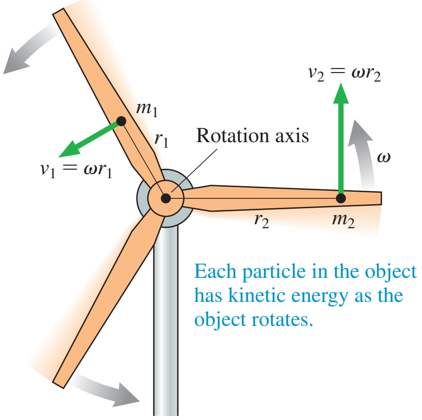


FIGURE 10.13 Rotational kinetic energy is due to the circular motion of the particles.



Rotational Kinetic Energy

We've just found an expression for the kinetic energy of an object moving along a line or some other path. This energy is called **translational kinetic energy.** Consider now an object rotating about a fixed axis, such as a windmill blade. Although the blade has no overall translational motion, each particle in the blade is moving and hence has kinetic energy. Adding up the kinetic energy for all the particles that make up the blade, we find that the blade has **rotational kinetic energy,** the kinetic energy due to rotation.

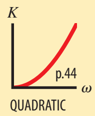
FIGURE 10.13 shows two of the particles making up a windmill blade that rotates with angular velocity ω. Recall from ◀◀ SECTION 7.1 that a particle moving with angular velocity ω in a circle of radius r has a speed $v = \omega r$. Thus particle 1, which rotates in a circle of radius r_1, moves with speed $v_1 = r_1\omega$ 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

$$K_{\text{rot}} = \frac{1}{2}I\omega^2 \tag{10.9}$$

Rotational kinetic energy of an object with moment of inertia I and angular velocity ω



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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:

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

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 10.6 Kinetic energy of a bicycle

Bike 1 has a 10.0 kg frame and 1.00 kg wheels; bike 2 has a 9.00 kg frame and 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 ridden at 12.0 m/s? Model each wheel as a hoop of radius 35.0 cm.

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 As the cyclists on these bikes accelerate from rest to 12 m/s, they must convert some of their internal chemical energy into the kinetic energy of the bikes. Racing cyclists want to use as little of their own energy as possible. Although both bikes have the same total mass, the one with the lighter wheels will take less energy to get it moving. Shaving a little extra weight off your wheels is more useful than taking that same weight off your frame.

It's important that racing bike wheels are as light as possible.

10.4 Potential Energy

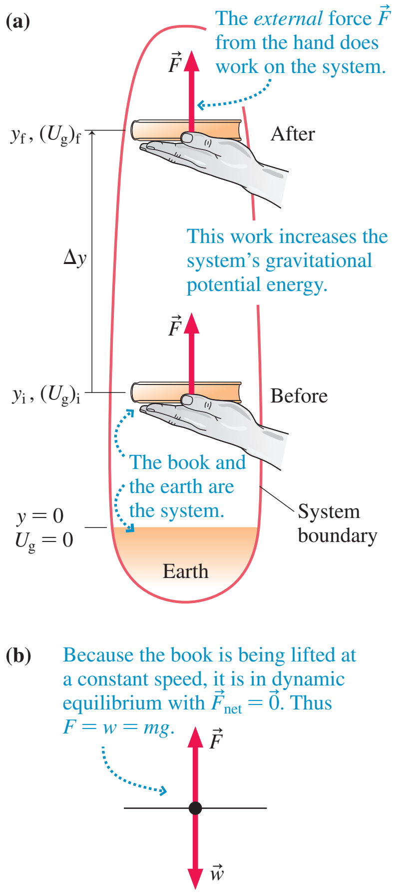
When two or more objects in a system interact, it is sometimes possible to *store* energy in the system in a way that the energy can be easily recovered. For instance, the earth and a ball interact by the gravitational force between them. If the ball is lifted up into the air, energy is stored in the 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.

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 crate is pushed across the floor, the crate and the floor interact via the force of friction, and the work done on the system is converted into thermal energy. But this energy is *not* stored up for later recovery—it slowly diffuses into the environment and cannot be recovered.

Interaction forces that can store useful energy are called **conservative forces.** The name comes from the important fact that, as we'll see, the mechanical energy of a system is *conserved* when only conservative forces act. Gravity and elastic forces are conservative forces, and later we'll find that the electric force is a conservative force as well. Friction, on the other hand, is a **nonconservative force.** When two objects interact via a friction force, energy is not stored. It is usually transformed into thermal energy.

Let's look more closely at the potential energies associated with the two conservative forces—gravity and springs—that we'll study in this chapter.

FIGURE 10.14 Lifting a book increases the system's gravitational potential energy.



Gravitational Potential Energy

To find an expression for gravitational potential energy, let's consider the system of the book and the earth shown in **FIGURE 10.14a**. 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

$$(U_g)_f = (U_g)_i + W \tag{10.11}$$

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 10.14b**, we see that $F = mg$. Thus $W = mg\,\Delta y$, and so

$$(U_g)_f = (U_g)_i + mg\Delta y \tag{10.12}$$

Because our final height was greater than our initial height, Δy 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.**

Equation 10.12 gives the final gravitational potential energy $(U_g)_f$ in terms of its initial value $(U_g)_i$. But what is the value of $(U_g)_i$? We can gain some insight by writing Equation 10.12 in terms of energy *changes:*

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

For example, if we lift a 1.5 kg book up by $\Delta y = 2.0$ m, we increase the system's gravitational potential energy by $\Delta U_g = (1.5 \text{ kg})(9.8 \text{ m/s}^2)(2.0 \text{ m}) = 29.4$ 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

$$U_g = mgy \tag{10.13}$$

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

EXAMPLE 10.7 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.

PREPARE We choose $y = 0$ m and hence $U_g = 0$ J at the ground floor of the building.

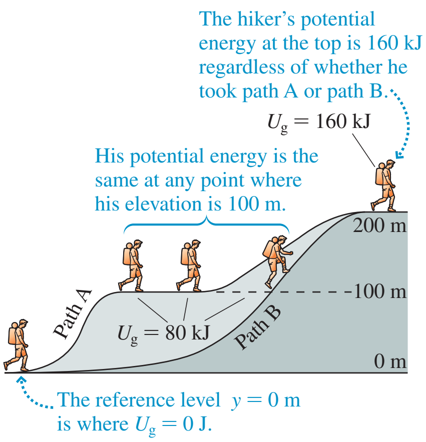
SOLVE At the top, the racer's gravitational potential energy is

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

Because the racer's gravitational potential energy was 0 J at the ground floor, the change in his potential energy is 2.2×10^5 J.

ASSESS This is a large amount of energy. According to Table 10.1, it's comparable to the energy of a speeding car. But if you think how hard it would be to climb the Empire State Building, it seems like a plausible result.

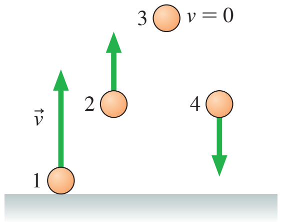
FIGURE 10.15 The hiker's gravitational potential energy depends only on his height above the $y = 0$ m reference level.



An important conclusion from Equation 10.13 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 291, 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 10.15**. 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.



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 reads

$$\Delta U_s = W \tag{10.14}$$

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 10.16 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 Δx is the displacement of the end of the spring from its equilibrium position and k is the spring constant. In Figure 10.16 we have set the origin of our coordinate system at the equilibrium position. The displacement from equilibrium Δx 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 $F_{avg} = \frac{1}{2}kx$. Thus the work done by the hand is

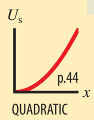
$$W = F_{avg}d = F_{avg}x = \left(\frac{1}{2}kx\right)x = \frac{1}{2}kx^2$$

This work is stored as potential energy in the spring, so we can use Equation 10.14 to find that as the spring is compressed, the elastic potential energy increases by

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

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

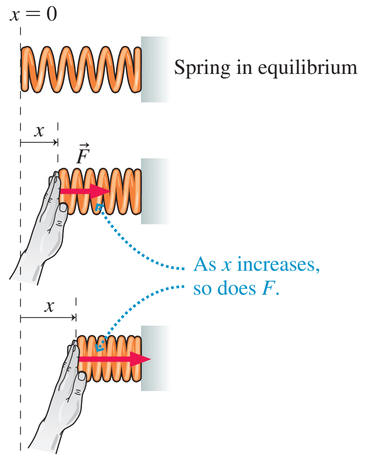
$$U_s = \frac{1}{2}kx^2 \tag{10.15}$$

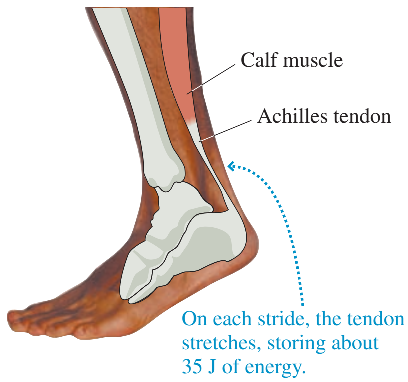


Elastic potential energy of a spring displaced a distance x from equilibrium (assuming $U_s = 0$ when the end of the spring is at $x = 0$)

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 10.16) or negative (the spring is stretched). ◀

FIGURE 10.16 The force required to compress a spring is not constant.





Spring in your step BIO As you run, you lose some of your mechanical energy each time your foot strikes the ground; this energy is transformed into unrecoverable thermal energy. Luckily, about 35% of the decrease of your mechanical energy when your foot lands 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. This recovered energy reduces the amount of internal chemical energy you use, increasing your efficiency.

EXAMPLE 10.8 Pulling back on a bow

An archer pulls back the string on her bow to a distance of 70 cm from its equilibrium position. To hold the string at this position takes a force of 140 N. How much elastic potential energy is stored in the bow?

PREPARE A bow is an elastic material, so we will model it as obeying Hooke's law, $F_s = -kx$, where x is the distance the string is pulled back. We can use the force required to hold the string, and the distance it is pulled back, to find the bow's spring constant k. Then we can use Equation 10.15 to find the elastic potential energy.

SOLVE From Hooke's law, the spring constant is

$$k = \frac{F}{x} = \frac{140\ \text{N}}{0.70\ \text{m}} = 200\ \text{N/m}$$

Then the elastic potential energy of the flexed bow is

$$U_s = \frac{1}{2}kx^2 = \frac{1}{2}(200\ \text{N/m})(0.70\ \text{m})^2 = 49\ \text{J}$$

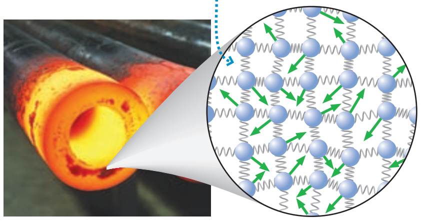
ASSESS When the arrow is released, this elastic potential energy will be transformed into the kinetic energy of the arrow. According to Table 10.1, the kinetic energy of a 100 mph fastball is about 150 J, so 49 J of kinetic energy for a fast-moving arrow seems reasonable.

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?

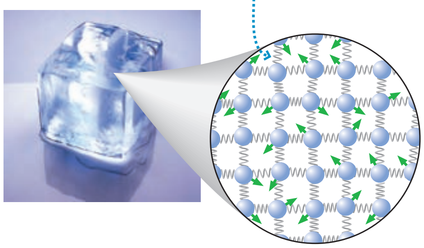
A. −4 J B. −2 J C. 2 J D. 4 J

FIGURE 10.17 A molecular view of thermal energy.

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



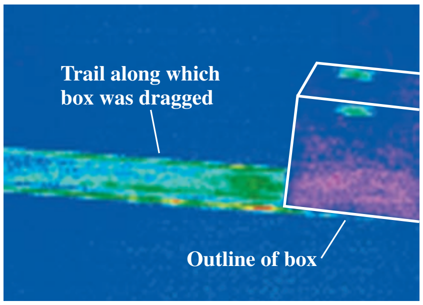
Cold object: Slow-moving molecules have little kinetic and elastic potential energy.



10.5 Thermal Energy

We noted earlier that thermal energy is related to the microscopic motion of the molecules of an object. As **FIGURE 10.17** shows, the molecules in a hot object jiggle around their average positions more than the molecules 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.** Increasing an object's thermal energy corresponds to increasing its temperature.

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



Creating Thermal Energy

FIGURE 10.18 shows a thermograph of a heavy box and the floor across which it has just been dragged. In this image, warmer areas appear light blue or green. You can see that the bottom of the box and the region of the floor that the box moved over are noticeably warmer than their surroundings. In the process of dragging the box, thermal energy has appeared in the box and the floor.

We can find a quantitative expression for the change in thermal energy by considering such a box pulled by a rope at a constant speed. 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: $F = f_k$.