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.

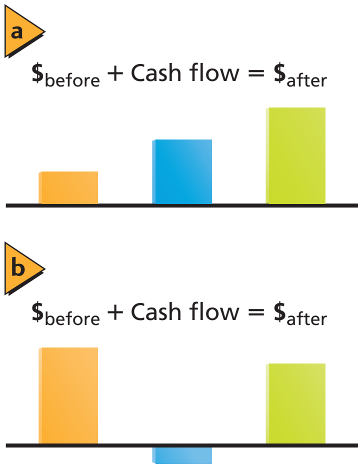
Objectives

- **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

■ **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).**



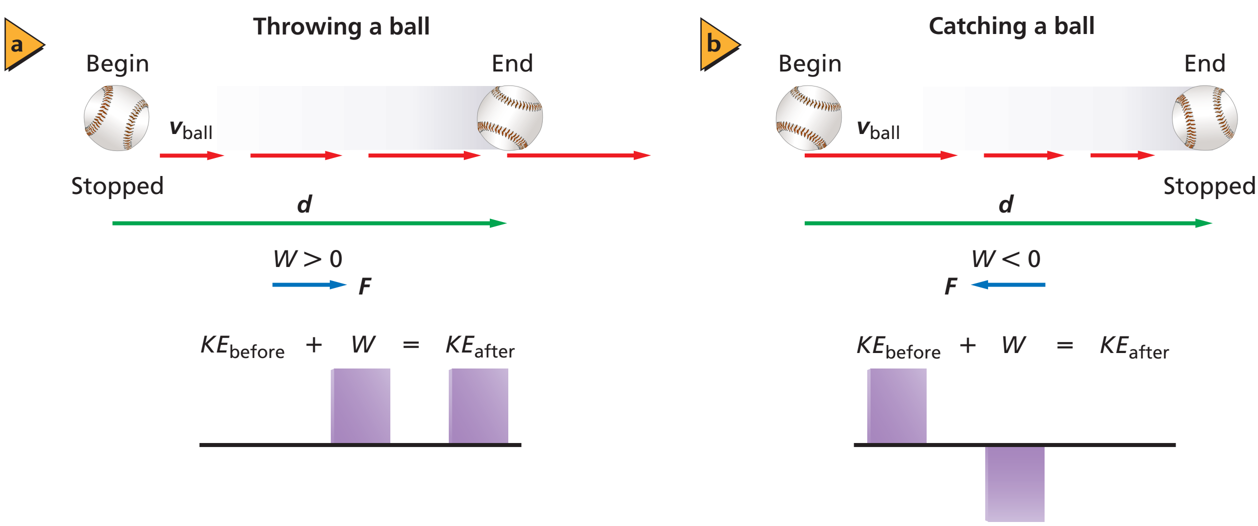
A Model of the Work-Energy Theorem

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.

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.

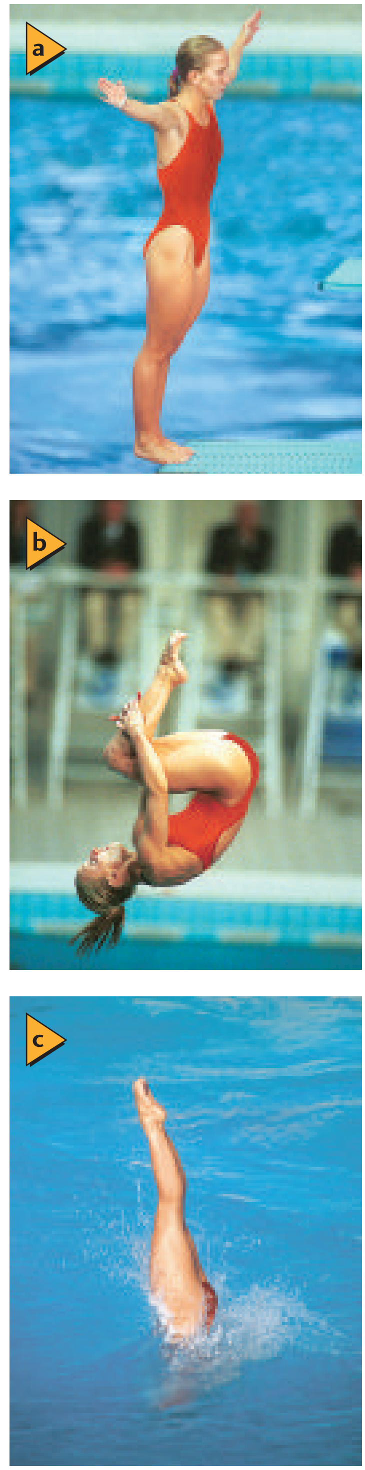


Figure 11-3 The diver does work as she pushes off of the diving board **(a).** This work produces rotational kinetic energy as she rotates about her center of mass **(b)** and she has linear kinetic energy when she slices into the water **(c).**

PRACTICE Problems **Additional Problems, Appendix B**

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.

Ken Redmond/Ken Redmond Photography

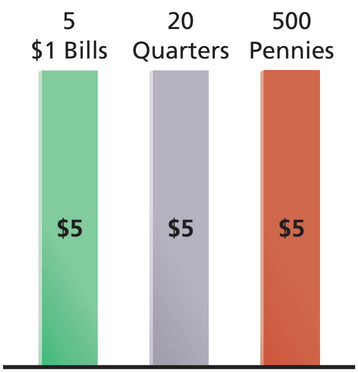
Stored Energy

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.

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



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

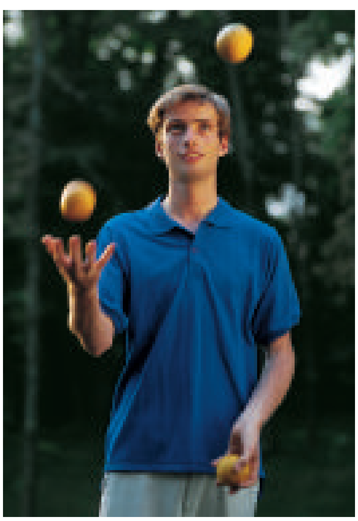
Gravitational Potential Energy

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 ball rises and is transformed back to kinetic energy as the ball 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.



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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.

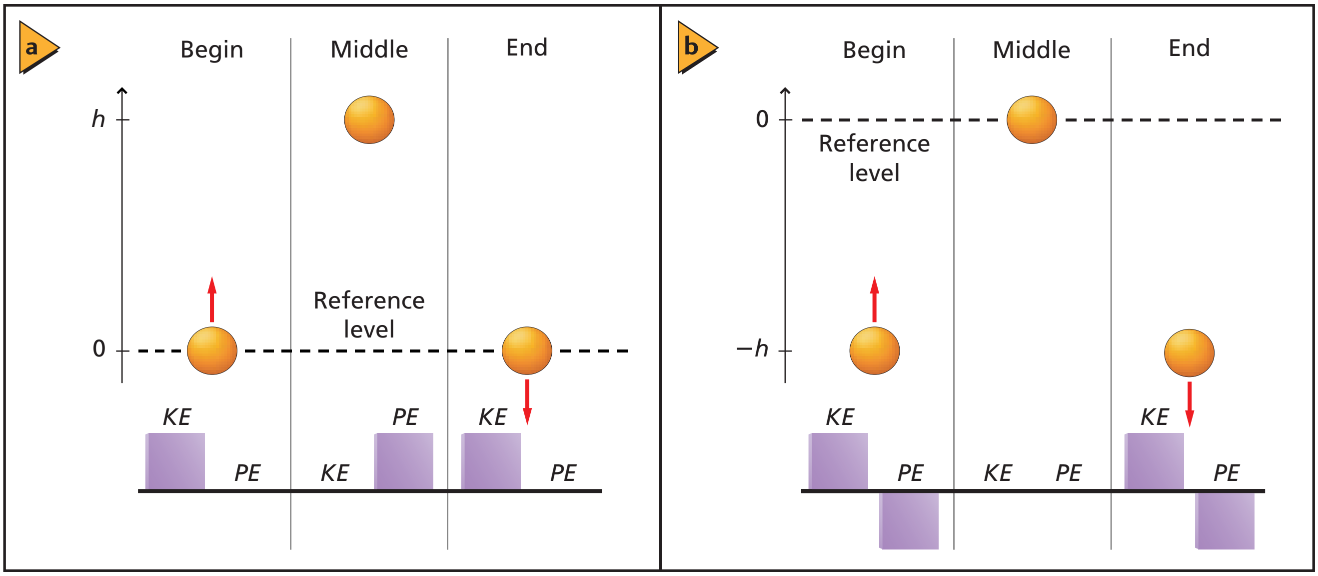


Figure 11-6 The energy of an orange is converted from one form to another in various stages of its flight **(a).** Note that the choice of a reference level is arbitrary, but that the total energy remains constant **(b).**

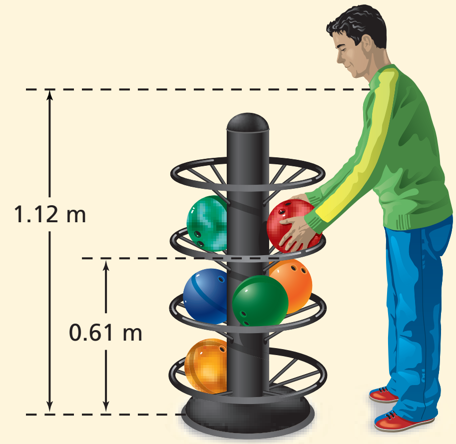
▶ EXAMPLE Problem 1

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?

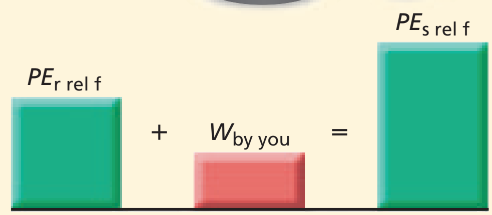
b. When the bowling ball is at your shoulder, what is its gravitational potential energy relative to the storage rack?

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:

$m = 7.30$ kg

$h_r = 0.610$ m (relative to the floor)

$h_s = 1.12$ m (relative to the floor)

$g = 9.80\ \text{m/s}^2$

Unknown:

$PE_{\text{s rel f}} = ?$

$PE_{\text{s rel r}} = ?$

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, $g = 9.80\ \text{m/s}^2$, $h_{\text{shoulder}} = 1.12$ 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, $g = 9.80\ \text{m/s}^2$, $h_s = 1.12$ m, $h_r = 0.610$ m**

$$= 36.5\ \text{J}$$ **This also is equal to the work done by you.**

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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, $g = 9.80\ \text{m/s}^2$, $h_s = 1.12$ 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

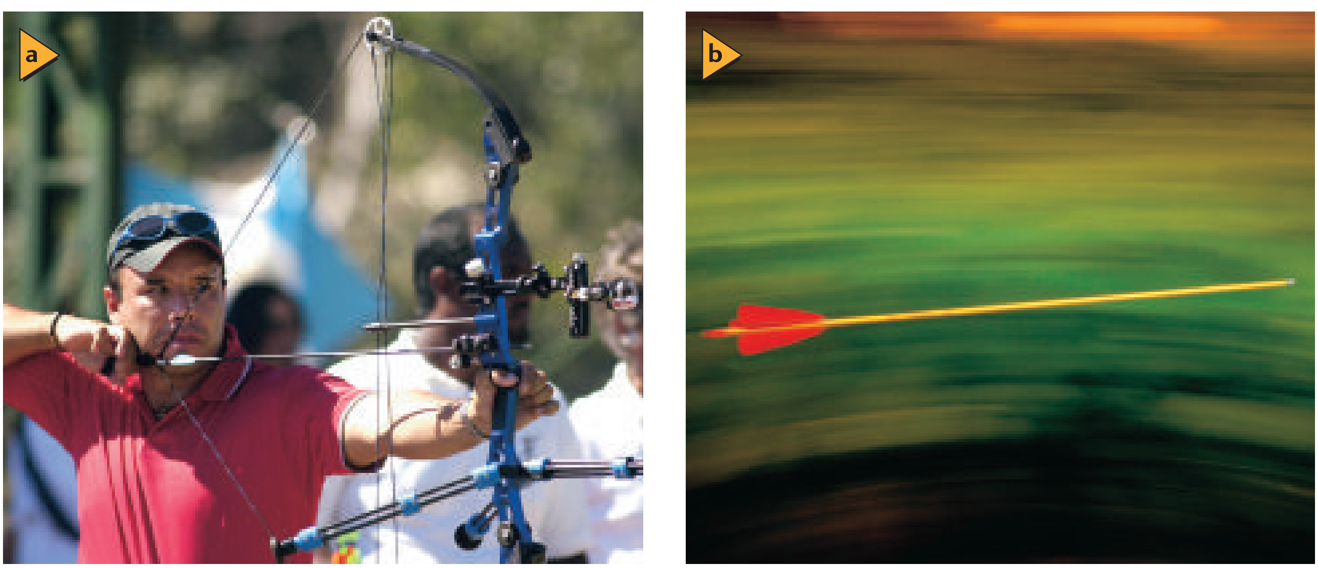
4. In Example Problem 1, what is the potential energy of the bowling ball relative to the rack when it is on the floor?
5. If you slowly lower a 20.0-kg bag of sand 1.20 m from the trunk of a car to the driveway, how much work do you do?
6. A boy lifts a 2.2-kg book from his desk, which is 0.80 m high, 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).**



(r)Getty Images, (l)Luis Romero/AP Wide World Photos

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.

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