

# 9

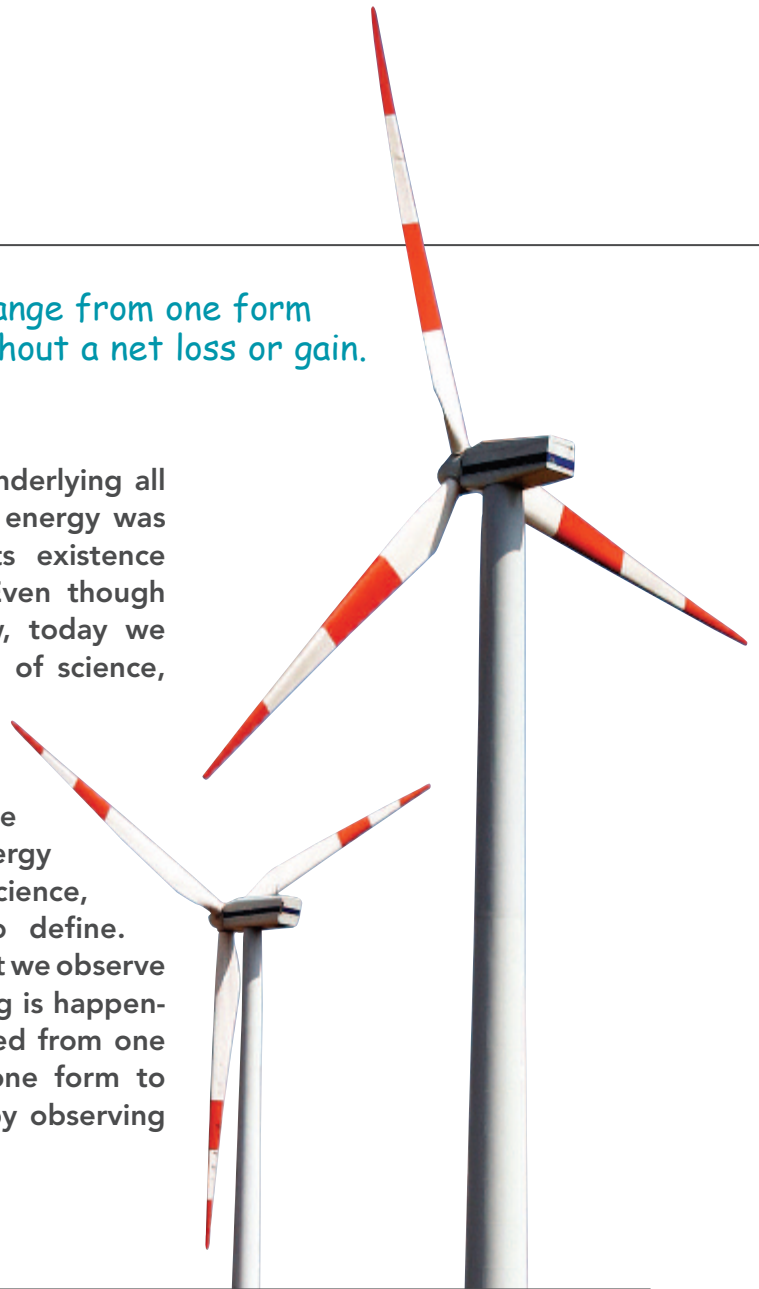
# ENERGY



## THE BIG IDEA

Energy can change from one form to another without a net loss or gain.

**E**nergy is the most central concept underlying all of science. Surprisingly, the idea of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Even though the concept of energy is relatively new, today we find it ingrained not only in all branches of science, but in nearly every aspect of human society. We are all quite familiar with energy. Energy comes to us from the sun in the form of sunlight, it is in the food we eat, and it sustains life. Energy may be the most familiar concept in science, yet it is one of the most difficult to define. Persons, places, and things have energy, but we observe only the effects of energy when something is happening—only when energy is being transferred from one place to another or transformed from one form to another. We begin our study of energy by observing a related concept, *work*.



## discover!

### Where Does a Popper Toy Get Its Energy?

1. Turn a popper (slice of a hollow rubber ball) inside out and place it on a table or floor. Observe what happens to the popper toy.
2. Once again compress the popper and drop it onto a table or floor. Observe what happens to the popper.

### Analyze and Conclude

1. **Observing** What propelled the popper into the air?
2. **Predicting** Will dropping the popper from greater heights make the popper jump higher? Explain.
3. **Making Generalizations** Describe where the popper got the energy to move upward and downward through the air.

## 9.1 Work

The previous chapter showed that the change in an object's motion is related to both force and how long the force acts. "How long" meant time. Remember, the quantity  $\text{force} \times \text{time}$  is called *impulse*. But "how long" need not always mean time. It can mean distance also. When we consider the quantity  $\text{force} \times \text{distance}$ , we are talking about the concept of work. **Work** is the product of the net force on an object and the distance through which the object is moved.

We do work when we lift a load against Earth's gravity. The heavier the load or the higher we lift it, the more work we do.

✔ **Work is done when a force acts on an object and the object moves in the direction of the force.**

Let's look at the simplest case, in which the force is constant and the motion takes place in a straight line in the direction of the force. Then the work done on an object by an applied force is the product of the force and the distance through which the object is moved.<sup>9.1</sup>

$$\text{work} = \text{net force} \times \text{distance}$$

In equation form,

$$W = Fd$$

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

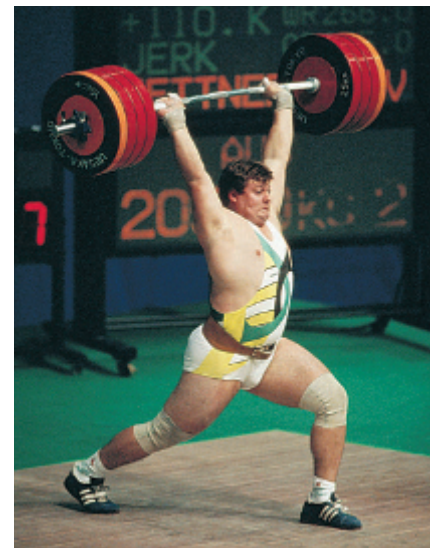
Notice that the definition of work involves both a force *and* a distance. The weight lifter in Figure 9.1 is holding a barbell weighing 1000 N over his head. He may get really tired holding it, but if the barbell is not moved by the force he exerts, he does no work on the barbell. Work may be done on the muscles by stretching and squeezing them, which is force times distance on a biological scale, but this work is not done on the barbell. Lifting the barbell, however, is a different story. When the weight lifter raises the barbell from the floor, he is doing work on it.

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

### think!

Suppose that you apply a 60-N horizontal force to a 32-kg package, which pushes it 4 meters across a mailroom floor. How much work do you do on the package?

Answer: 9.1



**FIGURE 9.1** ▲

Work is done in lifting the barbell but not in holding it steady. If the barbell could be lifted twice as high, the weight lifter would have to do twice as much work.

The physics of a weightlifter holding a stationary barbell overhead is no different than the physics of a table supporting a barbell's weight. No net force acts on the barbell, no work is done on it, and no change in its energy occurs.



The other category of work is work done to change the speed of an object. This kind of work is done in bringing an automobile up to speed or in slowing it down. In both categories, work involves a transfer of energy between something and its surroundings.

The unit of measurement for work combines a unit of force, N, with a unit of distance, m. The resulting unit of work is the newton-meter (N·m), also called the **joule** (rhymes with cool) in honor of James Joule. One joule (J) of work is done when a force of 1 N is exerted over a distance of 1 m, as in lifting an apple over your head. For larger values, we speak of kilojoules (kJ)—thousands of joules—or megajoules (MJ)—millions of joules. The weight lifter in Figure 9.1 does work on the order of kilojoules. To stop a loaded truck going at 100 km/h takes megajoules of work.

**CONCEPT CHECK:** When is work done on an object?

## 9.2 Power

The definition of work says nothing about how long it takes to do the work. When carrying a load up some stairs, you do the same amount of work whether you walk or run up the stairs. So why are you more tired after running upstairs in a few seconds than after walking upstairs in a few minutes? To understand this difference, we need to talk about how fast the work is done, or power. **Power** is the rate at which work is done. ✓ **Power equals the amount of work done divided by the time interval during which the work is done.**

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

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

The unit of power is the joule per second, also known as the **watt**, in honor of James Watt, the eighteenth-century developer of the steam engine. One watt (W) of power is expended when one joule of work is done in one second. One kilowatt (kW) equals 1000 watts. One megawatt (MW) equals one million watts. The space shuttle in Figure 9.2 uses 33,000 MW of power.

**FIGURE 9.2** ▼

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



In the United States, we customarily rate engines in units of horsepower and electricity in kilowatts, but either may be used. In the metric system of units, automobiles are rated in kilowatts. One horsepower (hp) is the same as 0.75 kW, so an engine rated at 134 hp is a 100-kW engine.

**CONCEPT CHECK:** How can you calculate power?

## think!

If a forklift is replaced with a new forklift that has twice the power, how much greater a load can it lift in the same amount of time? If it lifts the same load, how much faster can it operate? *Answer: 9.2*

## 9.3 Mechanical Energy

When work is done by an archer in drawing back a bowstring, the bent bow acquires the ability to do work on the arrow. When work is done to stretch a rubber band, the rubber band acquires the ability to do work on an object when it is released. When work is done to wind a spring mechanism, the spring acquires the ability to do work on various gears to run a clock, ring a bell, or sound an alarm.

In each case, something has been acquired that enables the object to do work. It may be in the form of a compression of atoms in the material of an object; a physical separation of attracting bodies; or a rearrangement of electric charges in the molecules of a substance. The property of an object or system that enables it to do work is **energy**.<sup>9.3</sup> Like work, energy is measured in joules. It appears in many forms that will be discussed in the following chapters. For now we will focus on mechanical energy. **Mechanical energy** is the energy due to the position of something or the movement of something. ✓ **The two forms of mechanical energy are kinetic energy and potential energy.**

**CONCEPT CHECK:** What are the two forms of mechanical energy?

## discover!

### What Happens When You Do Work on Sand?

1. Pour a handful of dry sand into a can.
2. Measure the temperature of the sand with a thermometer.
3. Remove the thermometer and cover the can.
4. Shake the can vigorously for a minute or so. Now remove the cover and measure the temperature of the sand again.
5. Describe what happened to the temperature of the sand after you shook it.
6. **Think** How can you explain the change in temperature of the sand in terms of work and energy?



What tells you whether or not work is done on something is a change in its energy. No change in energy means that no net work was done on it.



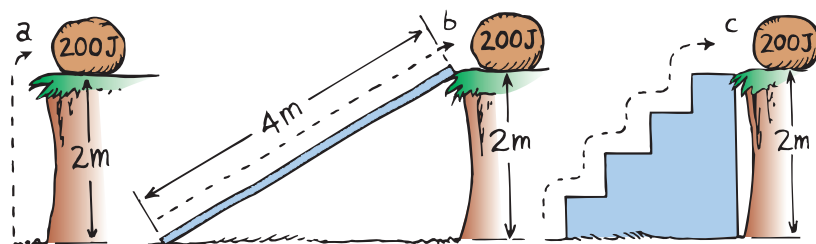
## 9.4 Potential Energy

An object may store energy by virtue of its position. Energy that is stored and held in readiness is called **potential energy** (PE) because in the stored state it has the potential for doing work. ✓ **Three examples of potential energy are elastic potential energy, chemical energy, and gravitational potential energy.**

**Elastic Potential Energy** A stretched or compressed spring, for example, has a potential for doing work. This type of potential energy is *elastic potential energy*. When a bow is drawn back, energy is stored in the bow. The bow can do work on the arrow. A stretched rubber band has potential energy because of its position. If the rubber band is part of a slingshot, it is also capable of doing work.

**Chemical Energy** The chemical energy in fuels is also potential energy. It is actually energy of position at the submicroscopic level. This energy is available when the positions of electric charges within and between molecules are altered, that is, when a chemical change takes place. Any substance that can do work through chemical reactions possesses chemical energy. Potential energy is found in fossil fuels, electric batteries, and the food we eat.

**Gravitational Potential Energy** Work is required to elevate objects against Earth's gravity. The potential energy due to elevated positions is *gravitational potential energy*. Water in an elevated reservoir and the raised ram of a pile driver have gravitational potential energy.



**FIGURE 9.3** ▲

The potential energy of the 100-N boulder with respect to the ground below is 200 J in each case because the work done in elevating it 2 m is the same whether the boulder is **a.** lifted with 100 N of force, **b.** pushed up the 4-m incline with 50 N of force, or **c.** lifted with 100 N of force up each 0.5-m stair. No work is done in moving it horizontally, neglecting friction.

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

$$\text{gravitational potential energy} = \text{weight} \times \text{height}$$
$$\text{PE} = mgh$$

Note that the height is the distance above some arbitrarily chosen reference level, such as the ground or the floor of a building. The gravitational potential energy,  $mgh$ , is relative to that level and depends only on  $mg$  and  $h$ . For example, if you're in a third-story classroom and a ball rests on the floor, you can say the ball is at height 0. Lift it and it has positive PE relative to the floor. Toss it out the window and it has negative PE relative to the floor. We can see in Figure 9.3 that the potential energy of the boulder at the top of the ledge does not depend on the path taken to get it there.

Hydroelectric power stations make use of gravitational potential energy. When a need for power exists, water from an upper reservoir flows through a long tunnel to an electric generator. Gravitational potential energy of the water is converted to electrical energy. Most of this energy is delivered to consumers during daylight hours. A few power stations *buy* electricity at night, when there is much less demand. They use this electricity to pump water from a lower reservoir back up to the upper reservoir. This process, called *pumped storage*, is practical when the cost of electricity is less at night. Then electrical energy is transformed to gravitational potential energy. Although the pumped storage system doesn't generate any overall net energy, it helps to smooth out differences between energy demand and supply.

**CONCEPT CHECK:** Name three examples of potential energy.

### think!

You lift a 100-N boulder 1 m.

- How much work is done on the boulder?
- What power is expended if you lift the boulder in a time of 2 s?
- What is the gravitational potential energy of the boulder in the lifted position? *Answer: 9.4*



For: Links on potential energy

Visit: [www.SciLinks.org](http://www.SciLinks.org)

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When  $h$  is below a reference point, PE is negative relative to that reference point.



Refer to Note 9.5 in Appendix G for the derivation of the equation  $W = \Delta KE$ .



## 9.5 Kinetic Energy

Push on an object and you can set it in motion. If an object is moving, then it is capable of doing work. It has energy of motion, or **kinetic energy** (KE). The kinetic energy of an object depends on the mass of the object as well as its speed. It is equal to half the mass multiplied by the square of the speed.

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

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

When you throw a ball, you do work on it to give it speed as it leaves your hand. The moving ball can then hit something and push it, doing work on what it hits. ✓ **The kinetic energy of a moving object is equal to the work required to bring it to its speed from rest, or the work the object can do while being brought to rest.**<sup>9.5</sup>

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

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

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

**CONCEPT:** How are work and the kinetic energy of a moving **CHECK:** object related?

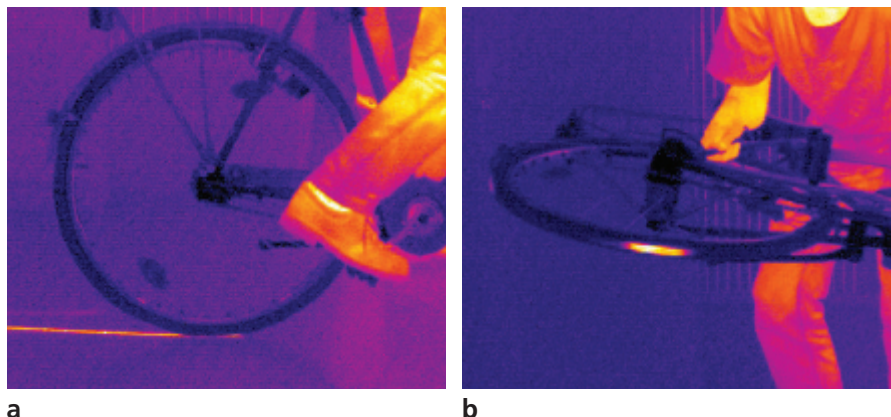


### Physics of Sports

#### The Sweet Spot

The sweet spot of a softball bat or a tennis racquet is the place where the ball's impact produces minimum vibrations in the racquet or bat. Strike a ball at the sweet spot and it goes faster and farther. Strike a ball in another part of the bat or racquet, and vibrations can occur that sting your hand! From an energy point of view, there is energy in the vibrations of the bat or racquet. There is energy in the ball after being struck. Energy that is not in vibrations is energy available to the ball. Do you see why a ball will go faster and farther when struck at the sweet spot?





◀ **FIGURE 9.4**  
 Due to friction, energy is transferred both into the floor and into the tire when the bicycle skids to a stop. **a.** An infrared camera reveals the heated tire track on the floor. **b.** The warmth of the tire is also revealed.

## 9.6 Work-Energy Theorem

So we see that to increase the kinetic energy of an object, work must be done on it. Or if an object is moving, work is required to bring it to rest. In either case, the change in kinetic energy is equal to the net work done. The **work-energy theorem** describes the relationship between work and energy. ✓ **The work-energy theorem states that whenever work is done, energy changes.** We abbreviate “change in” with the delta symbol,  $\Delta$ , and say

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

Work equals change in kinetic energy. The work in this equation is the *net* work—that is, the work based on the net force.

The work-energy theorem emphasizes the role of *change*. If there is no change in an object’s kinetic energy, then we know no net work was done on it. Push against a box on a floor. If it doesn’t slide, then you are not doing work on the box. Put the box on a very slippery floor and push again. If there is no friction at all, the work of your push times the distance of your push appears as kinetic energy of the box. If there is some friction, it is the *net* force of your push minus the frictional force that is multiplied by distance to give the gain in kinetic energy. If the box moves at a constant speed, you are pushing just hard enough to overcome friction. Then the net force and net work are zero, and, according to the work-energy theorem,  $\Delta\text{KE} = 0$ . The kinetic energy doesn’t change.

The work-energy theorem applies to decreasing speed as well. The more kinetic energy something has, the more work is required to stop it. Twice as much kinetic energy means twice as much work. When we apply the brakes to slow a car, or the bike in Figure 9.4, we do work on it. This work is the friction force supplied by the brakes multiplied by the distance over which the friction force acts.

### think!

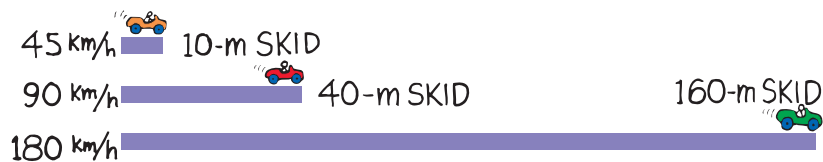
A friend says that if you do 100 J of work on a moving cart, the cart will gain 100 J of KE. Another friend says this depends on whether or not there is friction. What is your opinion of these statements? **Answer: 9.6.1**



Automobile brakes convert KE to heat. Professional drivers are familiar with another way to brake—shift to low gear and let the engine slow the vehicle. Hybrid cars similarly divert braking energy to stored energy in batteries.



Interestingly, the maximum friction that the brakes can supply is nearly the same whether the car moves slowly or quickly. In a panic stop with antilock brakes, the only way for the brakes to do more work is to act over a longer distance. A car moving at twice the speed of another has four times ( $2^2 = 4$ ) as much kinetic energy, and will require four times as much work to stop. Since the frictional force is nearly the same for both cars, the faster one takes four times as much distance to stop. The same rule applies to older-model brakes that can lock the wheels. The force of friction on a skidding tire is also nearly independent of speed. So, as accident investigators are well aware, an automobile going 100 kilometers per hour, with four times the kinetic energy it would have at 50 kilometers per hour, skids four times as far with its wheels locked as it would with a speed of 50 kilometers per hour. Figure 9.5 shows the skid distances for a car moving at 45 km/h, 90 km/h, and 180 km/h. The distances would be even greater if the driver's reaction time were taken into account. Kinetic energy depends on speed *squared*.



**FIGURE 9.5** ▲ Typical stopping distances for cars equipped with antilock brakes traveling at various speeds. The work done to stop the car is friction force  $\times$  distance of slide.

Kinetic energy often appears hidden in different forms of energy, such as heat, sound, light, and electricity. Random molecular motion is sensed as heat. Sound consists of molecules vibrating in rhythmic patterns. Even light energy originates in the motion of electrons within atoms. Electrons in motion make electric currents. We see that kinetic energy plays a role in other energy forms.

**CONCEPT CHECK:** What is the work-energy theorem?

### think!

When the brakes of a car are locked, the car skids to a stop. How much farther will the car skid if it's moving 3 times as fast?

Answer: 9.6.2

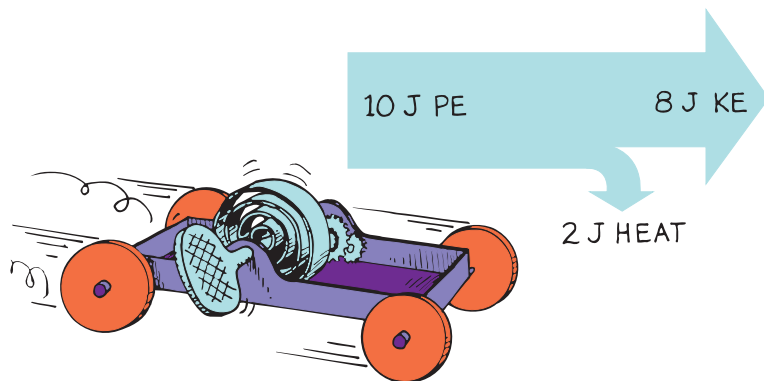
## 9.7 Conservation of Energy

More important than knowing *what energy is*, is understanding how it behaves—*how it transforms*. We can understand nearly every process that occurs in nature if we analyze it in terms of a transformation of energy from one form to another.

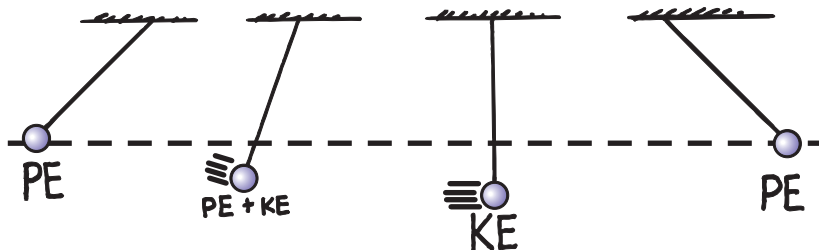
As you draw back the arrow in a bow, as shown in Figure 9.6, you do work stretching the bow. The bow then has potential energy. When released, the arrow has kinetic energy equal to this potential energy. It delivers this energy to its target. The small distance the arrow moves multiplied by the average force of impact doesn't quite match the kinetic energy of the target. But if you investigate further, you'll find that both the arrow and target are a bit warmer. By how much? By the energy difference. Energy changes from one form to another without a net loss or a net gain.

The study of the various forms of energy and the transformations from one form into another is the **law of conservation of energy**.

✔ The law of conservation of energy states that energy cannot be created or destroyed. It can be transformed from one form into another, but the total amount of energy never changes.



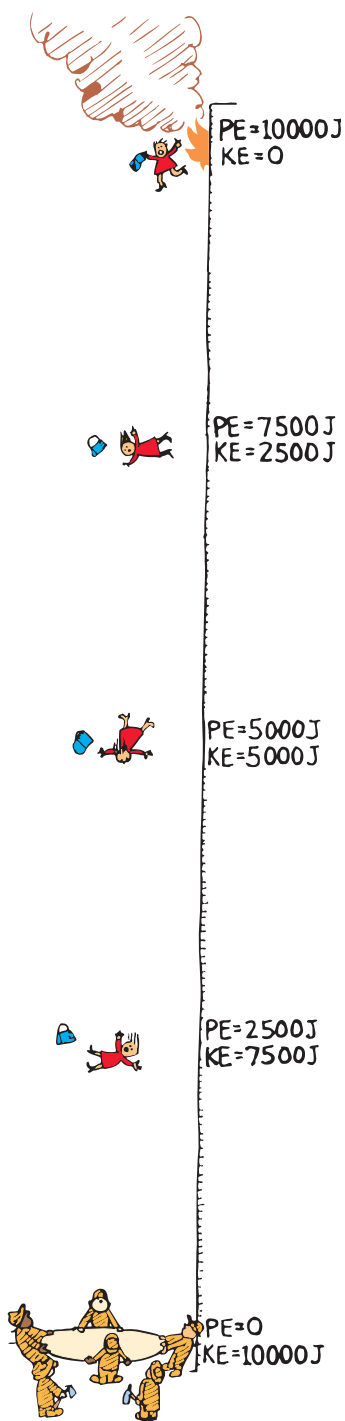
Figures 9.7 and 9.8 demonstrate conservation of energy in two different systems. When you consider any system in its entirety, whether it is as simple as the swinging pendulum or as complex as an exploding galaxy, there is one quantity that does not change: energy. Energy may change form, but the total energy score stays the same.



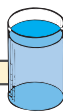
**FIGURE 9.6** ▲ When released, potential energy will become the kinetic energy of the arrow.

◀ **FIGURE 9.7** Part of the PE of the wound spring changes into KE. The remaining PE goes into heating the machinery and the surroundings due to friction. No energy is lost.

◀ **FIGURE 9.8** Everywhere along the path of the pendulum bob, the sum of PE and KE is the same. Because of the work done against friction, this energy will eventually be transformed into heat.



**FIGURE 9.9** ▲  
When the woman in distress leaps from the burning building, note that the sum of her PE and KE remains constant at each successive position all the way down to the ground.



### Link to CHEMISTRY

**Reactions** What process provides energy for rockets that lift the space shuttle into orbit? What process releases energy from the food we eat? The answer is *chemical reactions*. During a chemical reaction the bonds between atoms *break* and then reform. Breaking bonds requires energy, and forming bonds releases it. Pulling atoms apart is like pulling apart two magnets stuck together; it takes energy to do it. And when atoms join, it is like two separated magnets that slam together; energy is released. Rapid energy release can produce flames. Slow energy release occurs during the digestion of food. The conservation of energy rules chemical reactions. The amount of energy required to break a chemical bond is the same amount released when that bond is formed.



This energy score takes into account the fact that each atom that makes up matter is a concentrated bundle of energy. When the nuclei (cores) of atoms rearrange themselves, enormous amounts of energy can be released. The sun shines because some of its nuclear energy is transformed into radiant energy. In nuclear reactors, nuclear energy is transformed into heat.

Enormous compression due to gravity in the deep hot interior of the sun causes hydrogen nuclei to fuse and become helium nuclei. This high-temperature welding of atomic nuclei is called *thermonuclear fusion* and will be covered later, in Chapter 40. This process releases radiant energy, some of which reaches Earth. Part of this energy falls on plants, and some of the plants later become coal. Another part supports life in the food chain that begins with microscopic marine animals and plants, and later gets stored in oil. Part of the sun's energy is used to evaporate water from the ocean. Some water returns to Earth as rain that is trapped behind a dam. By virtue of its elevated position, the water behind the dam has potential energy that is used to power a generating plant below the dam. The generating plant transforms the energy of falling water into electrical energy. Electrical energy travels through wires to homes where it is used for lighting, heating, cooking, and operating electric toothbrushes. How nice that energy is transformed from one form to another!

**CONCEPT CHECK:** What does the law of conservation of energy state?

## 9.8 Machines

A **machine** is a device used to multiply forces or simply to change the direction of forces. The concept that underlies every machine is the conservation of energy. A machine cannot put out more energy than is put into it. A machine cannot create energy. ✓ **A machine transfers energy from one place to another or transforms it from one form to another.**

**Levers** Consider one of the simplest machines, the lever, shown in Figure 9.10. A **lever** is a simple machine made of a bar that turns about a fixed point. At the same time we do work on one end of the lever, the other end does work on the load. We see that the direction of force is changed. If we push *down*, the load is lifted *up*. If the heat from friction is small enough to neglect, the work input will be equal to the work output.

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

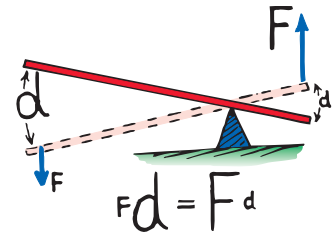
Since work equals force times distance, we can say

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

A little thought will show that the pivot point, or **fulcrum**, of the lever can be relatively close to the load. Then a small input force exerted through a large distance will produce a large output force over a correspondingly short distance. In this way, a lever can multiply forces. However, no machine can multiply work or energy. That's a conservation of energy no-no!

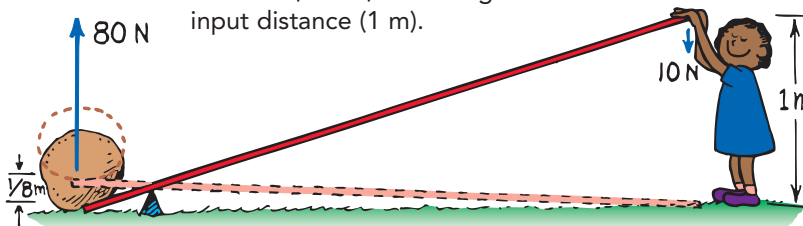
**FIGURE 9.10** ▼

In the lever, the work (force  $\times$  distance) done at one end is equal to the work done on the load at the other end.

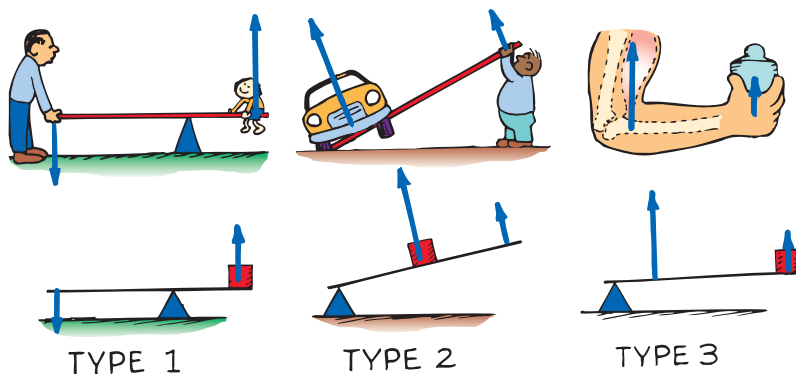


**FIGURE 9.11** ▼

The output force (80 N) is eight times the input force (10 N), while the output distance (1/8 m) is one-eighth of the input distance (1 m).



Consider the ideal weightless lever in Figure 9.11. The child pushes down 10 N and lifts an 80-N load. The ratio of output force to input force for a machine is called the **mechanical advantage**. Here the mechanical advantage is (80 N)/(10 N), or 8. Notice that the load moves only one-eighth of the distance the input force moves. Neglecting friction, the mechanical advantage can also be determined by the ratio of input distance to output distance.



**FIGURE 9.12** ▶ The three basic types of levers are shown here. Notice that the direction of the force is changed in type 1.

Three common ways to set up a lever are shown in Figure 9.12. A type 1 lever has the fulcrum between the force and the load, or between input and output. This kind of lever is commonly seen in a playground seesaw with children sitting on each end of it. Push down on one end and you lift a load at the other. You can increase force at the expense of distance. Note that the directions of input and output are opposite.

For a type 2 lever, the load is between the fulcrum and the input force. To lift a load, you *lift* the end of the lever. One example is placing one end of a long steel bar under an automobile frame and lifting on the free end to raise the automobile. Again, force on the load is increased at the expense of distance. Since the input and output forces are on the same side of the fulcrum, the forces have the same direction.

In the type 3 lever, the fulcrum is at one end and the load is at the other. The input force is applied between them. Your biceps muscles are connected to the bones in your forearm in this way. The fulcrum is your elbow and the load is in your hand. The type 3 lever increases distance at the expense of force. When you move your biceps muscles a short distance, your hand moves a much greater distance. The input and output forces are on the same side of the fulcrum and therefore they have the same direction.

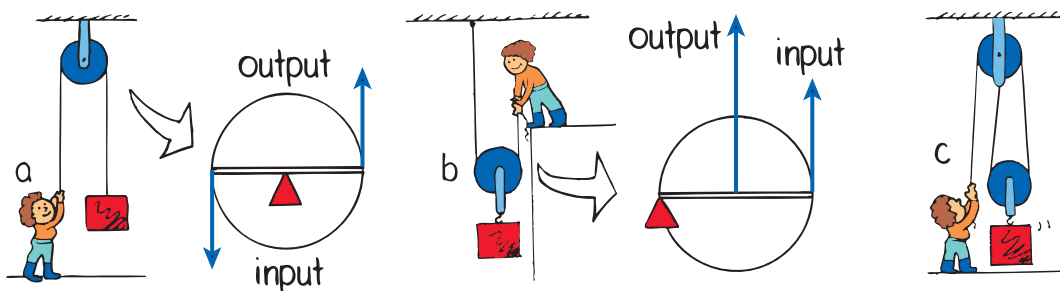
**Pulleys** A **pulley** is basically a kind of lever that can be used to change the direction of a force. Properly used, a pulley or system of pulleys can multiply forces.

The single pulley in Figure 9.13a behaves like a type 1 lever. The axis of the pulley acts as the fulcrum, and both lever distances (the radius of the pulley) are equal so the pulley does not multiply force. It simply changes the direction of the applied force. In this case, the mechanical advantage equals 1. Notice that the input distance equals the output distance the load moves.

A machine can multiply force, but never energy. No way!



In Figure 9.13b, the single pulley acts as a type 2 lever. Careful thought will show that the fulcrum is at the left end of the “lever” where the supporting rope makes contact with the pulley. The load is suspended halfway between the fulcrum and the input end of the lever, which is on the right end of the “lever.” Each newton of input will support two newtons of load, so the mechanical advantage is 2. This number checks with the distances moved. To raise the load 1 m, the woman will have to pull the rope up 2 m. We can say the mechanical advantage is 2 for another reason: the load is now supported by two strands of rope. This means each strand supports half the load. The force the woman applies to support the load is therefore only half of the weight of the load.



**Go Online**  
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 Visit: [PHSchool.com](http://PHSchool.com)  
 Web Code: csp – 1097

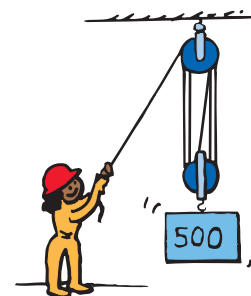
The mechanical advantage for simple pulley systems is the same as the number of strands of rope that actually support the load. In Figure 9.13a, the load is supported by one strand and the mechanical advantage is 1. In Figure 9.13b, the load is supported by two strands and the mechanical advantage is 2. Can you use this rule to state the mechanical advantage of the pulley system in Figure 9.13c?<sup>9,8</sup>

The mechanical advantage of the simple system in Figure 9.13c is 2. Notice that although three strands of rope are shown, only two strands actually support the load. The upper pulley serves only to change the direction of the force. Actually experimenting with a variety of pulley systems is much more beneficial than reading about them in a textbook, so try to get your hands on some pulleys, in or out of class. They’re fun.

The pulley system shown in Figure 9.14 is a bit more complex, but the principles of energy conservation are the same. When the rope is pulled 5 m with a force of 100 N, a 500-N load is lifted 1 m. The mechanical advantage is (500 N)/(100 N), or 5. Force is multiplied at the expense of distance. The mechanical advantage can also be found from the ratio of distances: (input distance)/(output distance) = 5.

**CONCEPT CHECK:** How does a machine use energy?

**FIGURE 9.13** ▲ A pulley is useful.  
**a.** A pulley can change the direction of a force.  
**b.** A pulley multiplies force.  
**c.** Two pulleys can change the direction and multiply force.



**FIGURE 9.14** ▲ A complex pulley system is shown here.

## 9.9 Efficiency

When it comes to energy, you can never get something for nothing.



The previous examples of machines were considered to be *ideal*. All the work input was transferred to work output. An ideal machine would have 100% efficiency. No real machine can be 100% efficient.

✔ In any machine, some energy is transformed into atomic or molecular kinetic energy—making the machine warmer. We say this wasted energy is dissipated as heat.<sup>9.9.1</sup>

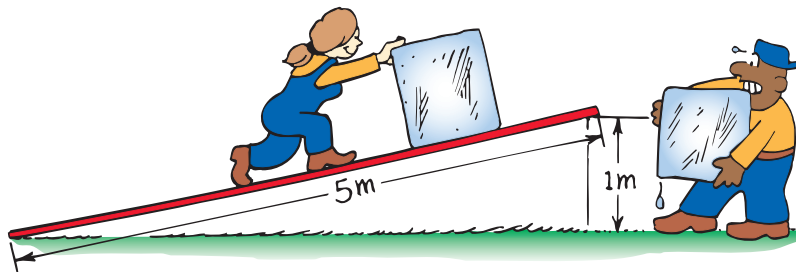
When a simple lever rocks about its fulcrum, or a pulley turns about its axis, a small fraction of input energy is converted into thermal energy. The **efficiency** of a machine is the ratio of useful energy output to total energy input, or the percentage of the work input that is converted to work output. Efficiency can be expressed as the ratio of useful work output to total work input.

$$\text{efficiency} = \frac{\text{useful work output}}{\text{total work input}}$$

We may put in 100 J of work on a lever and get out 98 J of work. The lever is then 98% efficient and we lose only 2 J of work input as heat. In a pulley system, a larger fraction of input energy is lost as heat. For example, if we do 100 J of work, the friction on the pulleys as they turn and rub on their axle can dissipate 40 J of heat energy. So the work output is only 60 J and the pulley system has an efficiency of 60%. The lower the efficiency of a machine, the greater is the amount of energy wasted as heat.

**FIGURE 9.15** ▶

Pushing the block of ice 5 times farther up the incline than the vertical distance it's lifted requires a force of only one-fifth its weight. Whether pushed up the plane or simply lifted, the ice gains the same amount of PE.



**Inclined Planes** An inclined plane is a machine. Sliding a load up an incline requires less force than lifting it vertically. Figure 9.15 shows a 5-m inclined plane with its high end elevated by 1 m. Using the plane to elevate a heavy load, we push the load five times farther than we lift it vertically. If friction is negligible, we need apply only one-fifth of the force required to lift the load vertically. The inclined plane shown has a *theoretical* mechanical advantage of 5.

An icy plank used to slide a block of ice up to some height might have an efficiency of almost 100%. However, when the load is a wooden crate sliding on a wooden plank, both the actual mechanical advantage and the efficiency will be considerably less. Friction will require you to exert more force (a greater work input) without any increase in work output.

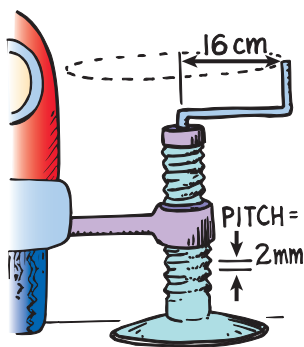
Efficiency can also be expressed as the ratio of actual mechanical advantage to theoretical mechanical advantage.

$$\text{efficiency} = \frac{\text{actual mechanical advantage}}{\text{theoretical mechanical advantage}}$$

Efficiency will always be a fraction less than 1. To convert efficiency to percent, we simply express it as a decimal and multiply by 100%. For example, an efficiency of 0.25 expressed in percent is  $0.25 \times 100\%$ , or 25%.



Energy is nature's way of keeping score.



◀ **FIGURE 9.16**

The auto jack is like an inclined plane wrapped around a cylinder. Every time the handle is turned one revolution, the load is raised a distance of one pitch.

**Complex Machines** The auto jack shown in Figure 9.16 is actually an inclined plane wrapped around a cylinder. You can see that a single turn of the handle raises the load a relatively small distance. If the circular distance the handle is moved is 500 times greater than the pitch, which is the distance between ridges, then the theoretical mechanical advantage of the jack is 500.<sup>9.2</sup> No wonder a child can raise a loaded moving van with one of these devices! In practice there is a great deal of friction in this type of jack, so the efficiency might be about 20%. Thus the jack actually multiplies force by about 100 times, so the actual mechanical advantage approximates an impressive 100. Imagine the value of one of these devices if it had been available when the great pyramids were being built!

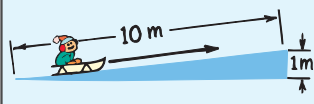
An automobile engine is a machine that transforms chemical energy stored in fuel into mechanical energy. The molecules of the gasoline break up as the fuel burns. Burning is a chemical reaction in which atoms combine with the oxygen in the air. Carbon atoms from the gasoline combine with oxygen atoms to form carbon dioxide, hydrogen atoms combine with oxygen, and energy is released. The converted energy is used to run the engine.



## think!

A child on a sled (total weight 500 N) is pulled up a 10-m slope that elevates her a vertical distance of 1 m. What is the theoretical mechanical advantage of the slope?

Answer: 9.9



As physicists learned in the nineteenth century, transforming 100% of thermal energy into mechanical energy is not possible. Some heat must flow from the engine. Friction adds more to the energy loss. Even the best-designed gasoline-powered automobile engines are unlikely to be more than 35% efficient. Some of the heat energy goes into the cooling system and is released through the radiator to the air. Some of it goes out the tailpipe with the exhaust gases, and almost half goes into heating engine parts as a result of friction.

On top of these contributors to inefficiency, the fuel does not burn completely. A certain amount of it goes unused. We can look at inefficiency in this way: In any transformation there is a dilution of the amount of *useful energy*. Useful energy ultimately becomes thermal energy. Energy is not destroyed, it is simply degraded. Through heat transfer, thermal energy is the graveyard of useful energy.

**CONCEPT CHECK:** Why can't a machine be 100% efficient?

## 9.10 Energy for Life

Every living cell in every organism is a machine. Like any machine, living cells need an energy supply. Most living organisms on this planet feed on various hydrocarbon compounds that release energy when they react with oxygen. There is more energy stored in gasoline than in the products of its combustion. ✓ **There is more energy stored in the molecules in food than there is in the reaction products after the food is metabolized. This energy difference sustains life.**<sup>9,10</sup>

The same principle of combustion occurs in the metabolism of food in the body and the burning of fossil fuels in mechanical engines. The main difference is the rate at which the reactions take place. During metabolism, the reaction rate is much slower and energy is released as it is needed by the body. Like the burning of fossil fuels, the reaction is self-sustaining once it starts. In metabolism, carbon combines with oxygen to form carbon dioxide.

The reverse process is more difficult. Only green plants and certain one-celled organisms can make carbon dioxide combine with water to produce hydrocarbon compounds such as sugar. This process is *photosynthesis* and requires an energy input, which normally comes from sunlight. Sugar is the simplest food. All other foods, such as carbohydrates, proteins, and fats, are also synthesized compounds containing carbon, hydrogen, oxygen, and other elements. Because green plants are able to use the energy of sunlight to make food that gives us and all other organisms energy, there is life.

In biology, you'll learn how the body takes energy from the food you eat to build molecules of adenosine triphosphate, or ATP, and how this supply of ATP is used to run all the chemical reactions that sustain life.



**CONCEPT CHECK:** What role does energy play in sustaining life?

## 9.11 Sources of Energy

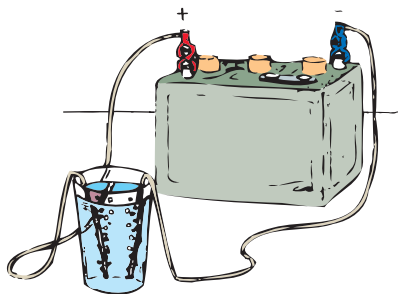
☑ **The sun is the source of practically all our energy on Earth.** (Exceptions are nuclear and geothermal energy.) The energy from burning wood comes from the sun. Even the energy we obtain from Earth's compost of the past—fossil fuels such as petroleum, coal, and natural gas—comes from the sun. These fuels are created by *photosynthesis*, the process by which plants trap solar energy and store it as plant tissue.

**Solar Power** Sunlight is directly transformed into electricity by photovoltaic cells, like those found in solar-powered calculators, or more recently, in the flexible solar shingles on the roof of the building in Figure 9.17. We use the energy in sunlight to generate electricity indirectly as well. Sunlight evaporates water, which later falls as rain; rainwater flows into rivers and turns water wheels, or it flows into modern generator turbines as it returns to the sea.

Wind, caused by unequal warming of Earth's surface, is another form of solar power. The energy of wind can be used to turn generator turbines within specially equipped windmills. Because wind is not steady, wind power cannot by itself provide all of our energy needs. But because the wind is always blowing somewhere, windmills spread out over a large geographical area and integrated into a power grid can make a substantial contribution to the overall energy mix. Harnessing the wind is very practical when the energy it produces is stored for future use, such as in the form of hydrogen.



◀ **FIGURE 9.17**  
Solar shingles look like traditional asphalt shingles but they are hooked into a home's electrical system.



**FIGURE 9.18 ▲**

When electric current passes through water, bubbles of hydrogen form at one wire and bubbles of oxygen form at the other. In a fuel cell, the reverse process occurs: hydrogen and oxygen combine to produce water and electricity.

**Fuel Cells** Hydrogen, the least polluting of all fuels, holds much promise for the future. Because it takes energy to make hydrogen (to extract it from water and carbon compounds), it is not a *source* of energy. A simple method to extract hydrogen from water is shown in Figure 9.18. Place two platinum wires that are connected to the terminals of an ordinary battery into a glass of water (with an electrolyte dissolved in the water for conductivity). Be sure the wires don't touch each other. Bubbles of hydrogen form on one wire, and bubbles of oxygen form on the other. Electricity splits water into its constituent parts.

If you make the electrolysis process run backward, you have a fuel cell. In a **fuel cell**, hydrogen and oxygen gas are compressed at electrodes to produce water and electric current. The space shuttle uses fuel cells to meet its electrical needs while producing drinking water for the astronauts. Here on Earth, fuel-cell researchers are developing fuel cells for buses, automobiles, and trains.

**Nuclear and Geothermal Energy** The most concentrated form of usable energy is stored in uranium and plutonium, which are nuclear fuels. Interestingly, Earth's interior is kept hot by producing a form of nuclear power, radioactivity, which has been with us since the Earth was formed.

A byproduct of radioactivity in Earth's interior is geothermal energy. Geothermal energy is held in underground reservoirs of hot water. Geothermal energy is a practical energy source in areas of volcanic activity, such as Iceland, New Zealand, Japan, and Hawaii. In these places, heated water near Earth's surface is tapped to provide steam for running turbogenerators.

Energy sources such as nuclear, geothermal, wind, solar, and water power are environmentally friendly. The combustion of fossil fuels, on the other hand, leads to increased atmospheric concentrations of carbon dioxide, sulfur dioxide, and other pollutants.

As the world population increases, so does our need for energy. With the rules of physics to guide them, technologists are now researching newer and cleaner energy sources. But they race to keep up with world population and greater demand in the developing world.

Watch for the growth of fuel-cell technology. The major hurdle for this technology is not the device itself, but with acquiring hydrogen fuel economically. One way is via solar cells.



**CONCEPT:** What is the source of practically all of our  
**CHECK:** energy on Earth?



## Science, Technology, and Society

**Energy Conservation** Most energy consumed in America comes from fossil fuels. Oil, natural gas, and coal supply the energy for almost all our industry and technology. About 70% of electrical power in the United States comes from fossil fuels, with about 21% from nuclear power. Worldwide, fossil fuels also account for most energy consumption. We have grown to depend on fossil fuels because they have been plentiful and inexpensive. Until recently, our consumption was small enough that we could ignore their environmental impact.



But things have changed. Fossil fuels are being consumed at a rate that threatens to deplete the entire world supply. Locally and globally, our fossil fuel consumption is measurably polluting the air we breathe and the water we drink. Yet, despite these problems, many people consider fossil fuels



to be as inexhaustible as the sun's glow and as acceptable as Mom's apple pie, because these fuels lasted and nurtured us through the 1900s. Financially, fossil fuels are still a bargain, but this is destined to change. Environmentally, the costs are already dramatic. Some other fuel must take the place of fossil fuels if we are to maintain the industry and technology to which we are accustomed. The French have chosen nuclear, with about 74% of their electricity coming from nuclear power plants. What energy source would you choose as an alternative?

In the meantime, we shouldn't waste energy. As individuals, we should limit the consumption of useful energy by such measures as turning off unused electrical appliances, using less hot water, going easy on heating and air conditioning, and driving energy-efficient automobiles. By doing these things, we are conserving useful energy.

**Critical Thinking** In how many reasonable ways can we reduce energy consumption?

## Concept Summary . . . . .

- Work is done when a force acts on an object and the object moves in the direction of the force.
- Power equals work divided by the time.
- The two forms of mechanical energy are kinetic energy and potential energy.
- Three examples of potential energy are elastic potential energy, chemical energy, and gravitational potential energy.
- The kinetic energy of a moving object is equal to the work done on it.
- The work-energy theorem states that whenever work is done, energy changes.
- Energy cannot be created or destroyed.
- A machine transfers energy from one place to another or transforms it from one form to another.
- In a machine, some energy is transformed into atomic kinetic energy.
- There is more energy stored in the molecules in food than there is in the reaction products after the food is metabolized. The energy difference sustains life.
- The sun supplies most of Earth's energy.

## Key Terms . . . . .

work (p. 145)  
joule (p. 146)  
power (p. 146)  
watt (p. 146)  
energy (p. 147)

mechanical energy (p. 147)  
potential energy (p. 148)  
kinetic energy (p. 150)

work-energy theorem (p. 151)  
law of conservation of energy (p. 153)  
machine (p. 155)  
lever (p. 155)

fulcrum (p. 155)  
mechanical advantage (p. 155)  
pulley (p. 156)  
efficiency (p. 158)  
fuel cell (p. 162)

## think! Answers

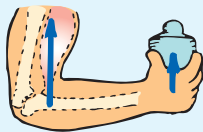
- 9.1  $W = Fd = 60 \text{ N} \times 4 \text{ m} = 240 \text{ J}$
- 9.2 The forklift that delivers twice the power will lift twice the load in the same time, or the same load in half the time.
- 9.4 a.  $W = Fd = 100 \text{ N} \cdot \text{m} = 100 \text{ J}$   
b.  $\text{Power} = \frac{100 \text{ J}}{2 \text{ s}} = 50 \text{ W}$   
c. It depends. Relative to its starting position, the boulder's PE is 100 J. Relative to some other reference level, its PE would be some other value.
- 9.6.1 Careful. Although you do 100 J of work on the cart, this may not mean the cart gains 100 J of KE. How much KE the cart gains depends on the net work done on it.
- 9.6.2 Nine times farther. The car has nine times as much kinetic energy when it travels three times as fast:  
 $\frac{1}{2}m(3v)^2 = 9(\frac{1}{2}mv^2)$
- 9.9 The ideal, or theoretical, mechanical advantage is  
 $\frac{\text{input distance}}{\text{output distance}} = \frac{10 \text{ m}}{1 \text{ m}} = 10$

# 9 ASSESS

## Check Concepts .....

### Section 9.1

1. A force sets an object in motion. When the force is multiplied by the time of its application, we call the quantity *impulse*, which changes the *momentum* of that object. What do we call the quantity  $force \times distance$ , and what quantity can this change?
2. Work is required to lift a barbell. How many times more work is required to lift the barbell three times as high?



3. Which requires more work, lifting a 10-kg load a vertical distance of 2 m or lifting a 5-kg load a vertical distance of 4 m?
4. How many joules of work are done on an object when a force of 10 N pushes it a distance of 10 m?

### Section 9.2

5. How much power is required to do 100 J of work on an object in a time of 0.5 s? How much power is required if the same work is done in 1 s?

### Section 9.3

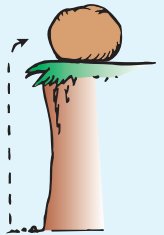
6. What are the two main forms of mechanical energy?

### Section 9.4

7. a. If you do 100 J of work to elevate a bucket of water, what is its gravitational potential energy relative to its starting position?  
b. What would the gravitational potential energy be if the bucket were raised twice as high?

### Section 9.5

8. A boulder is raised above the ground so that its potential energy relative to the ground is 200 J. Then it is dropped. What is its kinetic energy just before it hits the ground?



### Section 9.6

9. Suppose you know the amount of work the brakes of a car must do to stop a car at a given speed. How much work must they do to stop a car that is moving four times as fast? How will the stopping distances compare?
10. How does speed affect the friction between a road and a skidding tire?

### Section 9.7

11. What will be the *kinetic* energy of an arrow having a *potential* energy of 50 J after it is shot from a bow?
12. What does it mean to say that in any system the total energy score stays the same?
13. In what sense is energy from coal actually solar energy?

# 9 ASSESS *(continued)*

14. How does the amount of work done on an automobile by its engine relate to the energy content of the gasoline?

## Section 9.8

15. In what two ways can a machine alter an input force?

16. In what way is a machine subject to the law of energy conservation? Is it possible for a machine to multiply energy or work input?

17. What does it mean to say that a machine has a certain mechanical advantage?

18. In which type of lever is the output force smaller than the input force?

## Section 9.9

19. What is the efficiency of a machine that requires 100 J of energy to do 35 J of work?

20. Distinguish between theoretical mechanical advantage and actual mechanical advantage. How would these compare if a machine were 100% efficient?

21. What is the efficiency of her body when a cyclist expends 1000 W of power to deliver mechanical energy to the bicycle at the rate of 100 W?

## Section 9.10

22. In what sense are our bodies machines?

## Section 9.11

23. What is the ultimate source of the energy derived from the burning of fossil fuels, from dams, and from windmills?

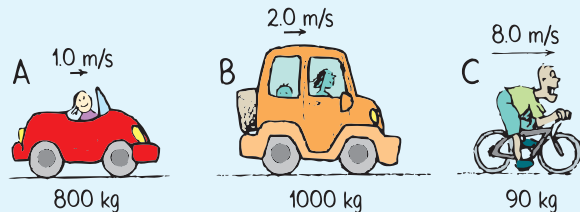
24. What is the ultimate source of geothermal energy?

25. Can we correctly say that a new source of energy is hydrogen? Why or why not?

## Think and Rank . . . . .

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g.,  $A = B$ )

26. The mass and speed of three vehicles are shown below.



- Rank the vehicles by momentum from greatest to least.
- Rank the vehicles by kinetic energy from greatest to least.

27. Consider these four situations.

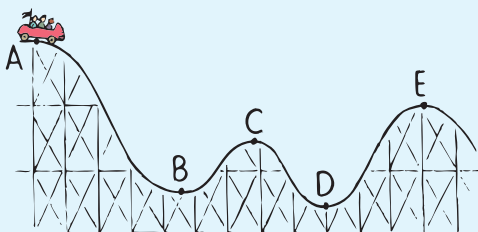
- a 3-kg ball at rest atop a 5-m-tall hill
- a 4-kg ball at rest atop a 5-m-tall hill
- a 3-kg ball moving at 2 m/s atop a 5-m-tall hill
- a 4-kg ball moving at 2 m/s at ground level

- Rank from greatest to least the potential energy of each ball.
- Rank from greatest to least the kinetic energy of each ball.
- Rank from greatest to least the total energy of each ball.

28. A ball is released at the left end of the metal track shown below. Assume it has only enough friction to roll, but not to lessen its speed.

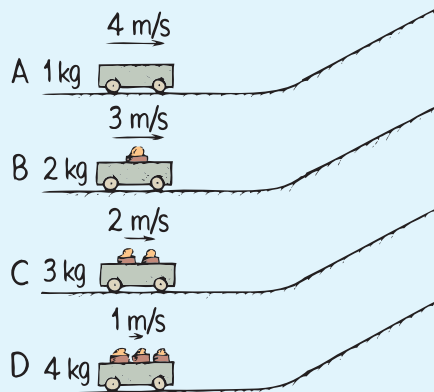


- Rank from greatest to least the ball's momentum at each point.
  - Rank from greatest to least the ball's kinetic energy at each point.
  - Rank from greatest to least the ball's potential energy at each point.
29. The roller coaster ride starts with the car at rest at point A.

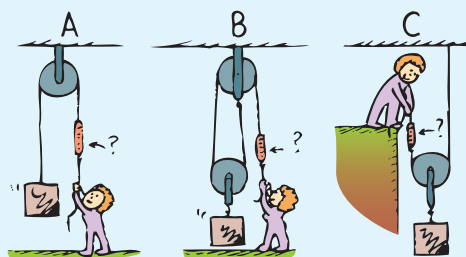


- Rank from greatest to least the car's speed at each point.
  - Rank from greatest to least the car's kinetic energy at each point.
  - Rank from greatest to least the car's potential energy at each point.
30. Rank the efficiency of these machines from highest to lowest.
- energy in 100 J; energy out 60 J
  - energy in 100 J; energy out 50 J
  - energy in 200 J; energy out 80 J
  - energy in 200 J; energy out 120 J

31. Carts moving along the lab floor run up short inclines. Friction effects are negligible.



- Rank the carts by kinetic energy before they meet the incline.
  - Rank the carts by how high they go up the incline.
  - Rank the carts by potential energy when they reach the highest point on the incline.
  - Why are your answers different for b and c?
32. Rank the scale readings from greatest to least. (Ignore friction.)





# 9 ASSESS *(continued)*

## Plug and Chug . . . . .

The key equations of the chapter are shown below in bold type.

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

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

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

36. Calculate the watts of power expended when a force of 1 N moves a book 2 m in a time interval of 1 s.
37. Calculate the power expended when a 20-N force pushes a cart 3.5 m in a time of 0.5 s.

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

38. How many joules of potential energy does a 1-kg book gain when it is elevated 4 m? When it is elevated 8 m? (Let  $g = 10 \text{ N/kg}$ .)
39. Calculate the increase in potential energy when a 20-kg block of ice is lifted a vertical distance of 2 m.

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

40. Calculate the number of joules of kinetic energy a 1-kg book has when tossed across the room at a speed of 2 m/s.

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

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

## Think and Explain . . . . .

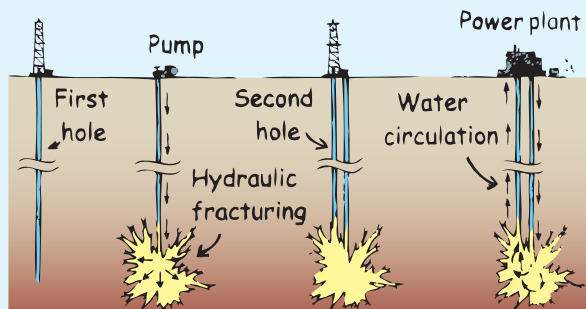
43. Which requires more work: stretching a strong spring a certain distance or stretching a weak spring the same distance? Defend your answer.
44. Two people who weigh the same amount climb a flight of stairs. The first person climbs the stairs in 30 s, while the second person climbs them in 40 s. Which person does more work? Which uses more power?
45. A physics teacher demonstrates energy conservation by releasing a heavy pendulum bob, as shown in the sketch, allowing it to swing to and fro. What would happen if, in his exuberance, he gave the bob a slight shove as it left his nose? Explain.



46. Consider the kinetic energy of a fly in the cabin of a fast-moving train. Does it have the same or different kinetic energies relative to the train? Relative to the ground outside?
47. When a driver applies brakes to keep a car going downhill at constant speed and constant kinetic energy, the potential energy of the car decreases. Where does this energy go? Where does most of it go in a hybrid vehicle?
48. What is the theoretical mechanical advantage for each of the three lever systems shown?



49. Dry-rock geothermal power can be a major contributor to power with no pollution. The bottom of a hole drilled down into Earth's interior is fractured, making a large-surfaced hot cavity. Water is introduced from the top by a second hole. Superheated water rising to the surface then drives a conventional turbine to produce electricity. What is the source of this energy?



## Think and Solve . . . . .

50. A stuntman on a cliff has a PE of 10,000 J. Show that when his potential energy is 2000 J, his kinetic energy is 8000 J.
51. Relative to the ground below, how many joules of PE does a 1000-N boulder have at the top of a 5-m ledge? If it falls, with how much KE will it strike the ground? What will be its speed on impact?
52. A hammer falls off a rooftop and strikes the ground with a certain KE. If it fell from a roof that was four times higher, how would its KE of impact compare? Its speed of impact? (Neglect air resistance.)
53. A car can go from 0 to 100 km/h in 10 s. If the engine delivered twice the power, how many seconds would it take?
54. If a car traveling at 60 km/h will skid 20 m when its brakes lock, how far will it skid if it is traveling at 120 km/h when its brakes lock? (This question is typical on some driver's license exams.)

## Activity . . . . .

55. Place a small rubber ball on top of a basketball and drop them together. How high does the smaller ball bounce? (Perhaps this is best done in the gym, or outdoors.) Can you reconcile this result with energy conservation?

