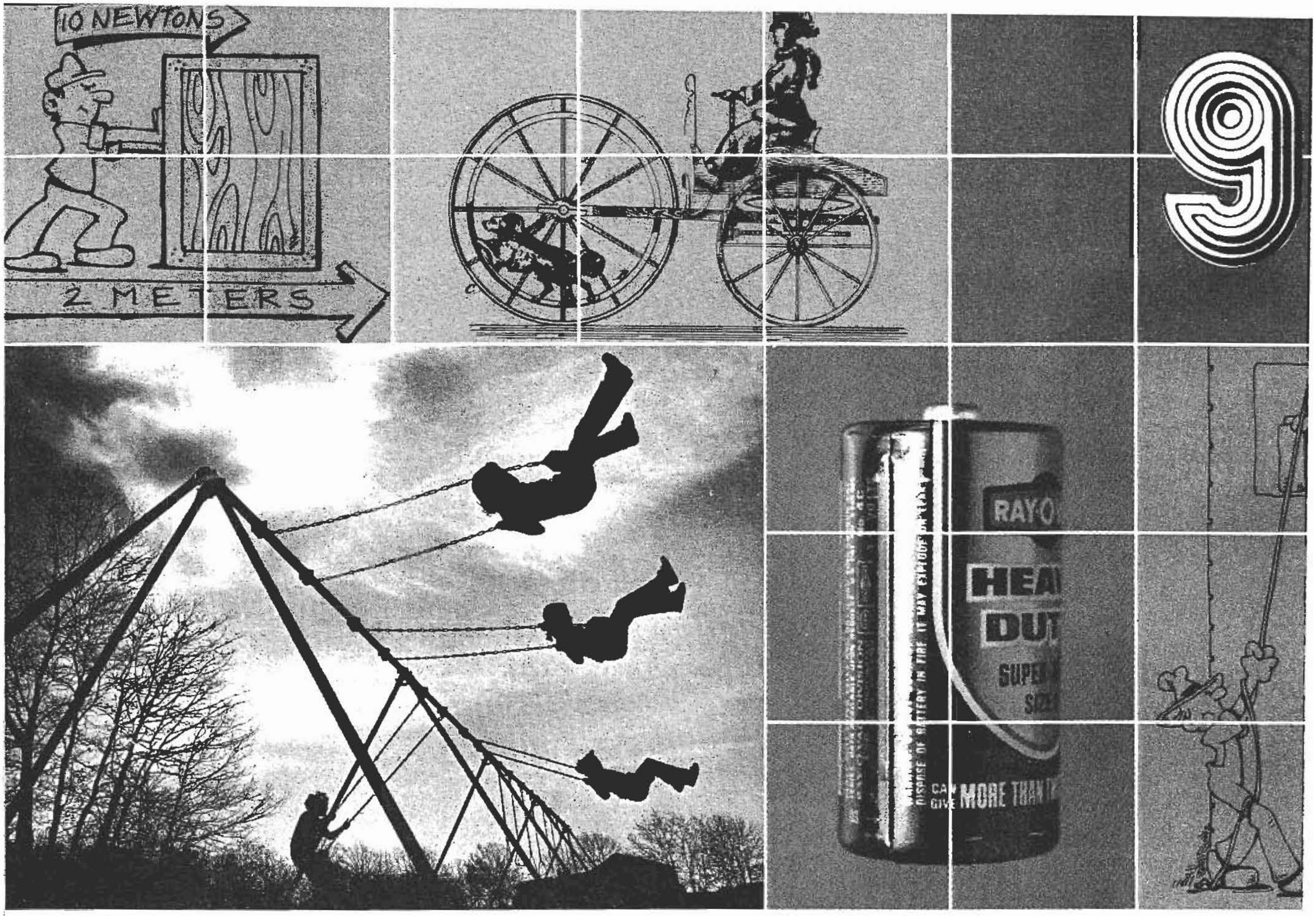


Figure 9·1

Energy

Swinging back and forth (Figure 9-1). The motion seems endless in its repetition. But, as young children and their parents qUickly learn, the sWing's motion is neither spontaneous nor enduring. Left to itself, a swing hangs motionless, the downward force of gravity balanced by the upward force of the rope. We have to pull it back or push it forward to get it going. Once moving, the swing constantly exchanges height for velocity. At the top, the swing stops-momentarily suspended in midair. Remember the sensation? Increasing speed as it descends, the swing reaches its maximum speed as it hits bottom, only to slow back down to zero again at the top. Each time the swing moves upw.ard, it reaches a lesser height; each time it swings downward, its velocity at the bottom is less. Unless we pull or push it again, the swing eventually stops.

We can describe the sWing's motion in terms of the forces acting on it: the parent's push, the force due to gravity, and so on. But we often reach for other words to describe what we see. When we pull the swing back, we *give* it something that enables it to move. This something seems to be transformed-from position to motion to position-as the swing moves back and forth. Finally, this something is gradually lost as the sWing slows down and stops. Whatever it is, seems irretrievably lost, for the swing never spontaneously starts to move again. The name we give to this something is energy.

Like momentum, *energy* is a commodity transferred during an interaction. In this chapter, we will look in detail at two forms of energy: *grauitational potential energy* and *kinetic energy*. We will see that when no friction exists, the sum of the gravitational potential energy and kinetic energy of a system remains *constant*. As we identify other forms of energy, we will generalize this constancy as the *law of conservation of energy*. When all parts of a system are identified and all forms of energy taken into account, the energy of a system is conserved.

INTERACTION, WORK, AND ENERGY

Change accompanies interaction. Whenever we observe a change, we know that an interaction has occurred. In Chapter 5 we introduced the concept of momentum to describe interactions in which objects change their velocities. Now we introduce energy, a concept that describes a much broader range of changes. Unlike momentum, there are many forms of energy.

The Energy Model

Intuitively, we define energy as the ability to make a change during an interaction. All objects possess energy-all are able to initiate change. We are not aware of this ability, however, until a change occurs. Consequently, we measure energy as it is transferred from one object to another. The giver is called the **energy source**, and the recipient is called the **energy receiver.** Energy transferred from a battery to a light bulb causes the bulb to emit light. Energy transferred from gasoline to an automobile engine causes the car to move. Energy transferred from you to the swing causes the swing to move. Energy transferred from the sun to a plant causes the plant to grow. In each case energy has been transferred from a source to a receiver, causing one of many possible kinds of change-production of light, motion, and growth, to name only a few.

In order to trace the transfer of energy from source to receiver, we need to be able to measure it. Because so many kinds of change can result from its transfer, measuring energy is not a simple matter. We begin by measuring energy in terms of work. Later, as we examine the many forms that energy can have, we will develop more direct ways of measuring it.

Energy and Work

Since real situations are often quite complex, let's begin with an idealized example. Imagine a box lying on a very well-waxed floor-so well waxed that we can ignore friction. Suppose you push the box with a force of 10 newtons (N) to the right while the box moves 2 meters (m) to the right (Figure 9-2). When you release the box, it will continue moving with the velocity it had the

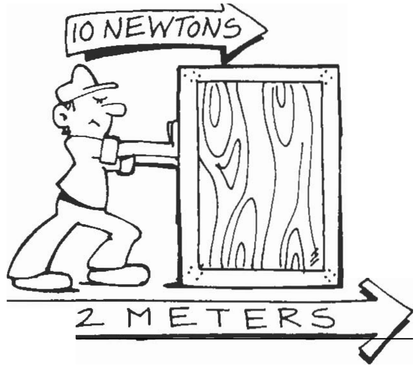


Figure 9-2
A force of 10 N to the right moves the box 2 meters to the right. The work done is 10 N X 2 m or 20 joules.

moment you stopped pushing. There is no friction to slow it down. In this situation, you have acted as an energy source and the box as an energy receiver. The evidence that energy has been transferred is the change in the box's motion. Initially the box was stationary; now it is moving at a constant velocity.

We can measure the amount of energy that was transferred in terms of the work you did in pushing the box. **Work** is defined as the product of the magnitude of the force exerted on the object and the distance the object moves in the same direction as the force. This definition is summarized by the equation

Work

\ (FOrce

$W = F\ell$

Distance moved in direction of force

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

Work is a scalar quantity. It depends only on the components of the force and distance that are in the same direction. The units in which work is measured are the units of force times the units of distance, newton-meters (N . m). This unit could be called a newton-meter, but it is given the name **joule** (J).

In moving the box, you exerted a force of ION to the right. The box moved a distance of 2 m to the right. Since the box moves in the same direction as you push, the work you do is equal to ION times 2 m, or 20 J. This work is a measure of the energy transferred from the energy source-you-to the energy receiver-the box. The box now has 20 J of energy that it did not have before, because you did 20 J worth of work on it. We are aware of this energy because the box is now moving.

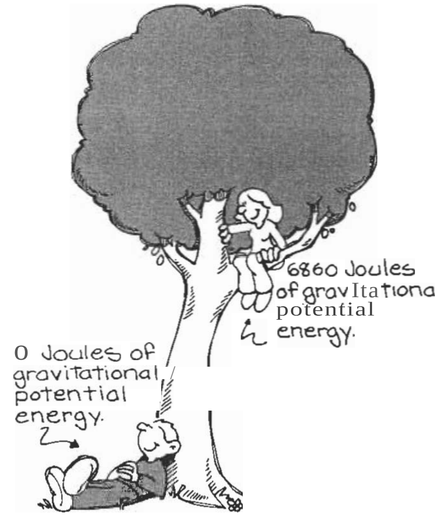
To give you some feeling for the size of the joule, Figure 9-3 includes the energy content measured in joules for some common energy sources. You are probably used to measuring the energy content of some of these sources in other units, called calories. Various units are used for different kinds of energy, but all of them can be converted into joules. Today we use the joule as the standard unit with which to measure energy and work.

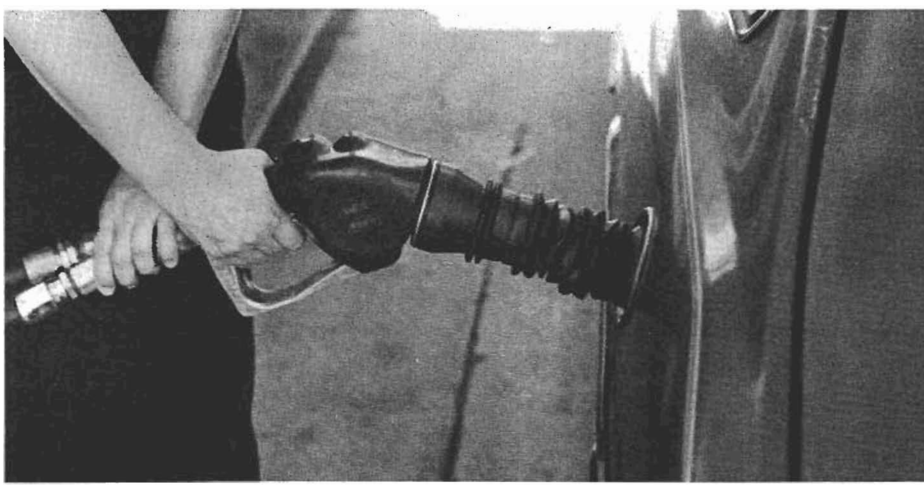
We commonly use the term *work* to describe any situation in which we exert forces, regardless of the result of our exertions. Most of us, for example, would claim that a weight lifter is doing work as she struggles but fails to lift a barbell (Figure 9-4). But physicists restrict their use of *work* to situations in which energy has actually been transferred. Until the barbell moves, the weight lifter has not transferred any energy to it. Consequently, she has done

16,700 J/battery

160,000 J/OL

5280 J/12 oz jar





130,000,000 J/gal.

Figure 9-3

Energy content, in joules, of several energy sources.

Figure 9-4

The weight lifter has not done any work on the barbell until she actually lifts it, causing it to change position.

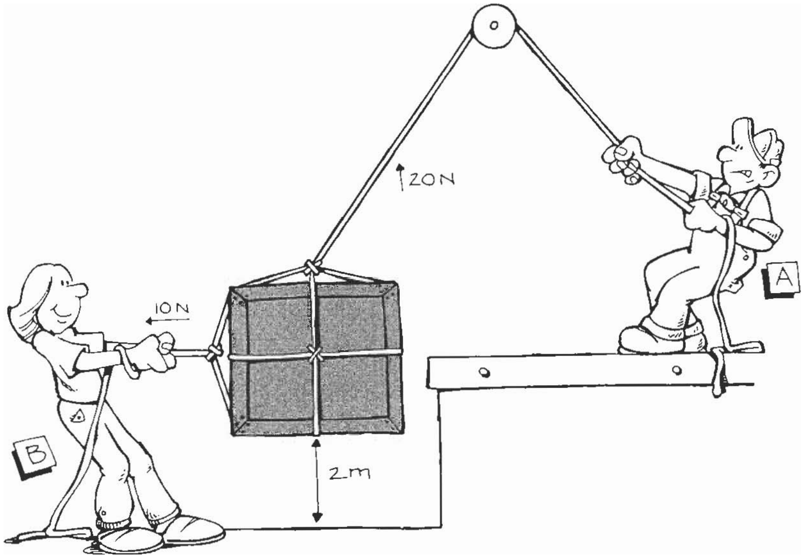


Figure 9-5

no work on it. This restriction is consistent with our definition of work. The struggling weight lifter exerts a force but does not move the weight any distance in the direction of the force.

SELF-CHECK **9A**

Figure 9-5 shows two workers lifting a crate up to a loading dock. One lifts the crate upward with a force of 20 N, while the second pulls outward with a force of 10 N to keep the crate from swinging into the wall. The box moves upward a distance of 2 m.

a. Calculate the work done by each worker.

b. How much energy has been transferred to the box?

ENERGY OF POSITION

A house painter, startled by a wasp, jumps off a ladder. As he strikes the ground, energy is transferred from him (the energy source) to the ground (the energy receiver). While the energy is not actually transferred to the ground until he reaches it, the potential-or possibility-for this energy transfer existed as soon as he stepped on the ladder because of his height. Consider another example. We drop the pile driver shown in Figure 9-6. As it strikes the nail, energy is transferred from the hammerhead (source) to the nail (receiver). The energy is not transferred until the hammerhead hits the nail, but the potential for energy transfer existed as soon as the hammerhead moved upward. The painter and hammer both gain energy from their positions relative to the ground.

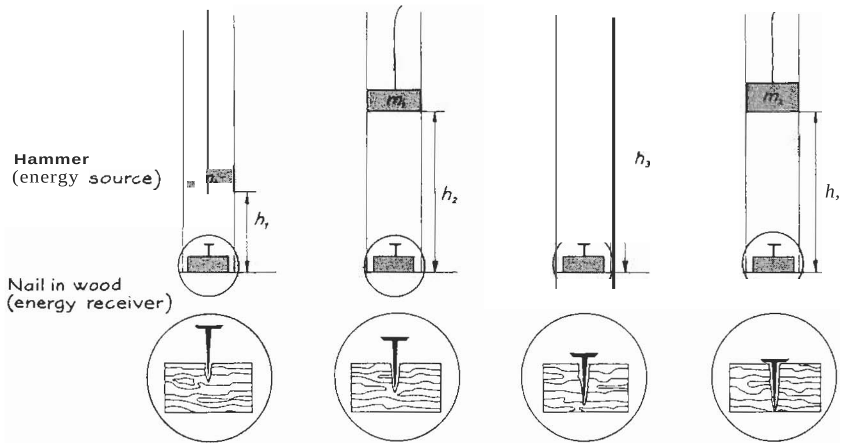


Figure 9-6

The hammer acts as an energy source and the nail as an energy receiver. The amount of energy transferred can be described in terms of the distance the nail is driven into the wood. The greater the height from which the hammer is dropped, the more energy it transfers to the nail. The greater the mass of the hammer-head, the more energy it transfers to the nail.

Gravitational Potential Energy

Gravitational potential energy is the energy stored in an object because of its position relative to a massive object, such as the earth. As the hammerhead is pulled upward, it gains gravitational potential energy because the earth is pulling it back downward. We must do work to raise the hammerhead against the force due to gravity. In the process of doing this work, we transfer energy to the hammerhead. The evidence that energy has been transferred is the new position of the hammerhead relative to the earth.

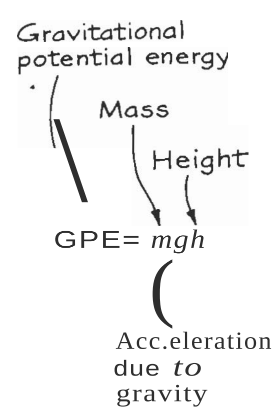
We can use the concept of work to develop a more complete definition of gravitational potential energy. The work done in moving an object away from the earth equals the gravitational potential energy gained by the object. To lift the hammer, for example, we must exert a force vertically upward. The magnitude of the force we exert is equal to the weight of the hammer—the product of its mass and the acceleration due to gravity. This is the force needed to keep the hammerhead moving at a constant velocity against the pull of gravity. The distance the hammer moves is its final height above the bottom of the pile driver. Since the force we exert is in the same direction as the hammer moves, the work we do is:

Work = force X distance

= (weight of hammer) X (height of hammer)

= (mass of hammer) X (acceleration due to gravity) X (height)

In lifting the hammerhead, we act as the energy source and the hammer acts as the energy receiver. The work we do becomes the gravitational potential energy stored in the hammerhead. Consequently, we define **gravitational potential energy** as the product of an object's mass, the acceleration due to gravity, and the object's height above some reference point:



Gravitational potential energy = (mass of hammer) X (acceleration due to gravity) X (height)

When mass is given in kilograms (kg), acceleration due to gravity in (meters/second)/second, and height in meters, gravitational potential energy is given in joules.

This definition allows us to calculate the gravitational potential energy stored in any object, regardless of how complex the energy-transfer process is. The house painter, for example, supplies his own energy as he climbs the ladder. Energy supplied by the food he eats is released in a series of complex chemical reactions; this enables him to climb the ladder. Without knowing any details of the process, we can calculate the increase in his gravitational potential energy from his mass (70 kg) and the height he climbs (4 m). He gains (70 kg){9.8 (m/s)/s){4 m) = 2744 J. As he stands at the top of the ladder, he has 2744 J of gravitational potential energy. When you eat $\frac{1}{20}$ tablespoon of yogurt, you gain about this much energy. It isn't much!

The Pile Driver

So far we have considered the hammerhead as an energy receiver. It is raised from the bottom of the pile driver and, in the process, acquires gravitational potential energy. Once raised, the hammerhead can act as an energy source. Its gravitational potential energy is eventually used to drive a nail into a piece of wood. The distance the nail is driven into the wood provides a rough estimate of the amount of gravitational potential energy the hammerhead had before its descent. We can use this relationship to gain additional insight into our definition of gravitational potential energy.

The definition of gravitational potential energy tells us that the hammer's energy depends on its mass, its height above the nail, and the acceleration due to gravity. Figure 9-6 describes the results of experiments in which the hammerhead's height and mass were varied. Dropped from different heights, the same hammer drives the nail different distances into the wood. Roughly speaking, when we double the height from which the hammer is dropped, we double the distance the nail is driven into the wood. Dropped from the same height, different hammerheads also drive the nail different distances into the wood. The larger the mass of the hammerhead, the greater the distance the nail is driven. The hammer's energy depends on its mass and on the height from which it is dropped.

A third variable is the effect of gravity. If our hammer were moved to an orbiting space station, it would never fall. Both the hammerhead and the space station fall toward the earth together; consequently, they do not move relative to one another. A less extreme example would be to take the hammer to the moon. There the gravitational attraction is about one-sixth that on earth. In an experiment identical to one performed on earth, the nail would be driven in only one-sixth as far on the moon. The hammer's energy depends on the strength of the gravitational force at its location.

The experiments with the pile driver increase our confidence in the definition of gravitational potential energy. The distance the nail is driven into the wood depends on the mass of the hammerhead, the height from which the hammerhead was dropped, and the acceleration due to gravity at the location

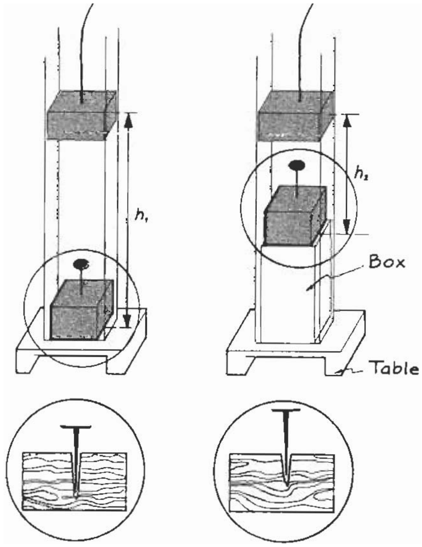


Figure 9-7
Relative to the table, both hammers have the same gravitational potential energy. Relative to the nail, the hammer on the left has more gravitational potential energy than the hammer on the right.

at which the experiment is performed-the same variables that define the gravitational potential energy of the hammerhead. The energy that the hammerhead transfers to the nail is equal to the energy the hammerhead gained when it was raised.

Gravitational Potential Energy is a Relative Concept

Gravitational potential energy is a relative, not absolute, concept. The acceleration due to gravity and mass are defined by the location and object, respectively; so these quantities are the same regardless of the energy receiver chosen. The height, however, depends on the position of the energy receiver chosen.

We can demonstrate the importance of the location of the energy receiver chosen with the experiment shown in Figure 9-7. The hammerhead has been lifted to a height of 1 m above the table. In (a) the nail is placed directly on the table. In (b) the nail is placed on a box halfway between the hammerhead and the table. While the height of the hammer relative to the table is the same in both cases, its height relative to the nail is not.

Once the hammer is dropped, the importance of the reference point chosen becomes apparent. Relative to the table, the hammer had the same gravitational potential energy in both situations. Relative to the nail, the hammer in (a) had the greater gravitational potential energy. The nail has been driven in further in (a) than in (b). The amount of gravitational potential energy possessed by the hammer is only of interest to us when it has been transferred to an energy receiver. Consequently, the vertical distance from the energy source to energy receiver (hammer to nail) is used to calculate the gravitational potential energy of the source.

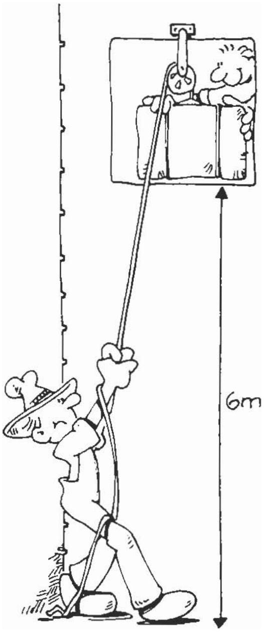


Figure 9-8

SELF-CHECK 98

In the good old days, hay bales were lifted to barn lofts by pulleys and ropes, as shown in Figure 9-8.

a. What is the gravitational potential energy of the 10-kg hay bale relative to the farmer?

b. What is the gravitational potential energy relative to his son?

c. If the bale drops, who would receive more energy—the father or the son?

Cable Cars and Swings

Our civilization has many devices for changing the gravitational potential energy of people and objects. Ski lifts and elevators change the gravitational potential energy of people. Cranes change the gravitational potential energy of building materials as the cranes lift the materials high above the steel skeletons of giant skyscrapers. Usually other forms of energy-electricity, oil, or diesel fuel-are used to accomplish these changes. The San Francisco cable car system, however, uses the decrease in the gravitational potential energy of one object to increase the gravitational potential energy of another.

San Francisco, with its steep hills, presents a challenge to nearly all modes of transportation. In the 1870s its now-famous cable car system was designed and constructed. A cable car, as its name implies, is connected to long cables that move beneath the street. To move the car, the operator pulls a lever that connects the car to the cable. To stop the car, he or she releases the car from the cable and sets the brake. The cable for each car line forms a complete loop; so cars going uphill and cars going downhill are attached to the same cable (Figure 9-9).

The gravitational potential energy of the cars is constantly changing. Cars going up increase their gravitational potential energy, while cars going down decrease theirs. A car that is moving downhill does work on a car that needs to go uphill-it pulls it up. In this way the gravitational potential energy lost by a downhill car is gained by an uphill car-an extremely efficient design!

The chapter opened with the photograph of a swing. We were looking for concepts to describe its motion. Gravitational potential energy provides us with one such concept. Pulled back from rest (Figure 9-10), the swing gains gravitational potential energy. Though the swing is being pulled both outward and upward, only the change in vertical height contributes to this gain. Suppose an empty swing of mass 2 kg is pulled to a vertical height of 1.2 m above its position at rest. It will have gained (2 kg)(9.8 (m/s)/s)(1.2 m) = 23.5 J. Once the swing is released, this gravitational potential energy decreases to zero as the swing moves back to its original position.

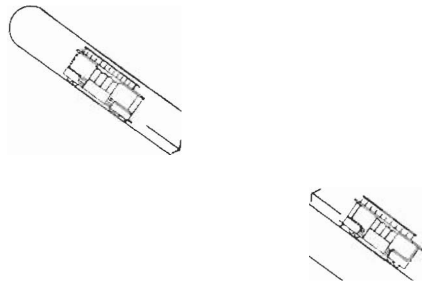


Figure 9-9
The cable forms a complete loop so that cars going downhill can transfer energy to the cars going uphill.

ENERGY AND MOTION

The sWing's speed increases as its gravitational potential energy decreases. The same is true about the house painter, the pile driver, and a San Francisco cable car. The instant before he hits the ground, the house painter has no gravitational potential energy, but he is moving. The instant before it transfers its energy to the nail, the hammerhead has no gravitational potential energy, but clearly it has energy to transfer. The motion of the cable cars traveling downhill somehow supplies the gravitational potential energy needed to move other cars uphill. Energy must be present in moving objects.

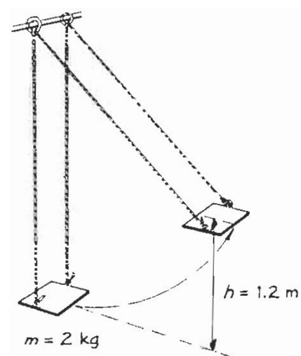


Figure 9-10
Pulled back from its rest position, a swing gains gravitational potential energy equal to its mass times the acceleration due to gravity times its vertical height above the rest position.

Variables that Affect Energy of Motion

A convenient example with which to investigate the energy associated with motion is a car. A moving car has energy. This energy changes when the frictional force of the brakes does work to bring the car to a stop. When we apply the brakes, the wheels lock; increased friction between the tires and the road stops the car. The product of the constant force exerted by friction and the distance the car travels in coming to a stop, called the *stopping distance,* is the work done by friction. Like the energy gained by the box when we did work in pushing it, the energy lost as the car comes to a stop should equal the work done by friction. This relationship between work and energy enables us to identify the variables that describe the car's energy while moving.

From experience we know that the faster we drive, the greater the stopping distance we require. Figure 9-11 shows a diagram found in most driver-training manuals. The average stopping distance is shown for cars moving initially at different speeds. Since the frictional force applied by the surface is

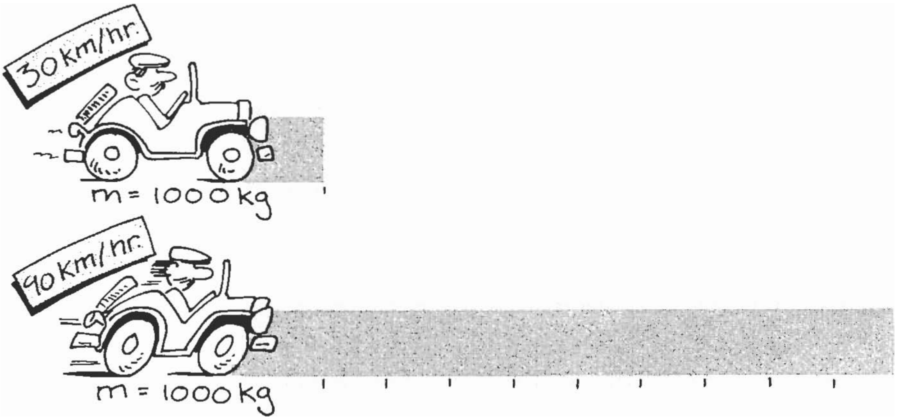


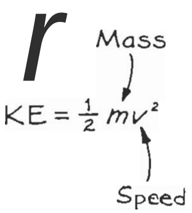
Figure 9-11
The stopping distance depends on speed. At 90 kilometers per hour, the stopping distance required is nine times that at 30 kilometers per hour.

roughly the same in each situation, the stopping distance provides a direct measure of the energy associated with the speed each car is moving. At 90 kilometers per hour (km/h), the stopping distance is four times that at 45 km/h and nine times that at 30 km/h. Doubling the speed quadruples the stopping distance required; tripling the speed increases the stopping distance by a factor of nine. Energy of motion is related to the square of the speed.

A second important variable is mass. Most owner's manuals include information about the stopping distance required when you apply the brakes to a car moving initially at 60 miles per hour (mi/h). This distance is listed for different loads-typically, light loads and maximum loads. If we were to examine the stopping distance for these different loads, we would find that doubling the mass of the car doubles the stopping distance required (Figure 9-12). The car's energy while moving is directly related to its total mass.

Kinetic Energy

Kinetic energy



Kinetic energy is the name given to the energy an object possesses by virtue of its motion. The swing, the house painter, the hammer, and the cable car all have kinetic energy as they move downward. Our experience with stopping distances for cars suggests that this energy is related to the mass of the object and the square of its speed. By combining Newton's laws with our definitions of work, velocity, and acceleration, we can develop a complete definition for kinetic energy:

$$\text{Kinetic energy} = \tfrac{1}{2} \times (\text{mass}) \times (\text{speed})^2$$

The **kinetic energy** (KE) of an object is one-half the product of the object's mass and the square of its speed. When mass is expressed in kilograms and speed in meters/second (m/s), the kinetic energy is given in joules.

This definition allows us to calculate the kinetic energy of any moving object, given its mass and speed. For example, we can compare the kinetic energy of a car moving along an interstate highway with that of the same car traveling in a school zone. Assume that the car has a mass of 1000 kg (subcompact size). The speed limit on an interstate highway is about 25 m/s (55 mi/h), while that in a school zone is about 9 m/s (20 mi/h).

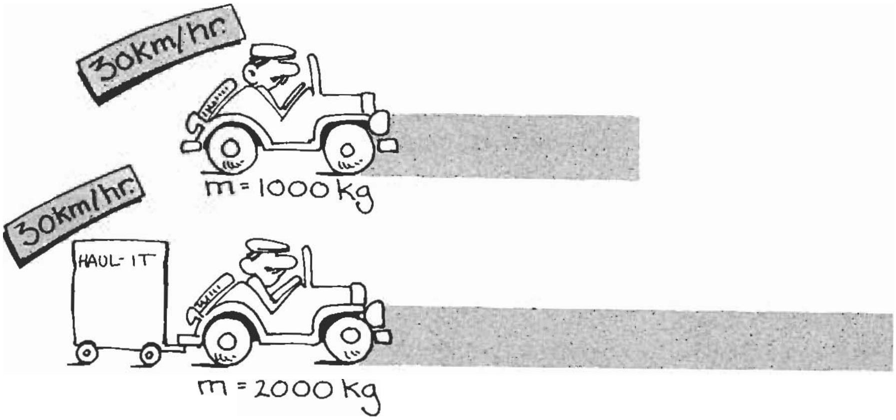


Figure 9-12
The stopping distance depends on mass. DOUbling the mass doubles the stopping distance required.

Interstate Highway	*Schoo/Zone*
$KE = \frac{1}{2}mv^2$	$KE = \frac{1}{2}mv^2$
$= \frac{1}{2}(1000\ kg)(25\ m/s)^2$	$= \frac{1}{2}(1000\ kg)(9\ m/s)^2$
$= 312{,}500\ J$	$= 40{,}500\ J$

Because kinetic energy depends on the square of the speed, the increase in kinetic energy is substantial. It is not hard to see why accidents are so much more devastating on the highway than in city traffic.

Kinetic energy is very similar to the concept of momentum introduced in Chapter 5. Both depend on the object's mass and motion. Momentum depends on the object's mass and its velocity. Kinetic energy depends on the object's mass and the square of its speed. When an object's velocity doubles, its momentum doubles, while its kinetic energy increases by a factor of four. Another important difference between the two concepts is that momentum is a vector quantity, while kinetic energy is a scalar. In a system consisting of two objects, the total momentum of the system can be zero even though both objects are moving. The total kinetic energy of this same system can never be zero. Kinetic energies always add.

SELF-CHECK 9C

The 2-kg swing In Figure 9-10 has a speed of 4.86 m/s at the bottom of Its swing. What Is Its kinetic energy? How much work must be done to stop It?

ENERGY IS CONSERVED

Let's return once more to the motion of the sWing. In pulling the swing back from rest, we do work on it-giving it the energy that enables it to move.

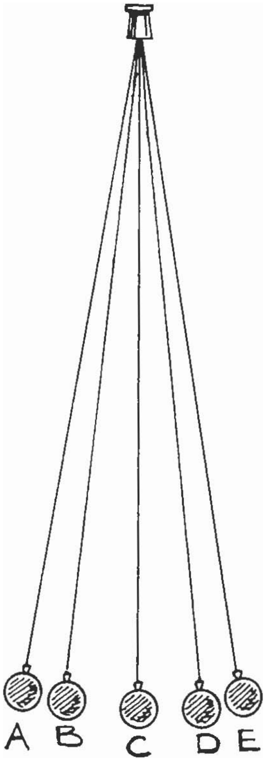


Figure 9-13
The motion of the pendulum bob captured in a strobe-like drawing shows the change in height and velocity of the pendulum ball.

Armed with the concepts of gravitational potential energy and kinetic energy, we can now describe this motion in more detail. To do so, we first examine the motion of a simplified version of the swing, the pendulum.

Potential Becomes Kinetic Becomes Potential

The strobe-like drawing in Figure 9-13 captures the motion of a pendulum bob through one complete swing. Successive images are closely spaced at A, become more widely spaced at C and then once again become more closely spaced at E. Using the methods developed in Chapter 2, we would describe the speed of the pendulum bob as being at a minimum at A and E and a maximum at C. By contrast, the height of the pendulum bob above its rest point is at a maximum at A and E and a minimum at C. Height seems to be exchanged for motion and then motion for height.

We can use the concepts of gravitational potential energy and kinetic energy to describe this interchange of height and motion. Figure 9-14 shows the motion of an idealized pendulum, one in which no friction acts to slow its motion. In order to calculate the gravitational potential energy of the pendulum bob at any point in its swing, we need to know the bob's mass, its height above the rest position, and the acceleration due to gravity. The kinetic energy of the pendulum bob depends on its mass and its speed at each specific location. Table 9-1 includes the height and speed of a 1 kg pendulum bob at several points along its path. The gravitational potential energy and kinetic energy have been calculated for each location.

As shown in Table 9-1, the pendulum bob has maximum gravitational potential energy at A. As it moves downward, its gravitational potential energy decreases steadily, while its kinetic energy increases. At the bottom of the swing, the bob has no gravitational potential energy but a maximum kinetic energy. As the pendulum moves upward, the process reverses itself: Kinetic energy decreases while gravitational potential energy increases. At E the gravitational potential energy is again at a maximum and the kinetic

Table 9-1 Gravitational Potential Energy and Kinetic Energy of Pendulum

Position (Figure 9-14)	Height (m)	Gravitational Potential Energy (J)	Speed (m/s)	Kinetic Energy (J)	Total Energy (GPE + KE) (J)
A	2.04	20	0	0	20
B	1.02	10	4.47	10	20
C	0	0	6.32	20	20
D	1.02	10	4.47	10	20
E	2.04	20	0	0	20

Throbbing Motion

The arteries and veins in our bodies form a network that is about 96,000 km long, through which about 5 liters of blood circulate. The rate at which this blood circulates depends on the energy supplied by the pumping action of the heart. We can use the concept of kinetic energy to compare this energy at both low and high levels of activity.

The heart rate increases as we increase our level of activity. This increased heart rate accomplishes two things: (1) it increases the mass of blood ejected with each contraction, and (2) it increases the speed with which the ejected blood moves. At a low level of activity, a single contraction of the heart ejects .06 kg of blood at an average speed of 0.3 *m/s*. At a higher rate of activity, each contraction ejects .12 kg of blood at an average speed of 0.6 *m/s*. The kinetic energy of the ejected blood associated with each level of activity is:

Low Level

$$KE = \tfrac{1}{2}mv^2$$
$$= \tfrac{1}{2}(.06\ \text{kg})(0.3\ m/s)^2$$
$$= 0.0027\ \text{J}$$

High Level

$$KE = \tfrac{1}{2}mv^2$$
$$= \tfrac{1}{2}(.12\ \text{kg})(0.6\ m/s)^2$$
$$= 0.0216\ \text{J}$$

Because both mass and speed are increased, the heart must supply considerably more energy at higher levels of actiVity.

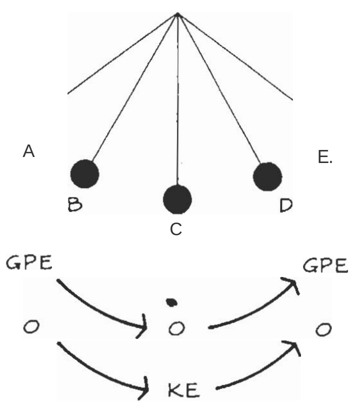


Figure 9-14
The gravitational potential energy is a maximum at each end and zero in the middle. The kinetic energy is a maximum in the middle and zero at each end.

energy is zero. Gravitational potential energy has been transformed into kinetic energy and back into graVitational potential energy.

Conservation of Energy

The transformation of graVitational potential energy into kinetic energy and back again can be understood in terms of a much broader concept-the law of conservation of energy. Notice that the graVitational potential energy of the pendulum bob at A is equal to the kinetic energy at C. In fact, if you add the gravitational potential energy and kinetic energy for each position of the swing, you'll see that it always totals 20 J. The sum of these two quantities is conserved.

REMINOER

In everyday use, to conserve means to save. In physics, to conserve means to keep constant. Confusing the everyday use with the physics definition may be hazardous to your understanding.

The **law of conservation of energy** states that the total energy of a closed system remains constant. In the case of our idealized pendulum, which does not interact with air or with any supporting mechanism, the closed system consists of the pendulum and the earth. In pulling the pendulum back from its rest position, we give the closed system 20 J of energy. Once we release the pendulum, the energy of that system remains constant. The interaction between the pendulum and the earth causes the energy to change form-from gravitational potential energy to kinetic energy and back again. As the gravitational potential energy decreases, the kinetic energy increases, keeping the total energy of the system constant at 20 J. We can summarize this with a single equation:

$$\text{Total energy at one time} = \text{total energy at later time}$$

$$(\text{GPE} + \text{KE})_{\text{time } 1} = (\text{GPE} + \text{KE})_{\text{lime } 2}$$

Because the energy of the system is conserved, our ideal pendulum keeps swinging forever! Of course, you have never seen a pendulum do this because you have never seen a closed system consisting of just the earth and the pendulum. Energy exchanges on earth, as you will see, involve other energy receivers and other forms of energy.

SELF-CHECK 90

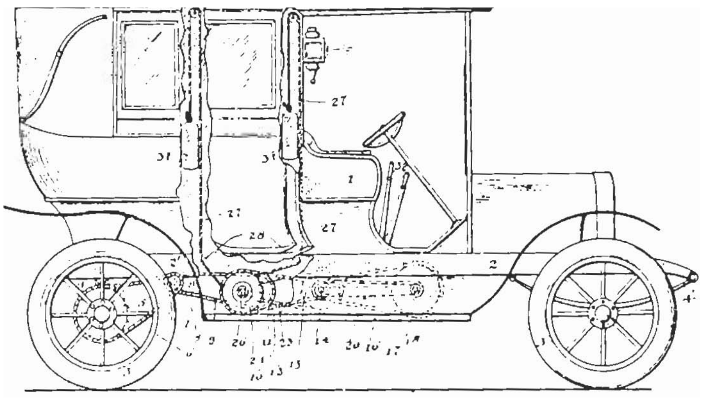
In Figure 9-6 the model pile driver has a hammer mass of 5 kg and is raised to a height of 1 m above the nail. Ignore frictional interactions.

a. What is the total energy of the system?

b. At a later time, the moment before the hammer strikes the nail, what is the total energy of the system?

c. What is the hammer's kinetic energy right before it strikes the nail?

EASIER THAN WALKING?



Why waste the energy provided by fossil fuels when we have all that gravitational potential energy around? That question was considered by Isaac Smyth in 1911 when he invented the gravity-powered automobile. Inside the walls of the car are weights (31), which can be raised to the roof level (30) by means of a crank (26). When released, the weights drop and transmit their gravitational potential energy through pulleys and cables (27 and 29) to the drive chains (9 and 20). Thus, the gravitational potential energy of the weights is converted into kinetic energy of the automobile. Unfortunately, the gravlty-driven car had a couple of disadvantages. First, the back wheels had to be lifted off the ground while raising the weights. More importantly, the energy to raise the weights had to come from somewhere. The driver needed to supply a lot of energy in order to get to the grocery store!

ENERGY TAKES MANY FORMS

like conservation of momentum, conservation of energy demonstrates our search for quantities that remain constant throughout interactions. Unlike momentum, energy can assume more than one form. Conservation logic has enabled us to identify these other forms of energy.

Energy Does Not Always Seem To Be Conserved

You do work-giving a child a push on a swing. The child seems to be enjoying thoroughly the change from gravitational potential energy to kinetic energy and back again. The next thing you know, the swing stops and the child is crying. The child has neither gravitational potential energy nor kinetic energy. Real swings and real pendulums eventually stop.

The ski lift takes you to the top of the mountain. Using energy supplied by the lift, you have increased your gravitational potential energy. As you ski down the hill, your kinetic energy increases-but never as much as your gravitational potential energy decreases. When you reach the bottom of the mountain, you gradually come to a stop. Both your gravitational potential energy and your kinetic energy are gone.

In real interactions, the sum of the gravitational potential energy and kinetic energy does not remain constant. If we watch the skier or the swing long enough, we see the sum of these two forms of energy gradually decrease. If energy is really conserved, this lost energy must be transferred to other receivers within our closed system. Let's look for these receivers and methods by which the "lost" energy could have been transferred to them.

Thermal Energy

The skier-earth and swing-earth systems are not closed. In both situations, interactions occur with other objects through frictional forces. The skier slides along the snow. The swing rubs against its point of suspension. Both the swing and the skier experience air resistance. These interactions identify the other energy receivers.

We can measure the amount of energy transferred to these objects in terms of the work done by frictional forces. The energy transferred from the skier to the snow, for example, is equal to the product of the frictional force exerted by the snow and the distance the skier travels.

Energy transferred to snow

Distance traveled

$E_s = F_f \ell$

(Frictional force

Energy transferred to snow = work done by friction

= (force of friction exerted by snow) X (distance traveled)

A frictional force of 0.1 N applied along a ski slope 100 m long results in 10 J of energy being transferred to the snow. This energy usually appears in the form of heat, or **thermal energy.** Careful measurements of the snow would show a slight increase in its temperature. We could repeat the analysis for the frictional force offered by air resistance. We expect to find that the surrounding air would be warmed slightly as energy is transferred from the skier to the air.

Energy is still conserved. Our law of conservation of energy is simply modified to take into account this new form of energy.

Total energy at one time = total energy at later time

$$(\text{GPE} + \text{KE} + \text{thermal})_{\text{time 1}} = (\text{GPE} + \text{KE} + \text{thermal})_{\text{time 2}}$$

The addition of a new form of energy means that we need to look for changes other than changes in position or motion. Chapter 10 deals with the changes that result from a transfer of thermal energy.

SELF-CHECK 9E

A skier whose total mass is 80 kg stood at the top of a ski stope whose vertical height was 100 m. At the bottom of the slope, the skier's kinetic energy was 50,000 J.

a. What was the skier's gravitational potential energy at the top of the slope?

b: Was all of this energy coiwertedinto kinetic energy? If not, where did it go?

Other Forms of Energy

The analysis we have just completed illustrates the process by which physicists identify other forms of energy. Conservation logic is such a compelling part of our experience that whenever conservation of energy seems to fail, we begin looking for a previously unknown form of energy. So far this procedure has always worked, and many forms of energy have been identified. All forms of energy can be categorized as potential or kinetic.

Potential energy describes the energy an object has by virtue of its position. It can be thought of as energy stored with the object. In the case of gravitational potential energy, the object's position is measured relative to the earth. The work done in opposing the graVitational force leads to an increase in an object's gravitational potential energy. Each of the other fundamental interactions-electrical, strong nuclear, and weak nuclear-also have forms of potential energy associated with them. Electrical interactions are the glue that holds matter together. Electrical forces bind electrons to atomic nuclei; they bind atoms to one another to form molecules; they bind molecules together to form cohesive materials. Because electrical interactions are such a fundamental part of matter, **electrical potential energy** can take many forms. A coiled spring, for example, has **elastic potential energy** that results from electrical interactions between molecules in the spring. Another example is the **chemical potential energy** in molecules of chemical compounds. This stored energy is due to the electrical interactions that hold atoms in specific positions within molecules of the compounds. Both elastic and chemical potential energy are the result of work-forces acting over distances to compress the spring or to arrange the atoms into molecules. **Nuclear potential energy** exists for both strong and weak nuclear interactions. The most awesome demonstration of this form of energy occurred when the nuclear bombs were dropped at Hiroshima and Nagasaki.

Kinetic energy is the energy of motion. While we have used it only to describe the energy of motion associated with large objects, we can use it to describe other forms of energy associated with the motion of atoms or molecules. For large objects we measure kinetic energy in terms of the mass and speed of each object. At the microscopic level, we measure energy of motion in terms of the temperature of the object. Atoms and molecules move constantly, transferring their energy to one another through collisions. We perceive this transfer as temperature change. This kind of energy of motion is called **thermal energy,** or heat. A third form of energy that involves motion is **wave energy.** Common examples include sound and light.

Mass is a Form of Energy Too

One of the more surprising forms energy takes is mass. Suppose we are exerting a net force on an object, causing it to accelerate. We act as the energy source and the object acts as the energy receiver. The work we do as we apply this net force appears as an increase in the object's kinetic energy. At usual speeds the object's kinetic energy quadruples each time its speed doubles. As discussed in Chapter 6, however, we cannot keep accelerating the object forever. As the object's speed approaches that of light, its mass increases. From our point of View, we have to exert even more force to accelerate it further. We are still delivering energy to the object, but the energy no longer produces the same change in speed as it did at lower speeds. At speeds near that of light, our energy appears in the increased mass of the object. Energy is being converted into mass.

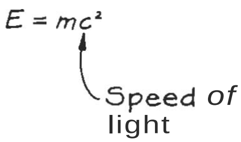
Total energy

O;fObrjeC:e,at;V;5t;c

mass

Einstein described this **mass-energy equivalence** in what is probably the most famous equation of twentieth-century physics:

$$\text{Energy} = \text{mass} \times (\text{speed of light})^2$$

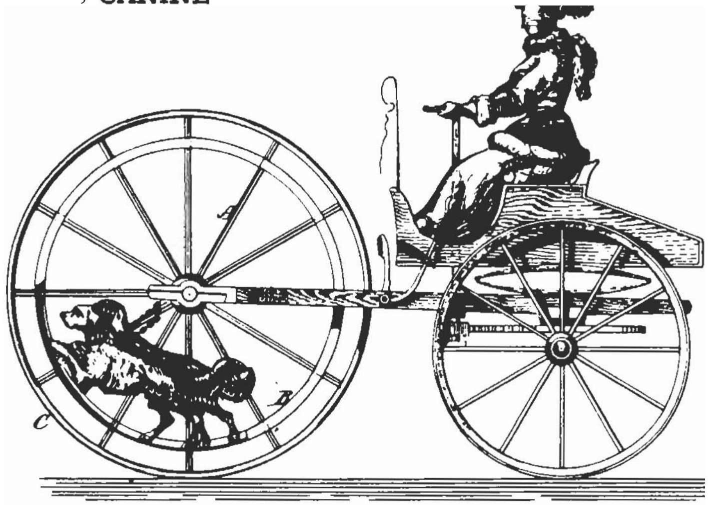


It states that the total energy of an object equals its relativistic mass times the speed of light squared. When mass is expressed in kilograms and the speed of light in meters per second, the energy is given in joules. As we saw in Chapter 6, the relativistic mass of an object varies with its speed. Now we see that this increase in mass reflects an increase in the amount of energy stored with that object.

The most surprising conclusion of mass-energy equivalence comes when an object is not moving. At zero speed, an object still has mass, its rest mass. Einstein's equation tells us that we can associate this mass with a certain amount of energy-the object's rest mass times the speed of light squared. If we could convert all the rest mass found in 2 kg of potatoes into energy, we would have $(2 \text{ kg}) \times (3 \times 10^8 \text{ m/s})2 = 18 \times 10^{16}$ J of energy. Because the speed of light is such a large number, the energy equivalent of an object's rest mass is enormous!

Mass-energy equivalence requires that we modify our conservation principles. The total energy of a system must now include the energy equivalent of the rest masses of the objects found in the system. In everyday interactions, the rest masses of objects remain constant, so we can effectively ignore them. At high speeds or in interactions in which the total mass of the system changes, the energy associated with mass becomes important. Mass-energy eqUivalence has been dramatically demonstrated in nuclear interactions. Both nuclear reactors and nuclear weapons derive their energy from decreases in

CHANGING ENERGY FORMS, CANINE TO KINETIC



Modern vehicles use the chemical potential energy stored in gasoline to create the kinetic energy of the car. Just about the same time as the automobile was being invented, F. H. C. Mey came up with the idea of using the chemical potential energy stored in a different source-a source *(B)* available in many homes. The users feed their dogs lots of energy in the form of food. Then, the dogs are placed in the hollow wheel *(C)* of Mr. Mey's specially designed vehicleo With a little urging from the whip (unlabeled), the dogs start running and turn the wheel that pulls the vehicle and its passenger. The chemical potential energy of the dog food is converted into kinetic energy of the person and vehicle.

the mass of atomic nuclei. These interactions will be discussed in more detail in Chapter 22. When the total mass of the system changes, mass-energy equivalence must be included in order to conserve energy.

The process by which we developed definitions of gravitational potentiai energy and kinetic energy can be used to develop definitions of these other forms of energy. The remaining chapters in this book deal with many of these forms of energy in turn. Chapters JO-13 consider the electrical potential energy and thermal energy found in matter. Chapters 14-16 discuss wave energy. Chapters 17 and 18 look at the electrical energy involved in the atom. Chapters 19 and 20 discuss electrical energy, and Chapters 21 and 22 discuss nuclear energy. The breadth of phenomena encompassed by the various· forms of energy make energy a powerful concept-one that unites the var· ious fields of physics.

CHAPTER SUMMARY

Energy is the ability to make a change during an interaction. Like momentum and unlike force, it is a commodity that is transferred from one object to another during an interaction. Energy that is transferred from an *energy source* to an *energy receiver* results in an observed change in the energy receiver. Energy can be measured in terms of the work done on the receiver. *Work* is defined as the product of the force exerted on an object and the distance the object moves in the same direction as the force. Work and energy are measured in units called *joules.*

This chapter formally defines two of the many forms of energy. *Gravitational potential energy* is the energy due to the position of an object relative to a massive object such as the earth. It is formally defined as the product of the object's mass, its height relative to a selected reference point, and the acceleration due to gravity. Kinetic *energy* is energy associated with the motion of an object. It is defined as one-half the mass of the object times the square of its velocity. In a closed system in which no friction exists, the sum of the gravitational potential energy and kinetic energy remains constant. The *total energy* of the system is *conserved.*

As we apply the principle of energy conservation to more complex systems, new forms of energy are discovered. These forms of energy can be categorized as being energy due to position (potential energy) or energy due to motion (kinetic energy). Each of the four fundamental interactions has a form of potential energy associated with it: *gravitational potential, electrical potential,* strong *nuclear potential,* and *weak nuclear potential* energies. Energy of motion includes the kinetic energy we defined for large objects, *thermal energy* associated with the motion of atoms and molecules in matter, and *wave energy* associated with sound and light. At speeds near that of light, energy is stored in the increased mass of the object. Einstein demonstrated a mass-*energy equivalence,* in which the total energy of an object is the product of its relativistic mass and the speed of light squared. The energy of a closed system remains constant at all times in systems in which all forms of energy have been identified. This principle is called the *law of* conservation *of energy.* The concept of energy unites the various fields of physics.

ANSWERS TO SELF-CHECKS

9A. a. Worker A:

$$\begin{aligned} \text{Work} &= \text{force} \times \text{distance} \\ &= (20\ \text{N}) \times (2\ \text{m}) \\ &= 40\ \text{J} \end{aligned}$$

Worker B does no work on the crate. The force B exerts does not result in any horizontal motion of the crate. Consequently, the distance the box moves in the direction of B's force is zero.

b. 40 J of energy have been transferred to the crate.

98. a. The bale is 6 m above the farmer.

$$\begin{aligned} \text{GPE} = mgh &= (10\ \text{kg})[9.8\ (\text{m/s})/\text{s}](6\ \text{m}) \\ &= 588\ \text{J} \end{aligned}$$

b. The bale is 0 m above his son.

$$GPE = mgh = (10\ kg)[9.8\ (m/s)/s](O\ m)$$
$$= 0\ J$$

c. The farmer would receive more energy.

9C.

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}(2\ kg)(4.86\ m/s)2$$
$$= 23.6\ J$$

Work done to stop the swing is equal to the kinetic energy lost by the swing: work = 23.6 J.

9D. a. Initially, the total energy of the system is the gravitational potential energy of the hammer.

$$\text{Total energy} = GPE = mgh$$
$$= (5\ kg)[9.8\ (m/s)/s]\ (1\ m)$$
$$= 49\ J$$

b. The total energy of the system is conserved.

Total energy at one time = total energy at later time

The total energy is 49 J.

c. The moment before the hammer strikes the nail, the gravitational potential energy is zero. The total energy of the system is now the kinetic energy of the hammer head.

$$\text{Total energy} = KE = 49\ J$$

9E. a.

$$GPE = mgh = (80\ kg)[9.8\ (m/s)/s](100\ m)$$
$$= 78{,}400\ J$$

b. The kinetic energy at the bottom was 50,000 J. Not all the gravitational potential energy has been converted into kinetic energy. (78,400 J - 50,000 J), or 28,400 J, went into thermal energy.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

AI. Define the terms listed below:

Energy	Gravitational potential energy	Thermal energy	Work
Energy source	Kinetic energy	Energy of position	Energy conservation
Energy receiver	Mass-energy equivalence	Energy of motion	

A2. In what units are work and energy measured?

A3. Why does the object have to move in the direction of the force in order for work to have been done?

A4. What variables affect the gravitational potential energy of an object?

AS. Why is gravitational potential energy a relative concept?

A6. What two variables affect the kinetic energy of an object?

A7. Which will cause the greater increase in an object's kinetic energy-doubling its mass or doubling its speed?

A8. How does common use of the term *to conserve* differ from the way it is used in physics?

A9. Describe the process by which new forms of energy are often discovered.

AlO. What two categories describe the various forms of energy?

A11. How would you determine the energy equivalent when you know the mass of an object? How does this equivalence modify the law of conservation of energy?

B. Using the Chapter Material

B1. A crane exerts a constant force of 9800 N and lifts a slab of concrete onto a section of scaffolding 100 m above the ground. What is the work done by the crane? What form of energy is transferred to the concrete?

B2. If the slab of concrete (mass = 100 kg) in Problem Bl falls, what is its kinetic energy just before it strikes the ground? (Neglect friction.)

B3. Include friction and explain why the actual kinetic energy of the concrete slab will be less than the value calculated in Problem B2.

B4. In which of the following situations is no work done?

a. A spaceship moves at constant velocity.
b. A child slides down a playground slide.
c. You push on a heavy box but cannot move it.
d. You slam on the brakes and your car stops qUickly.

B5. The acceleration due to gravity on Mars is *3.7 {m/s}/s*. What is the gravitational potential energy of a 70 kg Martian who is 3 m above the surface of the planet?

B6. A 500 kg elevator is stopped on the second floor of a bUilding. What is the gravitational potential energy relative to the first floor, 10 m below the second? Relative to the basement, 10 m below the first floor?

B7. What is the kinetic energy of a 50 kg skateboarder who is traveling at each of these speeds: 1 *mis*, 2 *mis*, 3 *mis*, 4 *mis*, *6 m/s?* How does kinetic energy vary with speed?

B8. What is the kinetic energy of bicyclists who are traveling at 5 *mls* and have the following masses: 40 kg, 50 kg, 80 kg, 100 kg? How does kinetic energy vary with mass?

B9. If you watch a gymnast revolving around a crossbar, you will notice that her speed is lowest when she is directly above the bar and greatest when she is directly below it. Explain this observation in terms of conservation of energy.

BIO. Juliet is locked in a tower by her father. Romeo, standing directly below her open window, wishes to throw her a rock with a message attached. The window is 10 m straight up and the rock and message have a mass of 0.3 kg. How much kinetic energy must Romeo give the rock in order for it to reach Juliet?

B11. If you were converted entirely to energy, how much energy would you be?

C. Extensions to New Situations

Cl. A child slides down a hill on a sled. At the top of the hill he has 800 J of gravitational potential energy. At the bottom he has 200 J of kinetic energy. How much energy was transformed into thermal energy due to the frictional interaction between the sled and the snow?

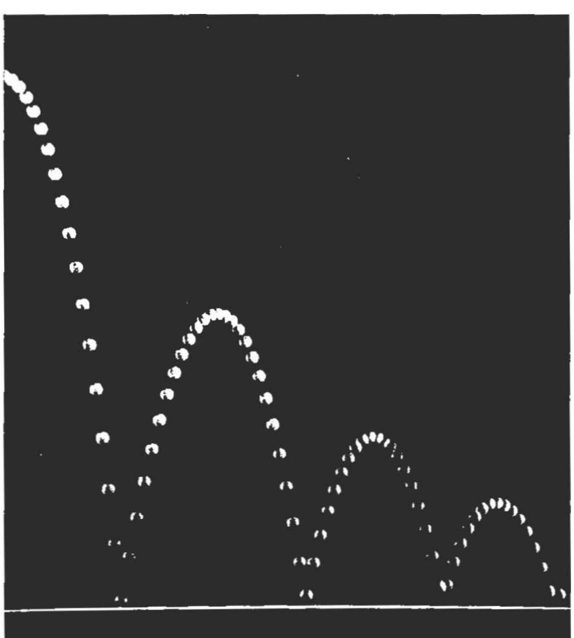
C2. Most roller coasters are pulled by a chain to the top of the first hill on the ride. At that point the speed of the roller coaster is approximately zero. After that no more energy is put into the roller coaster throughout the ride.

a. What types of energy must designers of roller coasters consider as they plan a new roller coaster?
b. Is it possible for any other hill to be higher than the first one?
c. For most roller coasters, each hill is shorter than the previous one. Is this design necessary?

C3. When we first studied collisions, we saw that momentum was conserved for collisions in a closed system. Consider energy conservation for these same collisions. The collision involved is one in which a 5 kg ball moving at 2 mjs strikes a stationary 5 kg ball head on. For parts (a)-(c) we assume that the balls do not stick together.

a. Use momentum conservation to determine the speed of each ball after the collision.
b. What is the kinetic energy of each ball before the collision? After the collision?
c. Is kinetic energy conserved in this collision?
d. Now assume that the two balls stick together after the collision. Use momentum conservation to determine their speed after the collision.
e. What is the total kinetic energy before the collision? After the collision?
f. Is kinetic energy conserved in the sticky collision?
g. Use the results of (a)-(f) to make a general statement about conservation of kinetic energy in collisions.

C4. A ball that strikes the floor changes its shape slightly as it interacts with the floor (Figure 9-C4). Usually some energy is changed from kinetic to other forms during this process.



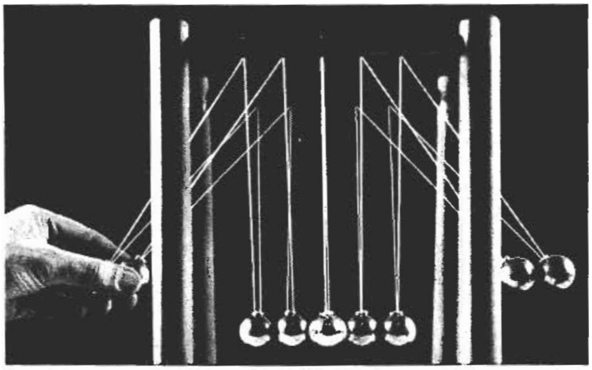
a. In this situation the maximum height reached after the first bounce will be less than the height from which the ball was dropped. Explain why.
b. How would the maximum height after each successive bounce compare to the one before it?

C5. A specific example of Problem C4 is a 0.5 kg ball that is dropped from a height of 4 m.

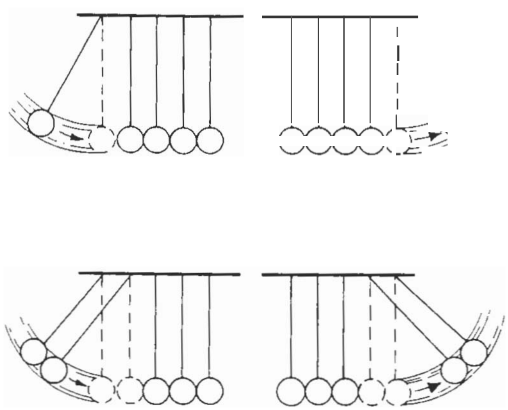
a. What is its gravitational potential energy at the start of the fall?
b. What is its kinetic energy just before it strikes the ground?
c. On the first bounce the ball returns to a maximum height of 3.5 m. What is its gravitational potential energy when it reaches that height?
d. What is its kinetic energy just as it leaves the ground after the first bounce?
e. How much energy was transformed into other forms of energy during the bounce?
f. What reasoning would you use to predict the approximate maximum height the ball would reach after the second, third, and fourth bounce?

C6. An interesting toy consists of five pendulums suspended as shown in Figure 9-C6 (a). The before-after pictures in Figure 9-C6(b) and (c) show what happens when we pull back and release different numbers of balls. Using momentum conservation alone, we could explain the after motion knowing only the before situation. But, momentum conservation allows events we never see. For example, in the situation in (c) we always see two balls go out after the collision. Yet one ball going out at twice the speed of the incoming balls would still conserve momentum. To understand what actually happens, consider an example in which two balls are moving before the collision. Each ball has a mass of 1 kg and, just before the collision, is moving at 1 mjs.

a. Is momentum conserved if, just after the collision, each of two balls has a speed of 1 mjs? If one ball has a speed of 2 mjs? If each of four balls has a speed of 0.71 mjs?
b. Is kinetic energy conserved if just after the collision each of two balls has a speed of 1 mjs? One ball has a speed



(a) © 1972, Fundamental Photographers.



(b)

of 2 mJs? Each of four balls has a speed of 0.71 mJs?

c. In which case are both momentum and energy conserved?

d. Why are the results shown in the figure the only ones that occur in nature?

C7. You can get from the bottom to the top of the Empire State Building (a distance of approximately 400 m) in two ways, by walking or by riding the elevator. For this problem, assume that you have a mass of 75 kg.

a. Does the amount of work done depend on the method you use to get to the top?

b. What (or who) does the work in each case?

c. How much is the change in gravitational potential energy?

C8. Airlines must continually worry about the fuel needed for their flights. Some regulations or practices are related to the energy they have to provide. Use both gravitational potential and kinetic energies when answering these questions.

a. On many international flights each passenger is limited to 20 kg of luggage. For more mass, the passenger must pay an extra charge. Does this regulation make sense in terms of energy use?

b. In a lighthearted moment, an airline executive suggested that overweight people should pay a higher price for airline tickets than people of average weight; underweight people should get a discount. In terms of energy, is this sensible?

c. Suppose you were given the job of establishing fares based on the ideas in (b). How would you use energy concepts to do so?

C9. When energy costs increased rapidly, airlines began looking for ways to cut the use of fuel. For example, TWA stripped the paint off the exterior of some of its airplanes, removed pillows, and swept the planes more often. The paint removed from the exterior had a mass of 100 kg and each pillow had a mass of about 0.5 kg.

a. How much work must be done to get the paint moving at a speed of 245 mJs (typical airline cruising speed)?

b. How much work is done to get a pillow to that speed?

c. What is the gravitational potential energy of the paint and pillow at a cruising altitude of 10,000 m?

d. Why should the TWA management think that these actions would decrease fuel consumption?

C10. When kinetic or gravitational potential energy seems to appear or disappear, we look for another form of energy. Use the concept of conservation of energy to identify at least one new form of energy in each example below. Explain how you arrived at your answer.

a. In a pinball machine you pull back and release a spring. Then the ball starts moving.

b. An ancient way to start a fire is to rub two sticks together.

c. A basketball player jumps up for a rebound.

d. A car moves by burning gasoline.
e. Elevators are lifted by electric motors.

C11. Some interactions result in a decrease in the total mass involved. The energy released in these interactions is the energy equivalent to the difference in total mass before and after the interaction. For each interaction described below, use Einstein's mass-energy equivalence relationship to calculate the energy released.

a. Uranium (mass = 3.918×10^{-25} kg) splits into five particles with a total mass of 3.915×10^{-25} kg.
b. Four hydrogen nuclei (mass of each nucleus is equal to 1.673×10^{-27} kg) combine to make one helium nucleus (mass = 6.6443×10^{-27} kg) and two other particles with masses of 0.0091×10^{-27} kg each.
c. An electron and a positron, each with a mass of 0.0091×10^{-27} kg, combine, releasing energy only. No mass is left over.

D. Activities

01. Keep a diary of the number of times you increase your gravitational potential energy during one day. Estimate how much your gravitational potential energy increases during the day.

02. Look up the stopping distances, load, and maximum load in the owner's manual for your automobile. Are the stopping distances listed consistent with our definition of kinetic energy?