Chapter 11

Energy and Its Conservation

What You'll Learn

- You will learn that energy is a property of an object that can change the object's position, motion, or its environment.
- You will learn that energy changes from one form to another, and that the total amount of energy in a closed system remains constant.

Why It's Important

Energy turns the wheels of our world. People buy and sell energy to operate electric appliances, automobiles, and factories.

Skiing The height of the ski jump determines the energy the skier has at the bottom of the ramp before jumping into the air and flying many meters down the slope. The distance that the ski jumper travels depends on his or her use of physical principles such as air resistance, balance, and energy.

Think About This ▶

How does the height of the ski ramp affect the distance that the skier can jump?

Physics Online

physicspp.com

LAUNCH Lab

How can you analyze the energy of a bouncing basketball?

Question

What is the relationship between the height a basketball is dropped from and the height it reaches when it bounces back?

Procedure

1. Place a meterstick against a wall. Choose an initial height from which to drop a basketball. Record the height in the data table.
2. Drop the ball and record how high the ball bounced.
3. Repeat steps 1 and 2 by dropping the basketball from three other heights.
4. **Make and Use Graphs** Construct a graph of bounce height (y) versus drop height (x). Find the best-fit line.

Analysis

Use the graph to find how high a basketball would bounce if it were dropped from a height of 10.0 m.

When the ball is lifted and ready to drop, it possesses energy. What are the factors that influence this energy?

Critical Thinking Why doesn't the ball bounce back to the height from which it was dropped?

11.1 The Many Forms of Energy

The word *energy* is used in many different ways in everyday speech. Some fruit-and-cereal bars are advertised as energy sources. Athletes use energy in sports. Companies that supply your home with electricity, natural gas, or heating fuel are called energy companies.

Scientists and engineers use the term *energy* much more precisely. As you learned in the last chapter, work causes a change in the energy of a system. That is, work transfers energy between a system and the external world.

In this chapter, you will explore how objects can have energy in a variety of ways. Energy is like ice cream—it comes in different varieties. You can have vanilla, chocolate, or peach ice cream. They are different varieties, but they are all ice cream and serve the same purpose. However, unlike ice cream, energy can be changed from one variety to another. In this chapter, you will learn how energy is transformed from one variety (or form) to another and how to keep track of the changes.

Objectives

- **Use** a model to relate work and energy.
- **Calculate** kinetic energy.
- **Determine** the gravitational potential energy of a system.
- **Identify** how elastic potential energy is stored.

Vocabulary

rotational kinetic energy
gravitational potential energy
reference level
elastic potential energy

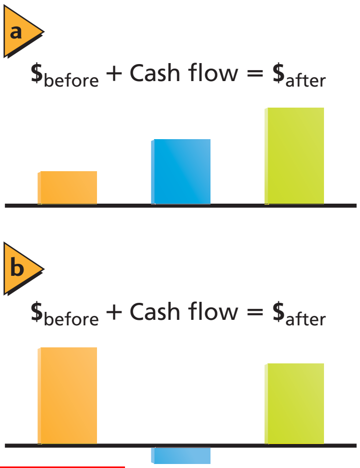
Horizons Companies

A Model of the Work-Energy Theorem

In the last chapter, you were introduced to the work-energy theorem. You learned that when work is done on a system, the energy of that system increases. On the other hand, if the system does work, then the energy of the system decreases. These are abstract ideas, but keeping track of energy is much like keeping track of your spending money.

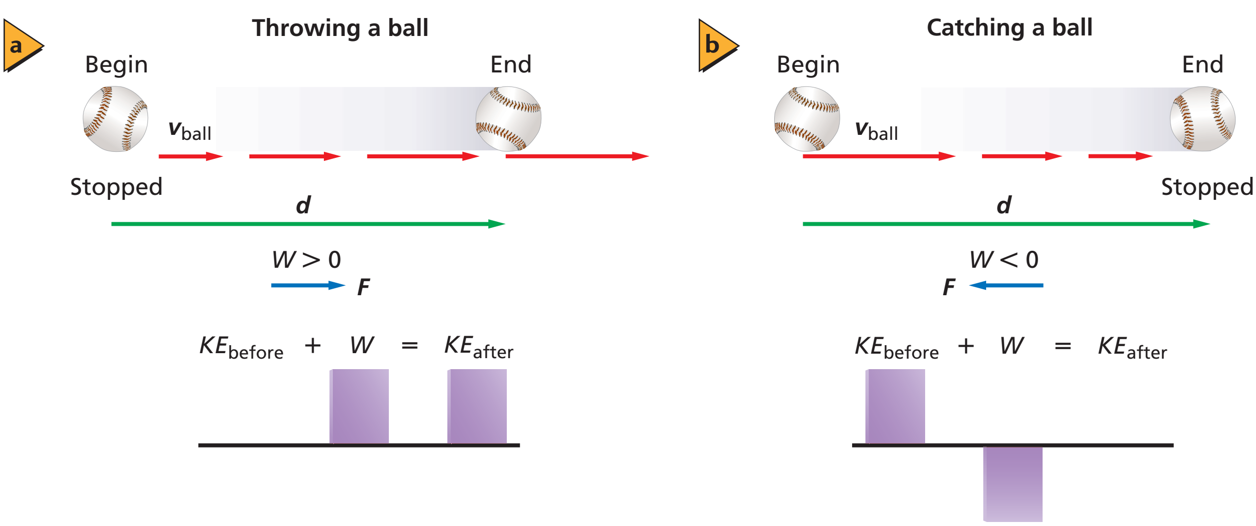
If you have a job, the amount of money that you have increases every time you are paid. This process can be represented with a bar graph, as shown in **Figure 11-1a.** The orange bar represents how much money you had to start with, and the blue bar represents the amount that you were paid. The green bar is the total amount that you possess after the payment. An accountant would say that your cash flow was positive. What happens when you spend the money that you have? The total amount of money that you have decreases. As shown in **Figure 11-1b,** the bar that represents the amount of money that you had before you bought that new CD is higher than the bar that represents the amount of money remaining after your shopping trip. The difference is the cost of the CD. Cash flow is shown as a bar below the axis because it represents money going out, which can be shown as a negative number. Energy is similar to your spending money. The amount of money that you have changes only when you earn more or spend it. Similarly, energy can be stored, and when energy is spent, it affects the motion of a system.

■ **Figure 11-1** When you earn money, the amount of cash that you have increases **(a).** When you spend money, the amount of cash that you have decreases **(b).**



Throwing a ball Gaining and losing energy also can be illustrated by throwing and catching a ball. In Chapter 10, you learned that when you exert a constant force, *F*, on an object through a distance, *d*, in the direction of the force, you do an amount of work, represented by $W = Fd$. The work is positive because the force and motion are in the same direction, and the energy of the object increases by an amount equal to *W*. Suppose the object is a ball, and you exert a force to throw the ball. As a result of the force you apply, the ball gains kinetic energy. This process is shown in **Figure 11-2a.** You can again use a bar graph to represent the process. This time, the height of the bar represents the amount of work, or energy, measured in joules. The kinetic energy after the work is done is equal to the sum of the initial kinetic energy plus the work done on the ball.

■ **Figure 11-2** The kinetic energy after throwing or catching a ball is equal to the kinetic energy before plus the input work.



Catching a ball What happens when you catch a ball? Before hitting your hands or glove, the ball is moving, so it has kineticc energy. In catching it, you exert a force on the ball in the direction opposite to its motion. Therefore, you do negative work on it, causing it to stop. Now that the ball is not moving, it has no kinetic energy. This process and the bar graph that represents it are shown in **Figure 11-2b.** Kinetic energy is always positive, so the initial kinetic energy of the ball is positive. The work done on the ball is negative and the final kinetic energy is zero. Again, the kinetic energy after the ball has stopped is equal to the sum of the initial kinetic energy plus the work done on the ball.

Kinetic Energy

Recall that kinetic energy, $KE = \frac{1}{2}mv^2$, where m is the mass of the object and v is the magnitude of its velocity. The kinetic energy is proportional to the object's mass. A 7.26-kg shot put thrown through the air has much more kinetic energy than a 0.148-kg baseball with the same velocity, because the shot put has a greater mass. The kinetic energy of an object is also proportional to the square of the object's velocity. A car speeding at 20 m/s has four times the kinetic energy of the same car moving at 10 m/s. Kinetic energy also can be due to rotational motion. If you spin a toy top in one spot, does it have kinetic energy? You might say that it does not because the top is not moving anywhere. However, to make the top rotate, someone had to do work on it. Therefore, the top has **rotational kinetic energy.** This is one of the several varieties of energy. Rotational kinetic energy can be calculated using $KE_{rot} = \frac{1}{2}I\omega^2$, where I is the object's moment of inertia and ω is the object's angular velocity.

The diver, shown in **Figure 11-3a,** does work as she pushes off of the diving board. This work produces both linear and rotational kinetic energies. When the diver's center of mass moves as she leaps, linear kinetic energy is produced. When she rotates about her center of mass, as shown in **Figure 11-3b,** rotational kinetic energy is produced. Because she is moving toward the water and rotating at the same time while in the tuck position, she has both linear and rotational kinetic energy. When she slices into the water, as shown in **Figure 11-3c,** she has linear kinetic energy.

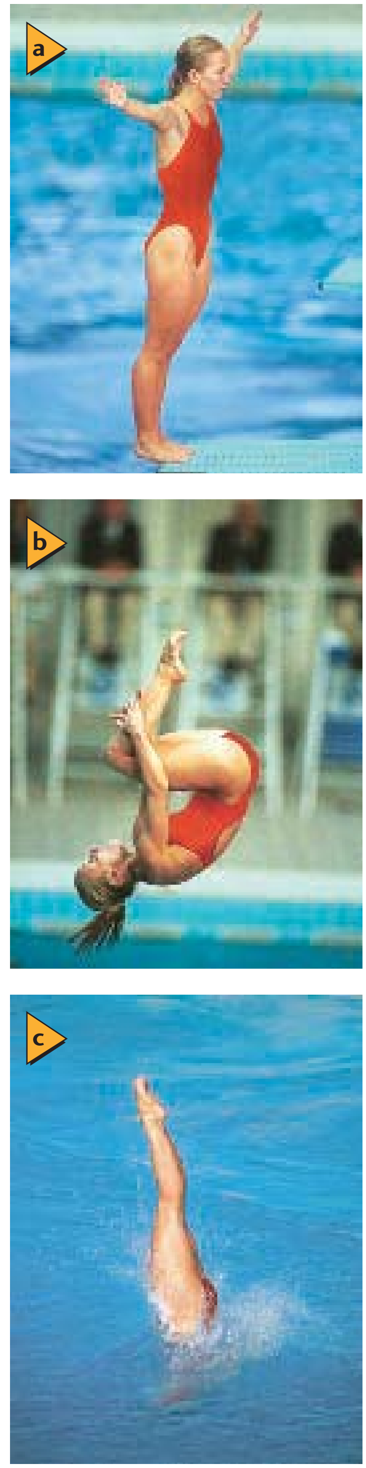


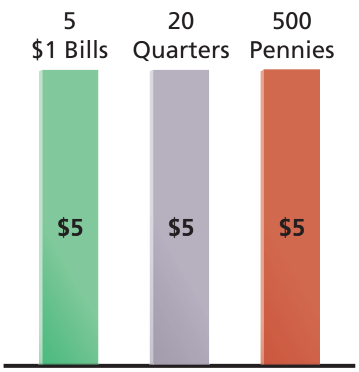
Figure 11-3 The diver does work as she pushes off of the diving board **(a).** This work produces rotational kinetic energy as she rotates about her center of mass **(b)** and she has linear kinetic energy when she slices into the water **(c).**

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

1. A skater with a mass of 52.0 kg moving at 2.5 m/s glides to a stop over a distance of 24.0 m. How much work did the friction of the ice do to bring the skater to a stop? How much work would the skater have to do to speed up to 2.5 m/s again?
2. An 875.0-kg compact car speeds up from 22.0 m/s to 44.0 m/s while passing another car. What are its initial and final energies, and how much work is done on the car to increase its speed?
3. A comet with a mass of 7.85×10^{11} kg strikes Earth at a speed of 25.0 km/s. Find the kinetic energy of the comet in joules, and compare the work that is done by Earth in stopping the comet to the 4.2×10^{15} J of energy that was released by the largest nuclear weapon ever built.

■ **Figure 11-4** Money in the form of bills, quarters, and pennies are different forms of the same thing.



$\$5 = \$1.00 \times 5$
$\$5 = \$0.25 \times 20$
$\$5 = \$0.01 \times 500$

Stored Energy

Imagine a group of boulders high on a hill. These boulders have been lifted up by geological processes against the force of gravity; thus, they have stored energy. In a rock slide, the boulders are shaken loose. They fall and pick up speed as their stored energy is converted to kinetic energy.

In the same way, a small, spring-loaded toy, such as a jack-in-the-box, has stored energy, but the energy is stored in a compressed spring. While both of these examples represent energy stored by mechanical means, there are many other means of storing energy. Automobiles, for example, carry their energy stored in the form of chemical energy in the gasoline tank. Energy is made useful or causes motion when it changes from one form to another.

How does the money model that was discussed earlier illustrate the transformation of energy from one form to another? Money, too, can come in different forms. You can have one five-dollar bill, 20 quarters, or 500 pennies. In all of these cases, you still have five dollars. The height of the bar graph in **Figure 11-4** represents the amount of money in each form. In the same way, you can use a bar graph to represent the amount of energy in various forms that a system has.

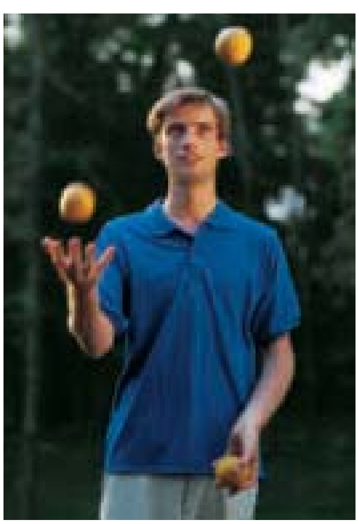
Gravitational Potential Energy

Look at the oranges being juggled in **Figure 11-5.** If you consider the system to be only one orange, then it has several external forces acting on it. The force of the juggler's hand does work, giving the orange its original kinetic energy. After the orange leaves the juggler's hand, only the force of gravity acts on it. How much work does gravity do on the orange as its height changes?

Work done by gravity Let h represent the orange's height measured from the juggler's hand. On the way up, its displacement is upward, but the force on the orange, F_g, is downward, so the work done by gravity is negative: $W_g = -mgh$. On the way back down, the force and displacement are in the same direction, so the work done by gravity is positive: $W_g = mgh$. Thus, while the orange is moving upward, gravity does negative work, slowing the orange to a stop. On the way back down, gravity does positive work, increasing the orange's speed and thereby increasing its kinetic energy. The orange recovers all of the kinetic energy it originally had when it returns to the height at which it left the juggler's hand. It is as if the orange's kinetic energy is stored in another form as the orange rises and is transformed back to kinetic energy as the orange falls.

Consider a system that consists of an object plus Earth. The gravitational attraction between the object and Earth is a force that always does work on the object as it moves. If the object moves away from Earth, energy is stored in the system as a result of the gravitational force between the object and Earth. This stored energy is called **gravitational potential energy** and is represented by the symbol PE. The height to which the object has risen is determined by using a **reference level,** the position where PE is defined to be zero. For an object with mass, m, that has risen to a height, h, above the reference level, gravitational potential energy is represented by the following equation.

■ **Figure 11-5** Kinetic and potential energy are constantly being exchanged when juggling.



Gravitational Potential Energy $PE = mgh$

The gravitational potential energy of an object is equal to the product of its mass, the acceleration due to gravity, and the distance from the reference level.

In the equation for gravitational potential energy, g is the acceleration due to gravity. Gravitational potential energy, like kinetic energy, is measured in joules.

Kinetic energy and potential energy of a system Consider the energy of a system consisting of an orange used by the juggler plus Earth. The energy in the system exists in two forms: kinetic energy and gravitational potential energy. At the beginning of the orange's flight, all the energy is in the form of kinetic energy, as shown in **Figure 11-6a.** On the way up, as the orange slows down, energy changes from kinetic energy to potential energy. At the highest point of the orange's flight, the velocity is zero. Thus, all the energy is in the form of gravitational potential energy. On the way back down, potential energy changes back into kinetic energy. The sum of kinetic energy and potential energy is constant at all times because no work is done on the system by any external forces.

Reference levels In Figure 11-6a, the reference level is the juggler's hand. That is, the height of the orange is measured from the juggler's hand. Thus, at the juggler's hand, $h = 0$ m and $PE = 0$ J. You can set the reference level at any height that is convenient for solving a given problem.

Suppose the reference level is set at the highest point of the orange's flight. Then, $h = 0$ m and the system's $PE = 0$ J at that point, as illustrated in **Figure 11-6b.** The potential energy of the system is negative at the beginning of the orange's flight, zero at the highest point, and negative at the end of the orange's flight. If you were to calculate the total energy of the system represented in Figure 11-6a, it would be different from the total energy of the system represented in Figure 11-6b. This is because the reference levels are different in each case. However, the total energy of the system in each situation would be constant at all times during the flight of the orange. Only changes in energy determine the motion of a system.

APPLYING PHYSICS

▶ Potential Energy of an Atom
It is interesting to consider the relative sizes of potential energy per atom. For instance, a carbon atom has a mass of about 2×10^{-26} kg. If you lift it 1 m above the ground, its gravitational potential energy is about 2×10^{-25} J. The electrostatic energy that holds the electrons on the atom has a value of about 10^{-19} J, and the nuclear potential energy that holds the nucleus together is greater than 10^{-12} J. The nuclear potential energy is at least a million million times greater than the gravitational potential energy. ◀

CLICK HERE

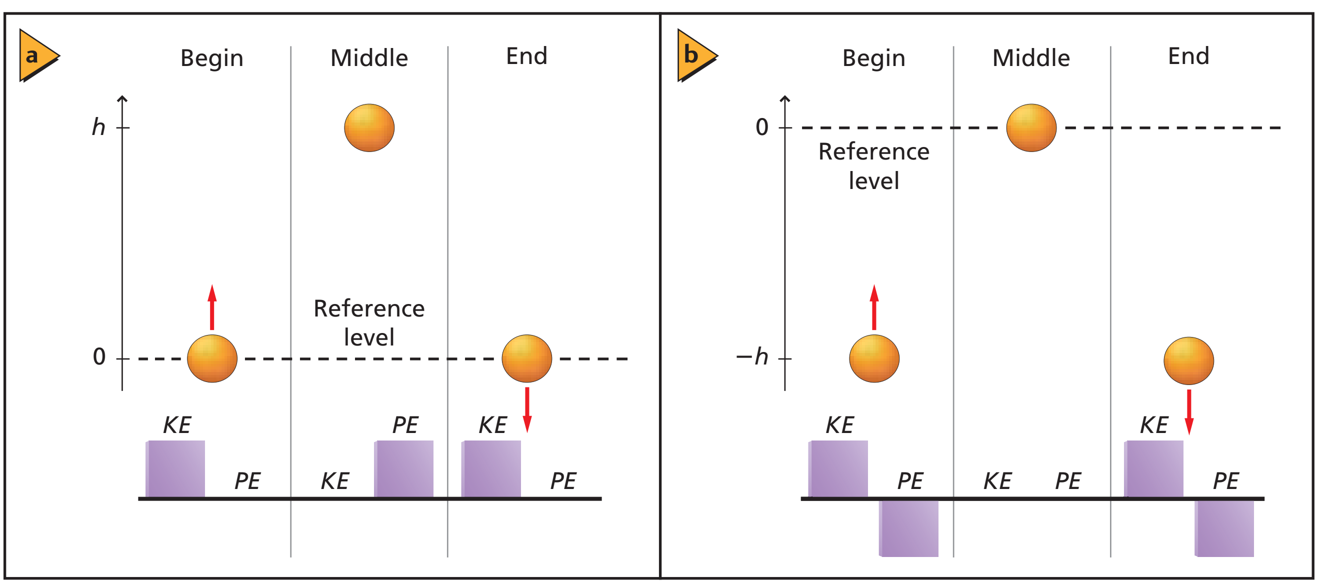


Figure 11-6 The energy of an orange is converted from one form to another in various stages of its flight **(a).** Note that the choice of a reference level is arbitrary, but that the total energy remains constant **(b).**

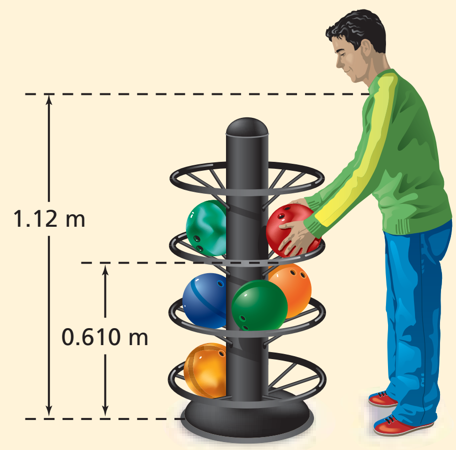
▶ EXAMPLE Problem 1

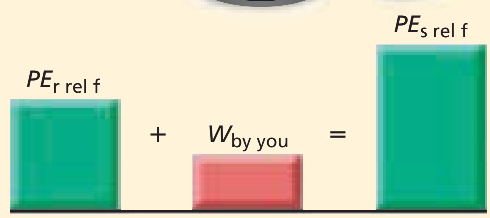
Gravitational Potential Energy You lift a 7.30-kg bowling ball from the storage rack and hold it up to your shoulder. The storage rack is 0.610 m above the floor and your shoulder is 1.12 m above the floor.

a. When the bowling ball is at your shoulder, what is the bowling ball's gravitational potential energy relative to the floor?

b. When the bowling ball is at your shoulder, what is its gravitational potential energy relative to the storage rack?

c. How much work was done by gravity as you lifted the ball from the rack to shoulder level?





1 Analyze and Sketch the Problem

- Sketch the situation.
- Choose a reference level.
- Draw a bar graph showing the gravitational potential energy with the floor as the reference level.

Known:	Unknown:
$m = 7.30$ kg	$PE_{\text{s rel f}} = ?$
$h_r = 0.610$ m (relative to the floor)	$PE_{\text{s rel r}} = ?$
$h_s = 1.12$ m (relative to the floor)	
$g = 9.80$ m/s^2	

2 Solve for the Unknown

a. Set the reference level to be at the floor.

Solve for the potential energy of the ball at shoulder level.

$$PE_{\text{s rel f}} = mgh_s$$
$$= (7.30\text{ kg})(9.80\text{ m/s}^2)(1.12\text{ m})$$ **Substitute $m = 7.30$ kg, $g = 9.80$ m/s^2, $h = 1.12$ m**
$$= 80.1\text{ J}$$

b. Set the reference level to be at the rack height.

Solve for the height of your shoulder relative to the rack.

$$h = h_s - h_r$$

Solve for the potential energy of the ball.

$$PE_{\text{s rel r}} = mgh$$
$$= mg(h_s - h_r)$$ **Substitute $h = h_s - h_r$**
$$= (7.30\text{ kg})(9.80\text{ m/s}^2)(1.12\text{ m} - 0.610\text{ m})$$ **Substitute $m = 7.3$ kg, $g = 9.80$ m/s^2, $h_s = 1.12$ m, $h_r = 0.610$ m**
$$= 36.5\text{ J}$$ **This also is equal to the work done by you.**

Math Handbook
Order of Operations
page 843

c. The work done by gravity is the weight of the ball times the distance the ball was lifted.

$$W = Fd$$
$$= -(mg)h$$ **Because the weight opposes the motion of lifting, the work is negative.**
$$= -(mg)(h_s - h_r)$$
$$= -(7.30\text{ kg})(9.80\text{ m/s}^2)(1.12\text{ m} - 0.610\text{ m})$$ **Substitute $m = 7.30$ kg, $g = 9.80$ m/s^2, $h_s = 1.12$ m, $h_r = 0.610$ m**
$$= -36.5\text{ J}$$

3 Evaluate the Answer

- **Are the units correct?** The potential energy and work are both measured in joules.
- **Is the magnitude realistic?** The ball should have a greater potential energy relative to the floor than relative to the rack, because the ball's distance above the reference level is greater.

PRACTICE Problems • Additional Problems, Appendix B • Solutions to Selected Problems, Appendix C

4. In Example Problem 1, what is the potential energy of the bowling ball relative to the rack when it is on the floor?

5. If you slowly lower a 20.0-kg bag of sand 1.20 m from the trunk of a car to the driveway, how much work do you do?

6. A boy lifts a 2.2-kg book from his desk, which is 0.80 m high, to a bookshelf that is 2.10 m high. What is the potential energy of the book relative to the desk?

7. If a 1.8-kg brick falls to the ground from a chimney that is 6.7 m high, what is the change in its potential energy?

8. A warehouse worker picks up a 10.1-kg box from the floor and sets it on a long, 1.1-m-high table. He slides the box 5.0 m along the table and then lowers it back to the floor. What were the changes in the energy of the box, and how did the total energy of the box change? (Ignore friction.)

Elastic Potential Energy

When the string on the bow shown in **Figure 11-7** is pulled, work is done on the bow, storing energy in it. Thus, the energy of the system increases. Identify the system as the bow, the arrow, and Earth. When the string and arrow are released, energy is changed into kinetic energy. The stored energy in the pulled string is called **elastic potential energy,** which is often stored in rubber balls, rubber bands, slingshots, and trampolines.

Energy also can be stored in the bending of an object. When stiff metal or bamboo poles were used in pole-vaulting, the poles did not bend easily. Little work was done on the poles, and consequently, the poles did not store much potential energy. Since flexible fiberglass poles were introduced, however, record pole-vaulting heights have soared.

Figure 11-7 Elastic potential energy is stored in the string of this bow. Before the string is released, the energy is all potential **(a).** As the string is released, the energy is transferred to the arrow as kinetic energy **(b).**

Figure 11-8 When a pole-vaulter jumps, elastic potential energy is changed into kinetic energy and gravitational potential energy.

A pole-vaulter runs with a flexible pole and plants its end into the socket in the ground. When the pole-vaulter bends the pole, as shown in **Figure 11-8**, some of the pole-vaulter's kinetic energy is converted to elastic potential energy. When the pole straightens, the elastic potential energy is converted to gravitational potential energy and kinetic energy as the pole-vaulter is lifted as high as 6 m above the ground. Unlike stiff metal poles or bamboo poles, fiberglass poles have an increased capacity for storing elastic potential energy. Thus, pole-vaulters are able to clear bars that are set very high.

Mass Albert Einstein recognized yet another form of potential energy: mass itself. He said that mass, by its very nature, is energy. This energy, E_0, is called rest energy and is represented by the following famous formula.

Rest Energy $E_0 = mc^2$

The rest energy of an object is equal to the object's mass times the speed of light squared.

According to this formula, stretching a spring or bending a vaulting pole causes the spring or pole to gain mass. In these cases, the change in mass is too small to be detected. When forces within the nucleus of an atom are involved, however, the energy released into other forms, such as kinetic energy, by changes in mass can be quite large.

11.1 Section Review

9. **Elastic Potential Energy** You get a spring-loaded toy pistol ready to fire by compressing the spring. The elastic potential energy of the spring pushes the rubber dart out of the pistol. You use the toy pistol to shoot the dart straight up. Draw bar graphs that describe the forms of energy present in the following instances.
   a. The dart is pushed into the gun barrel, thereby compressing the spring.
   b. The spring expands and the dart leaves the gun barrel after the trigger is pulled.
   c. The dart reaches the top of its flight.

10. **Potential Energy** A 25.0-kg shell is shot from a cannon at Earth's surface. The reference level is Earth's surface. What is the gravitational potential energy of the system when the shell is at 425 m? What is the change in potential energy when the shell falls to a height of 225 m?

11. **Rotational Kinetic Energy** Suppose some children push a merry-go-round so that it turns twice as fast as it did before they pushed it. What are the relative changes in angular momentum and rotational kinetic energy?

12. **Work-Energy Theorem** How can you apply the work-energy theorem to lifting a bowling ball from a storage rack to your shoulder?

13. **Potential Energy** A 90.0-kg rock climber first climbs 45.0 m up to the top of a quarry, then descends 85.0 m from the top to the bottom of the quarry. If the initial height is the reference level, find the potential energy of the system (the climber and Earth) at the top and at the bottom. Draw bar graphs for both situations.

14. **Critical Thinking** Karl uses an air hose to exert a constant horizontal force on a puck, which is on a frictionless air table. He keeps the hose aimed at the puck, thereby creating a constant force as the puck moves a fixed distance.
    a. Explain what happens in terms of work and energy. Draw bar graphs.
    b. Suppose Karl uses a different puck with half the mass of the first one. All other conditions remain the same. How will the kinetic energy and work differ from those in the first situation?
    c. Explain what happened in parts **a** and **b** in terms of impulse and momentum.

Physics Online physicspp.com/self_check_quiz

11.2 Conservation of Energy

Consider a ball near the surface of Earth. The sum of gravitational potential energy and kinetic energy in that system is constant. As the height of the ball changes, energy is converted from kinetic energy to potential energy, but the total amount of energy stays the same.

▶ **Objectives**

- **Solve** problems using the law of conservation of energy.
- **Analyze** collisions to find the change in kinetic energy.

▶ **Vocabulary**

law of conservation of energy
mechanical energy
thermal energy
elastic collision
inelastic collision

Conservation of Energy

In our everyday world, it may not seem as if energy is conserved. A hockey puck eventually loses its kinetic energy and stops moving, even on smooth ice. A pendulum stops swinging after some time. The money model can again be used to illustrate what is happening in these cases.

Suppose you have a total of \$50 in cash. One day, you count your money and discover that you are \$3 short. Would you assume that the money just disappeared? You probably would try to remember whether you spent it, and you might even search for it. In other words, rather than giving up on the conservation of money, you would try to think of different places where it might have gone.

Law of conservation of energy Scientists do the same thing as you would if you could not account for a sum of money. Whenever they observe energy leaving a system, they look for new forms into which the energy could have been transferred. This is because the total amount of energy in a system remains constant as long as the system is closed and isolated from external forces. The **law of conservation of energy** states that in a closed, isolated system, energy can neither be created nor destroyed; rather, energy is conserved. Under these conditions, energy changes from one form to another while the total energy of the system remains constant.

Conservation of mechanical energy The sum of the kinetic energy and gravitational potential energy of a system is called **mechanical energy, E.** In any given system, if no other forms of energy are present, mechanical energy is represented by the following equation.

Mechanical Energy of a System $E = KE + PE$

The mechanical energy of a system is equal to the sum of the kinetic energy and potential energy if no other forms of energy are present.

Imagine a system consisting of a 10.0-N ball and Earth, as shown in **Figure 11-9.** Suppose the ball is released from 2.00 m above the ground, which you set to be the reference level. Because the ball is not yet moving, it has no kinetic energy. Its potential energy is represented by the following equation:

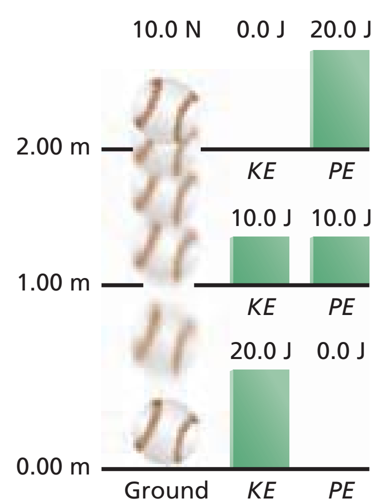
$$PE = mgh = (10.0\ \text{N})(2.00\ \text{m}) = 20.0\ \text{J}$$

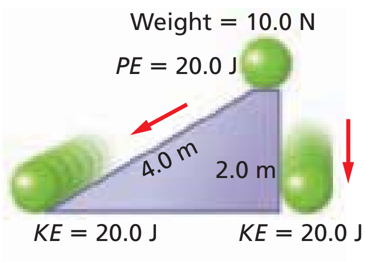
The ball's total mechanical energy, therefore, is 20.0 J. As the ball falls, it loses potential energy and gains kinetic energy. When the ball is 1.00 m above Earth's surface: $PE = mgh = (10.0\ \text{N})(1.00\ \text{m}) = 10.0\ \text{J}$.

CLICK HERE

■ **Figure 11-9** A decrease in potential energy is equal to the increase in kinetic energy.

Concepts In Motion
Interactive Figure To see an animation on conservation of mechanical energy, visit physicspp.com.





■ **Figure 11-10** The path that an object follows in reaching the ground does not affect the final kinetic energy of the object.

What is the ball's kinetic energy when it is at a height of 1.00 m? The system consisting of the ball and Earth is closed and isolated because no external forces are acting upon it. Hence, the total energy of the system, E, remains constant at 20.0 J.

$$E = KE + PE, \text{ so } KE = E - PE$$

$$KE = 20.0\text{ J} - 10.0\text{ J} = 10.0\text{ J}$$

When the ball reaches ground level, its potential energy is zero, and its kinetic energy is 20.0 J. The equation that describes conservation of mechanical energy can be written as follows.

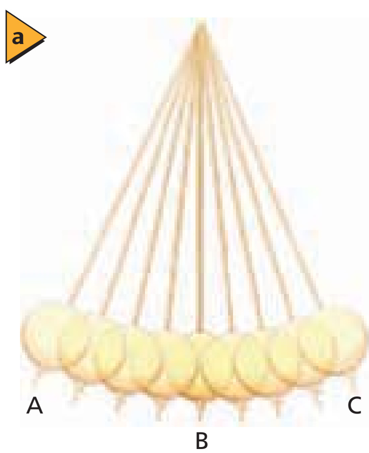
Conservation of Mechanical Energy

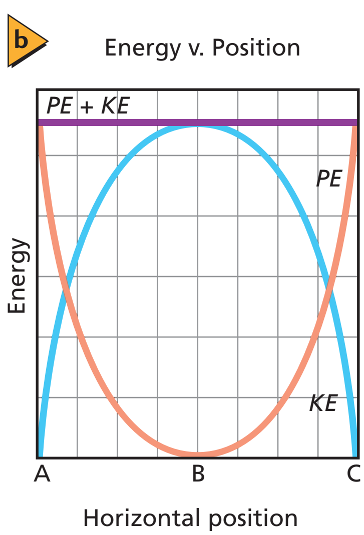
$$KE_{\text{before}} + PE_{\text{before}} = KE_{\text{after}} + PE_{\text{after}}$$

When mechanical energy is conserved, the sum of the kinetic energy and potential energy present in the system before the event is equal to the sum of the kinetic energy and potential energy in the system after the event.

CLICK HERE

■ **Figure 11-11** For the simple harmonic motion of a pendulum bob **(a),** the mechanical energy—the sum of the potential and kinetic energies—is a constant **(b).**





What happens if the ball does not fall down, but rolls down a ramp, as shown in **Figure 11-10?** If there is no friction, there are no external forces acting on the system. Thus, the system remains closed and isolated. The ball still moves down a vertical distance of 2.00 m, so its loss of potential energy is 20.0 J. Therefore, it gains 20.0 J of kinetic energy. As long as there is no friction, the path that the ball takes does not matter.

Roller coasters In the case of a roller coaster that is nearly at rest at the top of the first hill, the total mechanical energy in the system is the coaster's gravitational potential energy at that point. Suppose some other hill along the track were higher than the first one. The roller coaster would not be able to climb the higher hill because the energy required to do so would be greater than the total mechanical energy of the system.

Skiing Suppose you ski down a steep slope. When you begin from rest at the top of the slope, your total mechanical energy is simply your gravitational potential energy. Once you start skiing downhill, your gravitational potential energy is converted to kinetic energy. As you ski down the slope, your speed increases as more of your potential energy is converted to kinetic energy. In ski jumping, the height of the ramp determines the amount of energy that the jumper has to convert into kinetic energy at the beginning of his or her flight.

Pendulums The simple oscillation of a pendulum also demonstrates conservation of energy. The system is the pendulum bob and Earth. Usually, the reference level is chosen to be the height of the bob at the lowest point, when it is at rest. If an external force pulls the bob to one side, the force does work that gives the system mechanical energy. At the instant the bob is released, all the energy is in the form of potential energy, but as the bob swings downward, the energy is converted to kinetic energy. **Figure 11-11** shows a graph of the changing potential and kinetic energies of a pendulum. When the bob is at the lowest point, its gravitational potential energy is zero, and its kinetic energy is equal to the total mechanical energy in the system. Note that the total mechanical energy of the system is constant if we assume that there is no friction. You will learn more about pendulums in Chapter 14.

Loss of mechanical energy The oscillations of a pendulum eventually come to a stop, a bouncing ball comes to rest, and the heights of roller-coaster hills get lower and lower. Where does the mechanical energy in such systems go? Any object moving through the air experiences the forces of air resistance. In a roller coaster, there are frictional forces between the wheels and the tracks.

When a ball bounces off of a surface, all of the elastic potential energy that is stored in the deformed ball is not converted back into kinetic energy after the bounce. Some of the energy is converted into thermal energy and sound energy. As in the cases of the pendulum and the roller coaster, some of the original mechanical energy in the system is converted into another form of energy within members of the system or transmitted to energy outside the system, as in air resistance. Usually, this new energy causes the temperature of objects to rise slightly. You will learn more about this form of energy, called **thermal energy,** in Chapter 12. The following strategies will be helpful to you when solving problems related to conservation of energy.

PROBLEM-SOLVING **Strategies**

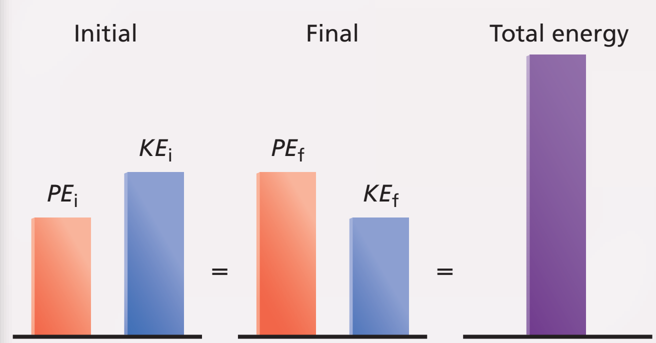
Conservation of Energy

When solving problems related to the conservation of energy, use the following strategies.

1. Carefully identify the system. Make sure it is closed. In a closed system, no objects enter or leave the system.
2. Identify the forms of energy in the system.
3. Identify the initial and final states of the system.
4. Is the system isolated?
   a. If there are no external forces acting on the system, then the system is isolated and the total energy of the system is constant.
   $$E_{\text{before}} = E_{\text{after}}$$
   b. If there are external forces, then the following is true.
   $$E_{\text{before}} + W = E_{\text{after}}$$
5. If mechanical energy is conserved, decide on the reference level for potential energy. Draw bar graphs showing initial and final energy like the bar graphs shown to the right.

Connecting **Math to Physics**

Energy Bar Graphs

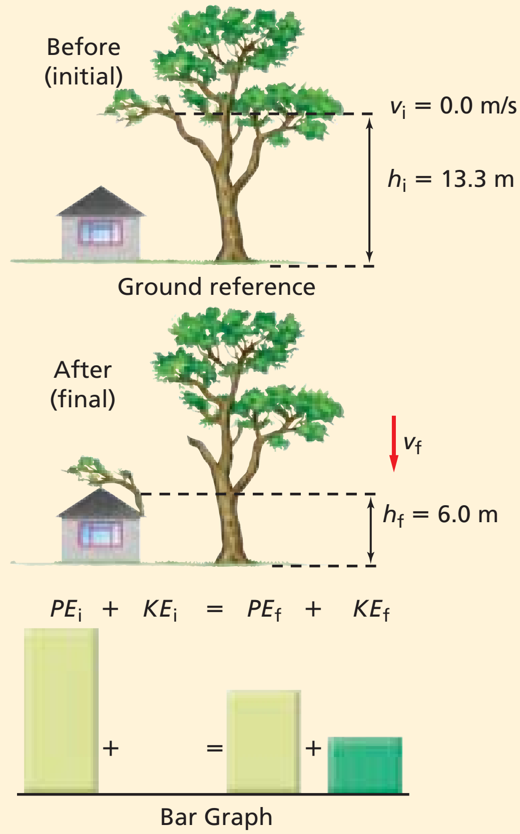


▶ EXAMPLE Problem 2

Conservation of Mechanical Energy During a hurricane, a large tree limb, with a mass of 22.0 kg and a height of 13.3 m above the ground, falls on a roof that is 6.0 m above the ground.

a. Ignoring air resistance, find the kinetic energy of the limb when it reaches the roof.

b. What is the speed of the limb when it reaches the roof?



1 Analyze and Sketch the Problem

- Sketch the initial and final conditions.
- Choose a reference level.
- Draw a bar graph.

Known:

$m = 22.0$ kg $g = 9.80$ m/s^2
$h_{limb} = 13.3$ m $v_i = 0.0$ m/s
$h_{roof} = 6.0$ m $KE_i = 0.0$ J

Unknown:

$PE_i = ?$ $KE_f = ?$
$PE_f = ?$ $v_f = ?$

2 Solve for the Unknown

a. Set the reference level as the height of the roof.

Solve for the initial height of the limb relative to the roof.

$$h = h_{limb} - h_{roof}$$
$$= 13.3 \text{ m} - 6.0 \text{ m} \quad \text{Substitute } h_{limb} = 13.3 \text{ m}, h_{roof} = 6.0 \text{ m}$$
$$= 7.3 \text{ m}$$

Solve for the initial potential energy of the limb.

$$PE_i = mgh$$
$$= (22.0 \text{ kg})(9.80 \text{ m/s}^2)(7.3 \text{ m}) \quad \text{Substitute } m = 22.0 \text{ kg}, g = 9.80 \text{ m/s}^2, h = 7.3 \text{ m}$$
$$= 1.6\times10^3 \text{ J}$$

Identify the initial kinetic energy of the limb.

$$KE_i = 0.0 \text{ J} \quad \text{The tree limb is initially at rest.}$$

The kinetic energy of the limb when it reaches the roof is equal to its initial potential energy because energy is conserved.

$$KE_f = PE_i \quad PE_f = 0.0 \text{ J because } h = 0.0 \text{ m at the reference level.}$$
$$= 1.6\times10^3 \text{ J}$$

b. Solve for the speed of the limb.

$$KE_f = \frac{1}{2}mv_f^2$$
$$v_f = \sqrt{\frac{2KE_f}{m}}$$
$$= \sqrt{\frac{2(1.6\times10^3 \text{ J})}{22.0 \text{ kg}}} \quad \text{Substitute } KE_f = 1.6\times10^3 \text{ J}, m = 22.0 \text{ kg}$$
$$= 12 \text{ m/s}$$

Physics Online

Personal Tutor For an online tutorial on square and cube roots, visit physicspp.com.

3 Evaluate the Answer

- **Are the units correct?** Velocity is measured in m/s and energy is measured in kg·m^2/s^2 = J.
- **Do the signs make sense?** *KE* and the magnitude of velocity are always positive.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

15. A bike rider approaches a hill at a speed of 8.5 m/s. The combined mass of the bike and the rider is 85.0 kg. Choose a suitable system. Find the initial kinetic energy of the system. The rider coasts up the hill. Assuming there is no friction, at what height will the bike come to rest?

16. Suppose that the bike rider in problem 15 pedaled up the hill and never came to a stop. In what system is energy conserved? From what form of energy did the bike gain mechanical energy?

17. A skier starts from rest at the top of a 45.0-m-high hill, skis down a 30° incline into a valley, and continues up a 40.0-m-high hill. The heights of both hills are measured from the valley floor. Assume that you can neglect friction and the effect of the ski poles. How fast is the skier moving at the bottom of the valley? What is the skier's speed at the top of the next hill? Do the angles of the hills affect your answers?

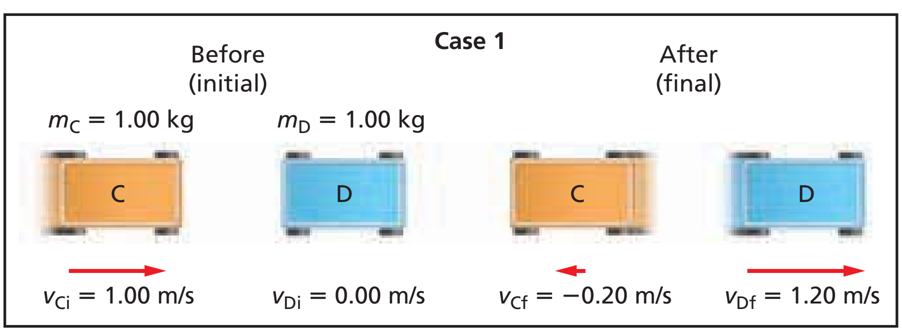
18. In a belly-flop diving contest, the winner is the diver who makes the biggest splash upon hitting the water. The size of the splash depends not only on the diver's style, but also on the amount of kinetic energy that the diver has. Consider a contest in which each diver jumps from a 3.00-m platform. One diver has a mass of 136 kg and simply steps off the platform. Another diver has a mass of 102 kg and leaps upward from the platform. How high would the second diver have to leap to make a competitive splash?

Analyzing Collisions

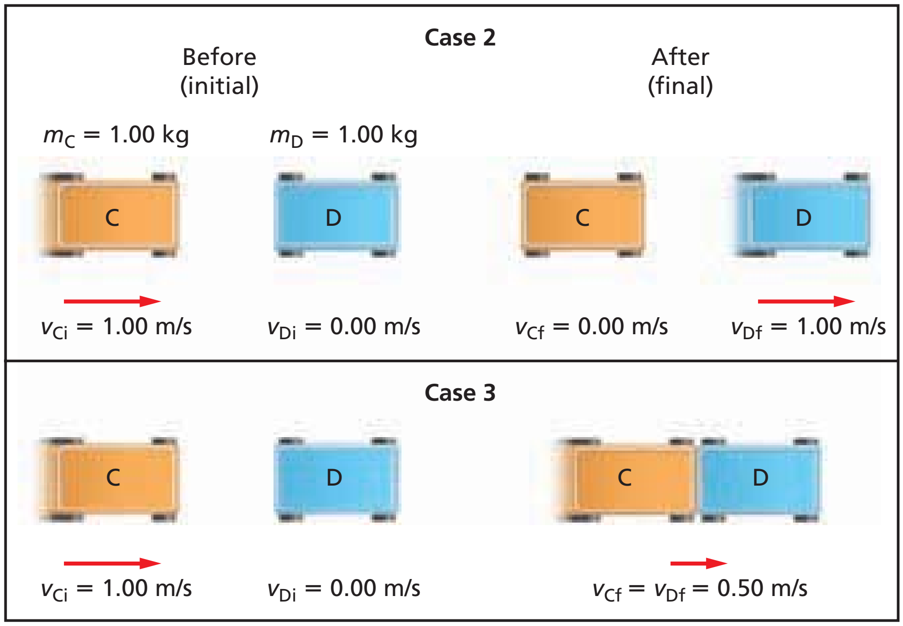
A collision between two objects, whether the objects are automobiles, hockey players, or subatomic particles, is one of the most common situations analyzed in physics. Because the details of a collision can be very complex during the collision itself, the strategy is to find the motion of the objects just before and just after the collision. What conservation laws can be used to analyze such a system? If the system is isolated, then momentum and energy are conserved. However, the potential energy or thermal energy in the system may decrease, remain the same, or increase. Therefore, you cannot predict whether or not kinetic energy is conserved. **Figure 11-12** and **Figure 11-13** on the next page show three different kinds of collisions. In case 1, the momentum of the system before and after the collision is represented by the following:

$$\begin{aligned} p_i = p_{Ci} + p_{Di} &= (1.00\ \text{kg})(1.00\ \text{m/s}) + (1.00\ \text{kg})(0.00\ \text{m/s}) \\ &= 1.00\ \text{kg·m/s} \\ p_f = p_{Cf} + p_{Df} &= (1.00\ \text{kg})(-0.20\ \text{m/s}) + (1.00\ \text{kg})(1.20\ \text{m/s}) \\ &= 1.00\ \text{kg·m/s} \end{aligned}$$

Thus, in case 1, the momentum is conserved. Look again at Figure 11-13 and verify for yourself that momentum is conserved in cases 2 and 3.



■ **Figure 11-12** Two moving objects can have different types of collisions. Case 1: the two objects move apart in opposite directions.



■ **Figure 11-13** Case 2: the moving object comes to rest and the stationary object begins to move. Case 3: the two objects are stuck together and move as one.

Next, consider the kinetic energy of the system in each of these cases. For case 1 the kinetic energy of the system before and after the collision is represented by the following equations:

$$\begin{aligned} KE_{\mathrm{Ci}} + KE_{\mathrm{Di}} &= \tfrac{1}{2}(1.00\ \mathrm{kg})(1.00\ \mathrm{m/s})^2 + \tfrac{1}{2}(1.00\ \mathrm{kg})(0.00\ \mathrm{m/s})^2 \\ &= 0.50\ \mathrm{J} \end{aligned}$$

$$\begin{aligned} KE_{\mathrm{Cf}} + KE_{\mathrm{Df}} &= \tfrac{1}{2}(1.00\ \mathrm{kg})(-0.20\ \mathrm{m/s})^2 + \tfrac{1}{2}(1.00\ \mathrm{kg})(1.20\ \mathrm{m/s})^2 \\ &= 0.74\ \mathrm{J} \end{aligned}$$

In case 1, the kinetic energy of the system increased. If energy in the system is conserved, then one or more of the other forms of energy must have decreased. Perhaps when the two carts collided, a compressed spring was released, adding kinetic energy to the system. This kind of collision is sometimes called a superelastic or explosive collision.

After the collision in case 2, the kinetic energy is equal to:

$$KE_{\mathrm{Cf}} + KE_{\mathrm{Df}} = (1.0\ \mathrm{kg})(0.00\ \mathrm{m/s})^2 + \tfrac{1}{2}(1.0\ \mathrm{kg})(1.0\ \mathrm{m/s})^2 = 0.50\ \mathrm{J}$$

Kinetic energy remained the same after the collision. This type of collision, in which the kinetic energy does not change, is called an **elastic collision.** Collisions between hard, elastic objects, such as those made of steel, glass, or hard plastic, often are called nearly elastic collisions.

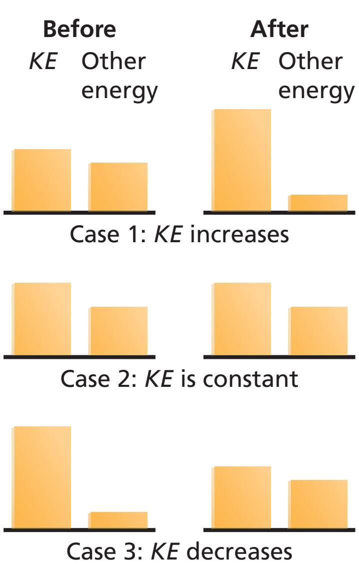
After the collision in case 3, the kinetic energy is equal to:

$$KE_{\mathrm{Cf}} + KE_{\mathrm{Df}} = \tfrac{1}{2}(1.00\ \mathrm{kg})(0.50\ \mathrm{m/s})^2 + \tfrac{1}{2}(1.00\ \mathrm{kg})(0.50\ \mathrm{m/s})^2 = 0.25\ \mathrm{J}$$

Kinetic energy decreased and some of it was converted to thermal energy. This kind of collision, in which kinetic energy decreases, is called an **inelastic collision.** Objects made of soft, sticky material, such as clay, act in this way.

The three kinds of collisions can be represented using bar graphs, such as those shown in **Figure 11-14.** Although the kinetic energy before and after the collisions can be calculated, only the change in other forms of energy can be found. In automobile collisions, kinetic energy is transferred into other forms of energy, such as heat and sound.

■ **Figure 11-14** Bar graphs can be drawn to represent the three kinds of collisions.



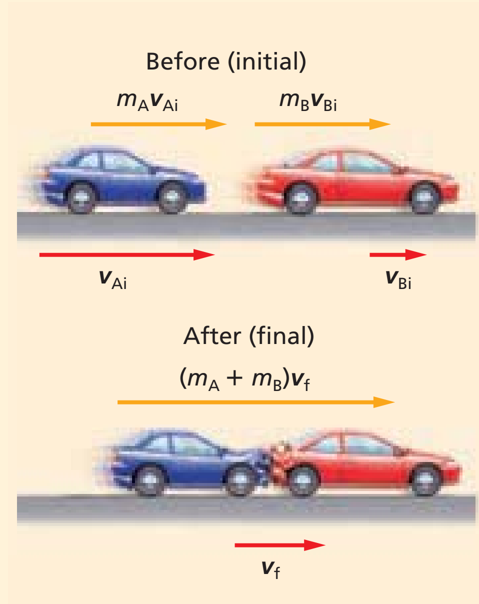
▶ EXAMPLE Problem 3

Kinetic Energy In an accident on a slippery road, a compact car with a mass of 575 kg moving at 15.0 m/s smashes into the rear end of a car with mass 1575 kg moving at 5.00 m/s in the same direction.

a. What is the final velocity if the wrecked cars lock together?

b. How much kinetic energy was lost in the collision?

c. What fraction of the original kinetic energy was lost?



1 Analyze and Sketch the Problem

- Sketch the initial and final conditions.
- Sketch the momentum diagram.

Known:

$m_A = 575$ kg $m_B = 1575$ kg

$v_{Ai} = 15.0$ m/s $v_{Bi} = 5.00$ m/s

$v_{Af} = v_{Bf} = v_f$

Unknown:

$v_f = ?$ $\Delta KE = KE_f - KE_i = ?$

Fraction of KE_i lost, $\Delta KE/KE_i = ?$

2 Solve for the Unknown

a. Use the conservation of momentum equation to find the final velocity.

Math Handbook
Isolating a Variable
page 845

$$p_{Ai} + p_{Bi} = p_{Af} + p_{Bf}$$

$$m_A v_{Ai} + m_B v_{Bi} = (m_A + m_B)v_f$$

$$v_f = \frac{(m_A v_{Ai} + m_B v_{Bi})}{(m_A + m_B)}$$

$$= \frac{(575 \text{ kg})(15.0 \text{ m/s}) + (1575 \text{ kg})(5.00 \text{ m/s})}{(575 \text{ kg} + 1575 \text{ kg})}$$

Substitute $m_A = 575$ kg, $v_{Ai} = 15.0$ m/s, $m_B = 1575$ kg, $v_{Bi} = 5.00$ m/s

$= 7.67$ m/s, in the direction of the motion before the collision

b. To determine the change in kinetic energy of the system, KE_f and KE_i are needed.

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

$$= \frac{1}{2}(m_A + m_B)v_f^2$$

Substitute $m = m_A + m_B$

$$= \frac{1}{2}(575 \text{ kg} + 1575 \text{ kg})(7.67 \text{ m/s})^2$$

Substitute $m_A = 575$ kg, $m_B = 1575$ kg, $v_f = 7.67$ m/s

$$= 6.32\times10^4 \text{ J}$$

$$KE_i = KE_{Ai} + KE_{Bi}$$

$$= \frac{1}{2}m_A v_{Ai}^2 + \frac{1}{2}m_B v_{Bi}^2$$

Substitute $KE_{Ai} = \frac{1}{2}m_A v_{Ai}^2$, $KE_{Bi} = \frac{1}{2}m_B v_{Bi}^2$

$$= \frac{1}{2}(575 \text{ kg})(15.0 \text{ m/s})^2 + \frac{1}{2}(1575 \text{ kg})(5.00 \text{ m/s})^2$$

Substitute $m_A = 575$ kg, $m_B = 1575$ kg, $v_{Ai} = 15.0$ m/s, $v_{Bi} = 5.00$ m/s

$$= 8.44\times10^4 \text{ J}$$

Solve for the change in kinetic energy of the system.

$$\Delta KE = KE_f - KE_i$$

$$= 6.32\times10^4 \text{ J} - 8.44\times10^4 \text{ J}$$

Substitute $KE_f = 6.32\times10^4$ J, $KE_i = 8.44\times10^4$ J

$$= -2.12\times10^4 \text{ J}$$

c. Calculate the fraction of the original kinetic energy that is lost.

$$\frac{\Delta KE}{KE_i} = \frac{-2.12\times10^4 \text{ J}}{8.44\times10^4 \text{ J}}$$

Substitute $\Delta KE = -2.11\times10^4$ J, $KE_i = 8.44\times10^4$ J

$= -0.251 = 25.1\%$ of the original kinetic energy in the system was lost.

3 Evaluate the Answer

- **Are the units correct?** Velocity is measured in m/s; energy is measured in J.
- **Does the sign make sense?** Velocity is positive, consistent with the original velocities.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

19. An 8.00-g bullet is fired horizontally into a 9.00-kg block of wood on an air table and is embedded in it. After the collision, the block and bullet slide along the frictionless surface together with a speed of 10.0 cm/s. What was the initial speed of the bullet?

20. A 0.73-kg magnetic target is suspended on a string. A 0.025-kg magnetic dart, shot horizontally, strikes the target head-on. The dart and the target together, acting like a pendulum, swing 12.0 cm above the initial level before instantaneously coming to rest.

a. Sketch the situation and choose a system.

b. Decide what is conserved in each part and explain your decision.

c. What was the initial velocity of the dart?

21. A 91.0-kg hockey player is skating on ice at 5.50 m/s. Another hockey player of equal mass, moving at 8.1 m/s in the same direction, hits him from behind. They slide off together.

a. What are the total energy and momentum in the system before the collision?

b. What is the velocity of the two hockey players after the collision?

c. How much energy was lost in the collision?

In collisions, you can see how momentum and energy are really very different. Momentum is almost always conserved in a collision. Energy is conserved only in elastic collisions. Momentum is what makes objects stop. A 10.0-kg object moving at 5.00 m/s will stop a 20.0-kg object moving at 2.50 m/s if they have a head-on collision. However, in this case, the smaller object has much more kinetic energy. The kinetic energy of the smaller object is $KE = \frac{1}{2}(10.0\ \text{kg})(5.0\ \text{m/s})^2 = 125\ \text{J}$. The kinetic energy of the larger object is $KE = \frac{1}{2}(20.0\ \text{kg})(2.50\ \text{m/s})^2 = 62.5\ \text{J}$. Based on the work-energy theorem, you can conclude that it takes more work to make the 10.0-kg object move at 5.00 m/s than it does to move the 20.0-kg object at 2.50 m/s. It sometimes is said that in automobile collisions, the momentum stops the cars but it is the energy in the collision that causes the damage.

It also is possible to have a collision in which nothing collides. If two lab carts sit motionless on a table, connected by a compressed spring, their total momentum is zero. If the spring is released, the carts will be forced to move away from each other. The potential energy of the spring will be transformed into the kinetic energy of the carts. The carts will still move away from each other so that their total momentum is zero.

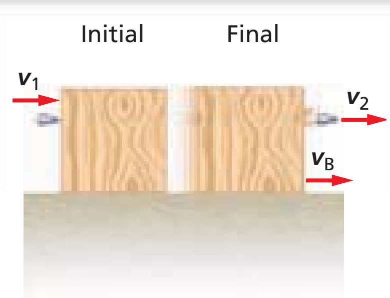
CHALLENGE PROBLEM

A bullet of mass m, moving at speed v_1, goes through a motionless wooden block and exits with speed v_2. After the collision, the block, which has mass m_B, is moving.

1. What is the final speed, v_B, of the block?

2. How much energy was lost to the bullet?

3. How much energy was lost to friction inside the block?



It is useful to remember two simple examples of collisions. One is the elastic collision between two objects of equal mass, such as when a cue ball with velocity, $\boldsymbol{v}$, hits a motionless billiard ball head-on. In this case, after the collision, the cue ball is motionless and the other ball rolls off at velocity, $\boldsymbol{v}$. It is easy to prove that both momentum and energy are conserved in this collision.

The other simple example is to consider a skater of mass m, with velocity $\boldsymbol{v}$, running into another skater of equal mass who happens to be standing motionless on the ice. If they hold on to each other after the collision, they will slide off at a velocity of $\frac{1}{2}\boldsymbol{v}$ because of the conservation of momentum. The final kinetic energy of the pair would be equal to $KE = \frac{1}{2}(2m)(\frac{1}{2}v)^2 = \frac{1}{4}mv^2$, which is half the initial kinetic energy. This is because the collision was inelastic.

You have investigated examples in which the conservation of energy, and sometimes the conservation of momentum, can be used to calculate the motions of a system of objects. These systems would be too complicated to comprehend using only Newton's second law of motion. The understanding of the forms of energy and how energy flows from one form to another is one of the most useful concepts in science. The term *energy conservation* appears in everything from scientific papers to electric appliance commercials. Scientists use the concept of energy to explore topics much more complicated than colliding billiard balls.

MINI LAB

Energy Exchange

1. Select different-sized steel balls and determine their masses.

2. Stand a spring-loaded laboratory cart on end with the spring mechanism pointing upward.

3. Place a ball on top of the spring mechanism and press down until the ball is touching the cart.

4. Quickly release the ball so that the spring shoots it upward. ***CAUTION: Stay clear of the ball when launching.***

5. Repeat the process several times, and measure the average height.

6. Estimate how high the other sizes of steel balls will rise.

Analyze and Conclude

7. Classify the balls by height attained. What can you conclude?

11.2 Section Review

22. Closed Systems Is Earth a closed, isolated system? Support your answer.

23. Energy A child jumps on a trampoline. Draw bar graphs to show the forms of energy present in the following situations.

a. The child is at the highest point.

b. The child is at the lowest point.

24. Kinetic Energy Suppose a glob of chewing gum and a small, rubber ball collide head-on in midair and then rebound apart. Would you expect kinetic energy to be conserved? If not, what happens to the energy?

25. Kinetic Energy In table tennis, a very light but hard ball is hit with a hard rubber or wooden paddle. In tennis, a much softer ball is hit with a racket. Why are the two sets of equipment designed in this way? Can you think of other ball-paddle pairs in sports? How are they designed?

26. Potential Energy A rubber ball is dropped from a height of 8.0 m onto a hard concrete floor. It hits the floor and bounces repeatedly. Each time it hits the floor, it loses $\frac{1}{5}$ of its total energy. How many times will it bounce before it bounces back up to a height of only about 4 m?

27. Energy As shown in **Figure 11-15,** a 36.0-kg child slides down a playground slide that is 2.5 m high. At the bottom of the slide, she is moving at 3.0 m/s. How much energy was lost as she slid down the slide?

Figure 11-15

28. Critical Thinking A ball drops 20 m. When it has fallen half the distance, or 10 m, half of its energy is potential and half is kinetic. When the ball has fallen for half the amount of time it takes to fall, will more, less, or exactly half of its energy be potential energy?

PHYSICS LAB

Conservation of Energy

Alternate CBL instructions can be found on the Web site.
physicspp.com

There are many examples of situations where energy is conserved. One such example is a rock falling from a given height. If the rock starts at rest, at the moment the rock is dropped, it only has potential energy. As it falls, its potential energy decreases as its height decreases, but its kinetic energy increases. The sum of potential energy and kinetic energy remains constant if friction is neglected. When the rock is about to hit the ground, all of its potential energy has been converted to kinetic energy. In this experiment, you will model a falling object and calculate its speed as it hits the ground.

QUESTION

How does the transfer of an object's potential energy to kinetic energy demonstrate conservation of energy?

Objectives

- **Calculate** the speed of a falling object as it hits the ground by using a model.
- **Interpret data** to find the relationship between potential energy and kinetic energy of a falling object.

Safety Precautions

Figure 1

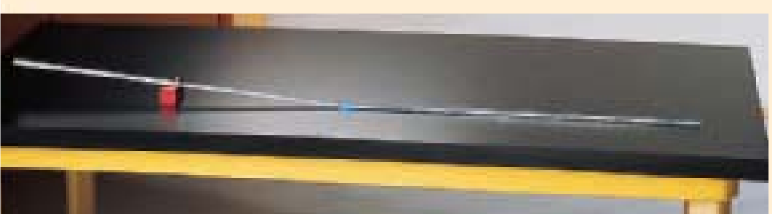


Figure 2

Figure 3

Materials

grooved track (two sections)
marble or steel ball
stopwatch
block of wood
electronic balance
metric ruler
graphing calculator

Procedure

1. Place the two sections of grooved track together, as shown in **Figure 1.** Raise one end of the track and place the block under it, about 5 cm from the raised end. Make sure the ball can roll smoothly across the junction of the two tracks.
2. Record the length of the level portion of the track in the data table. Place a ball on the track directly above the point supported by the block. Release the ball. Start the stopwatch when the ball reaches the level section of track. Stop timing when the ball reaches the end of the level portion of the track. Record the time required for the ball to travel that distance in the data table.
3. Move the support block so that it is under the midsection of the inclined track, as shown in **Figure 2.** Place the ball on the track just above the point supported by the block. Release the ball and measure the time needed for the ball to roll the length of the level portion of the track and record it in the data table. Notice that even though the incline is steeper, the ball is released from the same height as in step 2.
4. Calculate the speed of the ball on the level portion of the track in steps 2 and 3. Move the support block to a point about three-quarters down the length of the inclined track, as shown in **Figure 3.**

Data Table

Release Height (m)	Distance (m)	Time (s)	Speed (m/s)
0.05			
0.05			
0.05			
0.01			
0.02			
0.03			

5. Predict the amount of time the ball will take to travel the length of the level portion of the track. Record your prediction. Test your prediction.
6. Place the support block at the midpoint of the inclined track (Figure 2). Measure a point on the inclined portion of the track that is 1.0 cm above the level portion of the track. Be sure to measure 1.0 cm above the level portion, and not 1.0 cm above the table.
7. Release the ball from this point and measure the time required for the ball to travel on the level portion of the track and record it in the data table.
8. Use a ruler to measure a point that is 2.0 cm above the level track. Release the ball from this point and measure the time required for the ball to travel on the level portion of the track. Record the time in the data table.
9. Repeat step 8 for 3.0 cm, 4.0 cm, 5.0 cm, 6.0 cm, 7.0 cm, and 8.0 cm. Record the times.

Analyze

1. **Infer** What effect did changing the slope of the inclined plane in steps 2–6 have on the speed of the ball on the level portion of the track?
2. **Analyze** Perform a power law regression for this graph using your graphing calculator. Record the equation of this function. Graph this by inputting the equation into Y=. Draw a sketch of the graph.
3. Using the data from step 9 for the release point of 8.0 cm, find the potential energy of the ball before it was released. Use an electronic balance to find the mass of the ball. Note that height must be in m, and mass in kg.
4. Using the speed data from step 9 for the release point of 8.0 cm calculate the kinetic energy of the ball on the level portion of the track. Remember, speed must be in m/s and mass in kg.

Conclude and Apply

1. Solve for speed, y, in terms of height, x. Begin by setting $PE_i = KE_f$.
2. How does the equation found in the previous question relate to the power law regression calculated earlier?
3. Suppose you want the ball to roll twice as fast on the level part of the track as it did when you released it from the 2-cm mark. Using the power law regression performed earlier, calculate the height from which you should release the ball.
4. Explain how this experiment only models dropping a ball and finding its kinetic energy just as it hits the ground.
5. **Compare and Contrast** Compare the potential energy of the ball before it is released (step 8) to the kinetic energy of the ball on the level track (step 9). Explain why they are the same or why they are different.
6. **Draw Conclusions** Does this experiment demonstrate conservation of energy? Explain.

Going Further

What are potential sources of error in the experiment, and how can they be reduced?

Real-World Physics

How does your favorite roller coaster demonstrate the conservation of energy by the transfer of potential energy to kinetic energy?

Physics Online

To find out more about energy, visit the Web site: **physicspp.com**

Technology and Society

Running Smarter

The Physics of Running Shoes Today's running shoes are high-tech marvels. They enhance performance and protect your body by acting as shock absorbers. How do running shoes help you win a race? They reduce your energy consumption, as well as allow you to use energy more efficiently. Good running shoes must be flexible enough to bend with your feet as you run, support your feet, and hold them in place. They must be lightweight and provide traction to prevent slipping.

Running Shoes as Shock Absorbers Today, much of the focus of running shoe technology centers on the cushioned midsole that plays a key role as a shock-absorber and performance enhancer. Each time a runner's foot hits the ground, the ground exerts an equal and opposite force on the runner's foot. This force can be nearly four times a runner's weight, causing aches and pains, shin splints, and damage to knees and ankles over long distances.

Cushioning is used in running shoes to decrease the force absorbed by the runner. As a runner's foot hits the ground and comes to a stop, its momentum changes. The change in momentum is $\Delta p = F\Delta t$, where F is the force on that object and Δt is the time during which the force acts. The cushioning causes the change of momentum to occur over an extended time and reduces the force of the foot on the ground. The decreased force reduces the damage to the runner's body.

Running Shoes Boost Performance A shoe's cushioning system also affects energy consumption. The bones, muscles, ligaments, and tendons of the foot and leg are a natural cushioning system. But operating this system requires the body to use stored energy to contract muscles. So if a shoe can be worn that assists a runner's natural cushioning system, the runner does not expend as much of his or her own stored energy. The energy the runner saved can be spent to run farther or faster.

The cushioned midsole uses the law of conservation of energy to return as much of the energy to the runner as possible. The runner's kinetic energy transforms to elastic potential energy, plus heat, when the runner's foot hits the running surface. If the runner can reduce the amount of energy that is lost as heat, the runner's elastic potential energy can be converted back to useful kinetic energy.

Bouncy, springy, elastic materials that resist crushing over time commonly are used to create the cushioned midsole. Options now range from silicon gel pads to complex fluid-filled systems and even springs to give a runner extra energy efficiency.

Going Further

1. **Use Scientific Explanations** Use physics to explain why manufacturers put cushioned midsoles in running shoes.
2. **Analyze** Which surface would provide more cushioning when running: a grassy field or a concrete sidewalk? Explain why that surface provides better cushioning.
3. **Research** Some people prefer to run barefoot, even in marathon races. Why might this be so?

Chapter 11

Study Guide

11.1 The Many Forms of Energy

Vocabulary

- rotational kinetic energy (p. 287)
- gravitational potential energy (p. 288)
- reference level (p. 288)
- elastic potential energy (p. 291)

Key Concepts

- The kinetic energy of an object is proportional to its mass and the square of its velocity.
- The rotational kinetic energy of an object is proportional to the object's moment of inertia and the square of its angular velocity.
- When Earth is included in a system, the work done by gravity is replaced by gravitational potential energy.
- The gravitational potential energy of an object depends on the object's weight and its distance from Earth's surface.

$$PE = mgh$$

- The reference level is the position where the gravitational potential energy is defined to be zero.
- Elastic potential energy may be stored in an object as a result of its change in shape.
- Albert Einstein recognized that mass itself has potential energy. This energy is called rest energy.

$$E_0 = mc^2$$

11.2 Conservation of Energy

Vocabulary

- law of conservation of energy (p. 293)
- mechanical energy (p. 293)
- thermal energy (p. 295)
- elastic collision (p. 298)
- inelastic collision (p. 298)

Key Concepts

- The sum of kinetic and potential energy is called mechanical energy.

$$E = KE + PE$$

- If no objects enter or leave a system, the system is considered to be a closed system.
- If there are no external forces acting on a system, the system is considered to be an isolated system.
- The total energy of a closed, isolated system is constant. Within the system, energy can change form, but the total amount of energy does not change. Thus, energy is conserved.

$$KE_{before} + PE_{before} = KE_{after} + PE_{after}$$

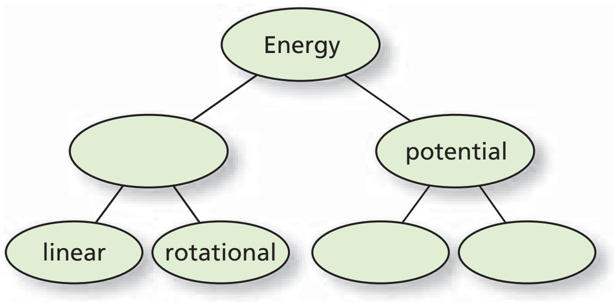
- The type of collision in which the kinetic energy after the collision is less than the kinetic energy before the collision is called an inelastic collision.
- The type of collision in which the kinetic energy before and after the collision is the same is called an elastic collision.
- Momentum is conserved in collisions if the external force is zero. The mechanical energy may be unchanged or decreased by the collision, depending on whether the collision is elastic or inelastic.

Chapter 11

Assessment

Concept Mapping

29. Complete the concept map using the following terms: *gravitational potential energy, elastic potential energy, kinetic energy.*



Mastering Concepts

Unless otherwise directed, assume that air resistance is negligible.

30. Explain how work and a change in energy are related. (11.1)

31. What form of energy does a wound-up watch spring have? What form of energy does a functioning mechanical watch have? When a watch runs down, what has happened to the energy? (11.1)

32. Explain how energy change and force are related. (11.1)

33. A ball is dropped from the top of a building. You choose the top of the building to be the reference level, while your friend chooses the bottom. Explain whether the energy calculated using these two reference levels is the same or different for the following situations. (11.1)
    - **a.** the ball's potential energy at any point
    - **b.** the change in the ball's potential energy as a result of the fall
    - **c.** the kinetic energy of the ball at any point

34. Can the kinetic energy of a baseball ever be negative? (11.1)

35. Can the gravitational potential energy of a baseball ever be negative? Explain without using a formula. (11.1)

36. If a sprinter's velocity increases to three times the original velocity, by what factor does the kinetic energy increase? (11.1)

37. What energy transformations take place when an athlete is pole-vaulting? (11.2)

38. The sport of pole-vaulting was drastically changed when the stiff, wooden poles were replaced by flexible, fiberglass poles. Explain why. (11.2)

39. You throw a clay ball at a hockey puck on ice. The smashed clay ball and the hockey puck stick together and move slowly. (11.2)
    - **a.** Is momentum conserved in the collision? Explain.
    - **b.** Is kinetic energy conserved? Explain.

40. Draw energy bar graphs for the following processes. (11.2)
    - **a.** An ice cube, initially at rest, slides down a frictionless slope.
    - **b.** An ice cube, initially moving, slides up a frictionless slope and instantaneously comes to rest.

41. Describe the transformations from kinetic energy to potential energy and vice versa for a roller-coaster ride. (11.2)

42. Describe how the kinetic energy and elastic potential energy are lost in a bouncing rubber ball. Describe what happens to the motion of the ball. (11.2)

Applying Concepts

43. The driver of a speeding car applies the brakes and the car comes to a stop. The system includes the car but not the road. Apply the work-energy theorem to the following situations.
    - **a.** The car's wheels do not skid.
    - **b.** The brakes lock and the car's wheels skid.

44. A compact car and a trailer truck are both traveling at the same velocity. Did the car engine or the truck engine do more work in accelerating its vehicle?

45. **Catapults** Medieval warriors used catapults to assault castles. Some catapults worked by using a tightly wound rope to turn the catapult arm. What forms of energy are involved in catapulting a rock to the castle wall?

46. Two cars collide and come to a complete stop. Where did all of their energy go?

47. During a process, positive work is done on a system, and the potential energy decreases. Can you determine anything about the change in kinetic energy of the system? Explain.

48. During a process, positive work is done on a system, and the potential energy increases. Can you tell whether the kinetic energy increased, decreased, or remained the same? Explain.

49. **Skating** Two skaters of unequal mass have the same speed and are moving in the same direction. If the ice exerts the same frictional force on each skater, how will the stopping distances of their bodies compare?

 For more problems, go to Additional Problems, Appendix B.

50. You swing a 55-g mass on the end of a 0.75-m string around your head in a nearly horizontal circle at constant speed, as shown in **Figure 11-16.**
  a. How much work is done on the mass by the tension of the string in one revolution?
  b. Is your answer to part **a** in agreement with the work-energy theorem? Explain.

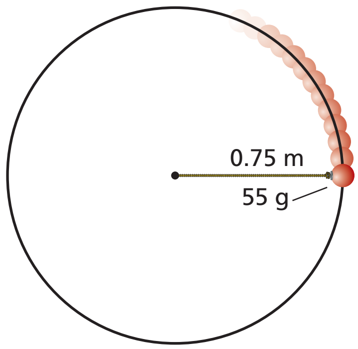


Figure 11-16

51. Give specific examples that illustrate the following processes.
  a. Work is done on a system, thereby increasing kinetic energy with no change in potential energy.
  b. Potential energy is changed to kinetic energy with no work done on the system.
  c. Work is done on a system, increasing potential energy with no change in kinetic energy.
  d. Kinetic energy is reduced, but potential energy is unchanged. Work is done by the system.

52. Roller Coaster You have been hired to make a roller coaster more exciting. The owners want the speed at the bottom of the first hill doubled. How much higher must the first hill be built?

53. Two identical balls are thrown from the top of a cliff, each with the same speed. One is thrown straight up, the other straight down. How do the kinetic energies and speeds of the balls compare as they strike the ground?

Mastering Problems

Unless otherwise directed, assume that air resistance is negligible.

11.1 The Many Forms of Energy

54. A 1600-kg car travels at a speed of 12.5 m/s. What is its kinetic energy?

55. A racing car has a mass of 1525 kg. What is its kinetic energy if it has a speed of 108 km/h?

56. Shawn and his bike have a combined mass of 45.0 kg. Shawn rides his bike 1.80 km in 10.0 min at a constant velocity. What is Shawn's kinetic energy?

57. Tony has a mass of 45 kg and is moving with a speed of 10.0 m/s.
  a. Find Tony's kinetic energy.
  b. Tony's speed changes to 5.0 m/s. Now what is his kinetic energy?
  c. What is the ratio of the kinetic energies in parts **a** and **b**? Explain.

58. Katia and Angela each have a mass of 45 kg, and they are moving together with a speed of 10.0 m/s.
  a. What is their combined kinetic energy?
  b. What is the ratio of their combined mass to Katia's mass?
  c. What is the ratio of their combined kinetic energy to Katia's kinetic energy? Explain.

59. Train In the 1950s, an experimental train, which had a mass of 2.50×10^4 kg, was powered across a level track by a jet engine that produced a thrust of 5.00×10^5 N for a distance of 509 m.
  a. Find the work done on the train.
  b. Find the change in kinetic energy.
  c. Find the final kinetic energy of the train if it started from rest.
  d. Find the final speed of the train if there had been no friction.

60. Car Brakes A 14,700-N car is traveling at 25 m/s. The brakes are applied suddenly, and the car slides to a stop, as shown in **Figure 11-17.** The average braking force between the tires and the road is 7100 N. How far will the car slide once the brakes are applied?

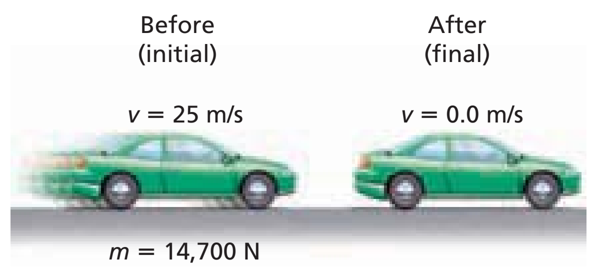


Figure 11-17

61. A 15.0-kg cart is moving with a velocity of 7.50 m/s down a level hallway. A constant force of 10.0 N acts on the cart, and its velocity becomes 3.20 m/s.
  a. What is the change in kinetic energy of the cart?
  b. How much work was done on the cart?
  c. How far did the cart move while the force acted?

62. How much potential energy does DeAnna, with a mass of 60.0 kg, gain when she climbs a gymnasium rope a distance of 3.5 m?

63. Bowling A 6.4-kg bowling ball is lifted 2.1 m into a storage rack. Calculate the increase in the ball's potential energy.

64. Mary weighs 505 N. She walks down a flight of stairs to a level 5.50 m below her starting point. What is the change in Mary's potential energy?

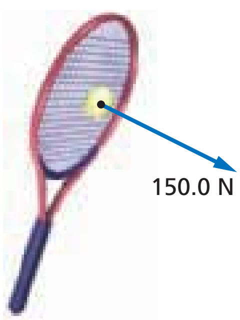
65. Weightlifting A weightlifter raises a 180-kg barbell to a height of 1.95 m. What is the increase in the potential energy of the barbell?

66. A 10.0-kg test rocket is fired vertically from Cape Canaveral. Its fuel gives it a kinetic energy of 1960 J by the time the rocket engine burns all of the fuel. What additional height will the rocket rise?

67. Antwan raised a 12.0-N physics book from a table 75 cm above the floor to a shelf 2.15 m above the floor. What was the change in the potential energy of the system?

68. A hallway display of energy is constructed in which several people pull on a rope that lifts a block 1.00 m. The display indicates that 1.00 J of work is done. What is the mass of the block?

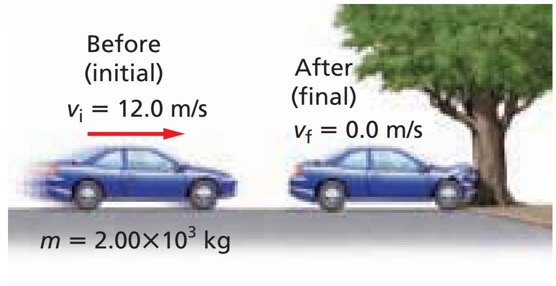
69. Tennis It is not uncommon during the serve of a professional tennis player for the racket to exert an average force of 150.0 N on the ball. If the ball has a mass of 0.060 kg and is in contact with the strings of the racket, as shown in **Figure 11-18,** for 0.030 s, what is the kinetic energy of the ball as it leaves the racket? Assume that the ball starts from rest.



■ **Figure 11-18**

70. Pam, wearing a rocket pack, stands on frictionless ice. She has a mass of 45 kg. The rocket supplies a constant force for 22.0 m, and Pam acquires a speed of 62.0 m/s.
a. What is Pam's final kinetic energy?
b. What is the magnitude of the force?

71. Collision A 2.00×10^3-kg car has a speed of 12.0 m/s. The car then hits a tree. The tree doesn't move, and the car comes to rest, as shown in **Figure 11-19.**
a. Find the change in kinetic energy of the car.
b. Find the amount of work done as the front of the car crashes into the tree.
c. Find the size of the force that pushed in the front of the car by 50.0 cm.



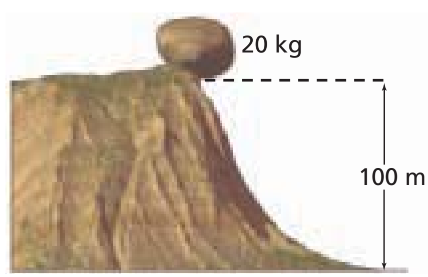
■ **Figure 11-19**

72. A constant net force of 410 N is applied upward to a stone that weighs 32 N. The upward force is applied through a distance of 2.0 m, and the stone is then released. To what height, from the point of release, will the stone rise?

11.2 Conservation of Energy

73. A 98.0-N sack of grain is hoisted to a storage room 50.0 m above the ground floor of a grain elevator.
a. How much work was done?
b. What is the increase in potential energy of the sack of grain at this height?
c. The rope being used to lift the sack of grain breaks just as the sack reaches the storage room. What kinetic energy does the sack have just before it strikes the ground floor?

74. A 20-kg rock is on the edge of a 100-m cliff, as shown in **Figure 11-20.**
a. What potential energy does the rock possess relative to the base of the cliff?
b. The rock falls from the cliff. What is its kinetic energy just before it strikes the ground?
c. What speed does the rock have as it strikes the ground?



■ **Figure 11-20**

75. Archery An archer puts a 0.30-kg arrow to the bowstring. An average force of 201 N is exerted to draw the string back 1.3 m.
a. Assuming that all the energy goes into the arrow, with what speed does the arrow leave the bow?
b. If the arrow is shot straight up, how high does it rise?

76. A 2.0-kg rock that is initially at rest loses 407 J of potential energy while falling to the ground. Calculate the kinetic energy that the rock gains while falling. What is the rock's speed just before it strikes the ground?

77. A physics book of unknown mass is dropped 4.50 m. What speed does the book have just before it hits the ground?

78. **Railroad Car** A railroad car with a mass of 5.0×10^5 kg collides with a stationary railroad car of equal mass. After the collision, the two cars lock together and move off at 4.0 m/s, as shown in **Figure 11-21.**

a. Before the collision, the first railroad car was moving at 8.0 m/s. What was its momentum?

b. What was the total momentum of the two cars after the collision?

c. What were the kinetic energies of the two cars before and after the collision?

d. Account for the loss of kinetic energy.

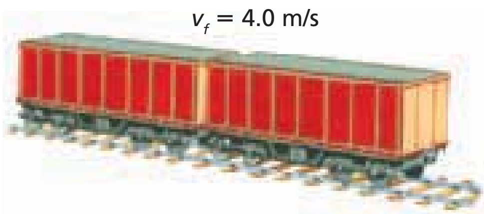


Figure 11-21

79. From what height would a compact car have to be dropped to have the same kinetic energy that it has when being driven at 1.00×10^2 km/h?

80. Kelli weighs 420 N, and she is sitting on a playground swing that hangs 0.40 m above the ground. Her mom pulls the swing back and releases it when the seat is 1.00 m above the ground.

a. How fast is Kelli moving when the swing passes through its lowest position?

b. If Kelli moves through the lowest point at 2.0 m/s, how much work was done on the swing by friction?

81. Hakeem throws a 10.0-g ball straight down from a height of 2.0 m. The ball strikes the floor at a speed of 7.5 m/s. What was the initial speed of the ball?

82. **Slide** Lorena's mass is 28 kg. She climbs the 4.8-m ladder of a slide and reaches a velocity of 3.2 m/s at the bottom of the slide. How much work was done by friction on Lorena?

83. A person weighing 635 N climbs up a ladder to a height of 5.0 m. Use the person and Earth as the system.

a. Draw energy bar graphs of the system before the person starts to climb the ladder and after the person stops at the top. Has the mechanical energy changed? If so, by how much?

b. Where did this energy come from?

Mixed Review

84. Suppose a chimpanzee swings through the jungle on vines. If it swings from a tree on a 13-m-long vine that starts at an angle of 45°, what is the chimp's velocity when it reaches the ground?

85. An 0.80-kg cart rolls down a frictionless hill of height 0.32 m. At the bottom of the hill, the cart rolls on a flat surface, which exerts a frictional force of 2.0 N on the cart. How far does the cart roll on the flat surface before it comes to a stop?

86. **High Jump** The world record for the men's high jump is about 2.45 m. To reach that height, what is the minimum amount of work that a 73.0-kg jumper must exert in pushing off the ground?

87. A stuntwoman finds that she can safely break her fall from a one-story building by landing in a box filled to a 1-m depth with foam peanuts. In her next movie, the script calls for her to jump from a five-story building. How deep a box of foam peanuts should she prepare?

88. **Football** A 110-kg football linebacker has a head-on collision with a 150-kg defensive end. After they collide, they come to a complete stop. Before the collision, which player had the greater momentum and which player had the greater kinetic energy?

89. A 2.0-kg lab cart and a 1.0-kg lab cart are held together by a compressed spring. The lab carts move at 2.1 m/s in one direction. The spring suddenly becomes uncompressed and pushes the two lab carts apart. The 2-kg lab cart comes to a stop, and the 1.0-kg lab cart moves ahead. How much energy did the spring add to the lab carts?

90. A 55.0-kg scientist roping through the top of a tree in the jungle sees a lion about to attack a tiny antelope. She quickly swings down from her 12.0-m-high perch and grabs the antelope (21.0 kg) as she swings. They barely swing back up to a tree limb out of reach of the lion. How high is this tree limb?

91. An 0.80-kg cart rolls down a 30.0° hill from a vertical height of 0.50 m as shown in **Figure 11-22.** The distance that the cart must roll to the bottom of the hill is 0.50 m/sin 30.0° = 1.0 m. The surface of the hill exerts a frictional force of 5.0 N on the cart. Does the cart roll to the bottom of the hill?

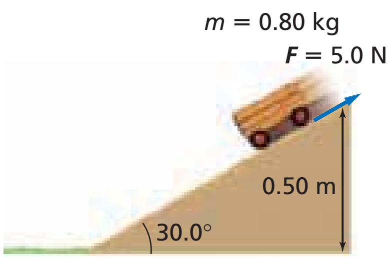


Figure 11-22

92. Object A, sliding on a frictionless surface at 3.2 m/s, hits a 2.0-kg object, B, which is motionless. The collision of A and B is completely elastic. After the collision, A and B move away from each other at equal and opposite speeds. What is the mass of object A?

93. Hockey A 90.0-kg hockey player moving at 5.0 m/s collides head-on with a 110-kg hockey player moving at 3.0 m/s in the opposite direction. After the collision, they move off together at 1.0 m/s. How much energy was lost in the collision?

Thinking Critically

94. Apply Concepts A golf ball with a mass of 0.046 kg rests on a tee. It is struck by a golf club with an effective mass of 0.220 kg and a speed of 44 m/s. Assuming that the collision is elastic, find the speed of the ball when it leaves the tee.

95. Apply Concepts A fly hitting the windshield of a moving pickup truck is an example of a collision in which the mass of one of the objects is many times larger than the other. On the other hand, the collision of two billiard balls is one in which the masses of both objects are the same. How is energy transferred in these collisions? Consider an elastic collision in which billiard ball m_1 has velocity $\boldsymbol{v}_1$ and ball m_2 is motionless.

a. If $m_1 = m_2$, what fraction of the initial energy is transferred to m_2?

b. If $m_1 >> m_2$, what fraction of the initial energy is transferred to m_2?

c. In a nuclear reactor, neutrons must be slowed down by causing them to collide with atoms. (A neutron is about as massive as a proton.) Would hydrogen, carbon, or iron atoms be more desirable to use for this purpose?

96. Analyze and Conclude In a perfectly elastic collision, both momentum and mechanical energy are conserved. Two balls, with masses m_A and m_B, are moving toward each other with speeds v_A and v_B, respectively. Solve the appropriate equations to find the speeds of the two balls after the collision.

97. Analyze and Conclude A 25-g ball is fired with an initial speed of v_1 toward a 125-g ball that is hanging motionless from a 1.25-m string. The balls have a perfectly elastic collision. As a result, the 125-g ball swings out until the string makes an angle of 37.0° with the vertical. What is v_1?

Writing in Physics

98. All energy comes from the Sun. In what forms has this solar energy come to us to allow us to live and to operate our society? Research the ways that the Sun's energy is turned into a form that we can use. After we use the Sun's energy, where does it go? Explain.

99. All forms of energy can be classified as either kinetic or potential energy. How would you describe nuclear, electric, chemical, biological, solar, and light energy, and why? For each of these types of energy, research what objects are moving and how energy is stored in those objects.

Cumulative Reveiw

100. A satellite is placed in a circular orbit with a radius of 1.0×10^7 m and a period of 9.9×10^3 s. Calculate the mass of Earth. *Hint: Gravity is the net force on such a satellite. Scientists have actually measured the mass of Earth this way.* (Chapter 7)

101. A 5.00-g bullet is fired with a velocity of 100.0 m/s toward a 10.00-kg stationary solid block resting on a frictionless surface. (Chapter 9)

a. What is the change in momentum of the bullet if it is embedded in the block?

b. What is the change in momentum of the bullet if it ricochets in the opposite direction with a speed of 99 m/s?

c. In which case does the block end up with a greater speed?

102. An automobile jack must exert a lifting force of at least 15 kN. (Chapter 10)

a. If you want to limit the effort force to 0.10 kN, what mechanical advantage is needed?

b. If the jack is 75% efficient, over what distance must the effort force be exerted in order to raise the auto 33 cm?

Standardized Test Practice

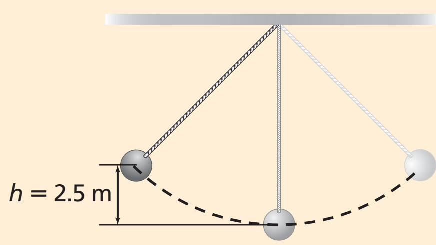
Multiple Choice

1. A bicyclist increases her speed from 4.0 m/s to 6.0 m/s. The combined mass of the bicyclist and the bicycle is 55 kg. How much work did the bicyclist do in increasing her speed?

- (A) 11 J
- (B) 28 J
- (C) 55 J
- (D) 550 J

2. The illustration below shows a ball swinging freely in a plane. The mass of the ball is 4.0 kg. Ignoring friction, what is the maximum speed of the ball as it swings back and forth?

- (A) 0.14 m/s
- (B) 21 m/s
- (C) 7.0 m/s
- (D) 49 m/s



3. You lift a 4.5-kg box from the floor and place it on a shelf that is 1.5 m above the ground. How much energy did you use in lifting the box?

- (A) 9.0 J
- (B) 49 J
- (C) 11 J
- (D) 66 J

4. You drop a 6.0×10^{-2}-kg ball from a height of 1.0 m above a hard, flat surface. The ball strikes the surface and loses 0.14 J of its energy. It then bounces back upward. How much kinetic energy does the ball have just after it bounces off the flat surface?

- (A) 0.20 J
- (B) 0.59 J
- (C) 0.45 J
- (D) 0.73 J

5. You move a 2.5-kg book from a shelf that is 1.2 m above the ground to a shelf that is 2.6 m above the ground. What is the change in the book's potential energy?

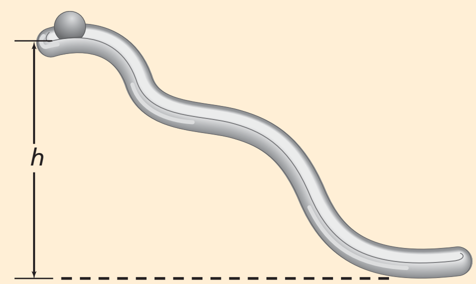
- (A) 1.4 J
- (B) 25 J
- (C) 3.5 J
- (D) 34 J

6. A ball of mass *m* rolls along a flat surface with a speed of v_1. It strikes a padded wall and bounces back in the opposite direction. The energy of the ball after striking the wall is half its initial energy. Ignoring friction, which of the following expressions gives the ball's new speed as a function of its initial speed?

- (A) $\frac{1}{2}v_1$
- (B) $\frac{\sqrt{2}}{2}(v_1)$
- (C) $\sqrt{2}(v_1)$
- (D) $2v_1$

7. The illustration below shows a ball on a curved track. The ball starts with zero velocity at the top of the track. It then rolls from the top of the track to the horizontal part at the ground. Ignoring friction, its velocity just at the moment it reaches the ground is 14 m/s. What is the height, *h*, from the ground to the top of the track?

- (A) 7 m
- (B) 14 m
- (C) 10 m
- (D) 20 m



Extended Answer

8. A box sits on a platform supported by a compressed spring. The box has a mass of 1.0 kg. When the spring is released, it gives 4.9 J of energy to the box, and the box flies upward. What will be the maximum height above the platform reached by the box before it begins to fall?

✓ Test-Taking TIP

Use the Process of Elimination

On any multiple-choice test, there are two ways to find the correct answer to each question. Either you can choose the right answer immediately or you can eliminate the answers that you know are wrong.