3

CHAPTER 3

Momentum and Energy

3.1 **Momentum and Impulse**
LEARNING OBJECTIVE: Describe the relationship between impulse and momentum.

3.2 **Impulse Changes Momentum**
LEARNING OBJECTIVE: Describe the role of force and time when momentum changes.

3.3 **Conservation of Momentum**
LEARNING OBJECTIVE: Relate the conditions under which momentum is and is not conserved.

3.4 **Energy and Work**
LEARNING OBJECTIVE: Describe how the work done on an object relates to its change in energy.

3.5 **Work–Energy Theorem**
LEARNING OBJECTIVE: Specify the relationship between work and kinetic energy.

3.6 **Conservation of Energy**
LEARNING OBJECTIVE: Relate conservation of energy to physics and science in general.

3.7 **Machines**
LEARNING OBJECTIVE: Relate the concept of energy conservation to machines.

3.8 **Efficiency**
LEARNING OBJECTIVE: Describe efficiency in terms of energy input and output.

3.9 **Sources of Energy**
LEARNING OBJECTIVE: Identify and describe the two ultimate sources of energy on Earth.

WE'VE LEARNED that Galileo's concept of inertia is incorporated into Newton's first law of motion. We discussed inertia in terms of objects at rest and objects in motion. In this chapter, we will consider the inertia of moving objects. When we combine the ideas of inertia and motion, we are dealing with momentum. *Momentum* is a property of moving things. All things have energy, and when moving, they have energy of motion—*kinetic energy*. Things at rest have another kind of energy—*potential energy,* as illustrated by Jill Johnsen, shown here increasing the potential energy of suspended loads with pulley systems. And all objects, whether at rest or moving, have an energy of being—$E = mc^2$. This chapter is about two of the most central concepts in mechanics—momentum and energy.

3.1 Momentum and Impulse

EXPLAIN THIS Why do cannonballs shot from long-barreled cannons experience a greater impulse for the same average force?

VIDEO: Definition of Momentum

We know that it's harder to stop a large truck than a small car when both are moving at the same speed. We say the truck has more momentum than the car. By **momentum,** we mean *inertia in motion* or, more specifically, the mass of an object multiplied by its velocity:

$$\text{Momentum} = \text{mass} \times \text{velocity}$$

Or, in shorthand notation,

$$\text{Momentum} = mv$$

When direction is not an important factor, we can say

$$\text{Momentum} = \text{mass} \times \text{speed}$$

which we still abbreviate mv.*

We can see from the definition that a moving object can have a large momentum if it has a large mass, a high speed, or both. A moving truck has more momentum than a car moving at the same speed because the truck has more mass. But a fast car can have more momentum than a slow truck. And a truck at rest has no momentum at all.

If the momentum of an object changes, then either the mass or the velocity or both change. If the mass remains unchanged, as is most often the case, then the velocity changes and acceleration occurs. What produces acceleration? We know the answer is *force.* The greater the net force on an object, the greater its change in velocity and, hence, the greater its change in momentum.

But something else is important in changing momentum: time—how long a time the force acts. If you apply a brief force to a stalled automobile, you produce a change in its momentum. Apply the same force over an extended period of time, and you produce a greater change in the automobile's momentum. A force sustained for a long time produces more change in momentum than does the same force applied briefly. So, both force and time interval are important in changing momentum.

The quantity *force* × *time interval* is called **impulse.** In shorthand notation,

$$\text{Impulse} = Ft$$

FIGURE 3.1
The boulder, unfortunately, has more momentum than the runner.

FIGURE 3.2
When you push with the same force for twice the time, you impart twice the impulse and produce twice the change in momentum.

CHECKPOINT

1. **Compare the momentum of a 1-kg cart moving at 10 m/s with that of a 2-kg cart moving at 5 m/s.**
2. **Does a moving object have impulse?**
3. **Does a moving object have momentum?**
4. **For the same force, which cannon imparts a greater impulse to a cannonball: a long cannon or a short one?**

Were these your answers?

1. Both have the same momentum (1 kg × 10 m/s = 2 kg × 5 m/s).
2. No, impulse is not something an object *has,* like momentum. Impulse is what an object can *provide* or what it can *experience* when it interacts

* The symbol for momentum is p. In most physics texts, $p = mv$.

with some other object. An object cannot possess impulse, just as it cannot possess force.
3. Yes, but, like velocity, in a relative sense—that is, with respect to a frame of reference, usually Earth's surface. The momentum possessed by a moving object with respect to a stationary point on Earth may be quite different from the momentum it possesses with respect to another moving object.
4. The long cannon imparts a greater impulse because the force acts over a longer time. (A greater impulse produces a greater change in momentum, so a long cannon imparts more speed to a cannonball than a short cannon does.)

3.2 Impulse Changes Momentum

VIDEO: Changing Momentum

VIDEO: Decreasing Momentum Over a Short Time

EXPLAIN THIS Why is it a good idea to have your knees bent when you land after a jump?

The greater the impulse exerted on something, the greater its change in momentum. The exact relationship is

$$\text{Impulse} = \text{change in momentum}$$

or, in abbreviated notation,*

$$Ft = \Delta(mv)$$

where Δ is the symbol for "change in."

The **impulse–momentum relationship** helps us analyze a variety of situations in which momentum changes. Here we will consider some ordinary examples in which impulse is related to increasing and decreasing momentum.

Timing is especially important when changing momentum.

Case 1: Increasing Momentum

To increase the momentum of an object, it makes sense to apply the greatest force possible for as long as possible. A golfer teeing off and a baseball player trying for a home run do both of these things when they swing as hard as possible and follow through with their swings. Following through extends the time of contact.

The forces involved in impulses usually vary from instant to instant. For example, a golf club that strikes a ball exerts zero force on the ball until it comes in contact; then the force increases rapidly as the ball is distorted (Figure 3.3). The force then diminishes as the ball comes up to speed and returns to its original shape. So when we speak of such forces in this chapter, we mean the *average* force.

FIGURE 3.3
The force of impact on a golf ball varies throughout the duration of impact.

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Case 2: Decreasing Momentum Over a Long Time

If you were in a truck that was out of control and you had to choose between hitting a concrete wall or a haystack, you wouldn't have to call on your knowledge of physics to make up your mind. Common sense tells you to choose the haystack. But knowing the physics helps you understand *why* hitting a soft object is entirely different from hitting a hard one. In the case of hitting either

* This relationship is derived by rearranging Newton's second law to make the time factor more evident. If we equate the formula for acceleration, $a = F/m$, with what acceleration actually is, $a = \Delta v/\Delta t$, we get $F/m = \Delta v/\Delta t$. From this we derive $F\Delta t = \Delta(mv)$. Calling Δt simply t, the time interval, we have $Ft = \Delta(mv)$.

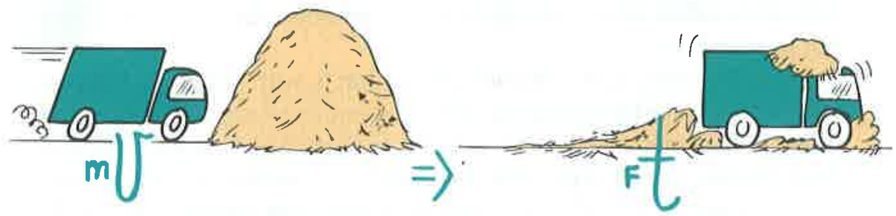

FIGURE 3.4
If the change in momentum occurs over a long time, then the hitting force is small.

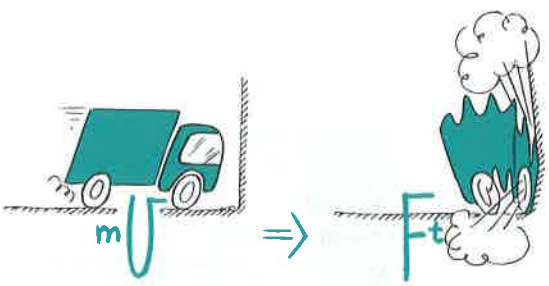

FIGURE 3.5
If the change in momentum occurs over a short time, then the hitting force is large.

the wall or the haystack and coming to a stop, it takes the *same* impulse to decrease your momentum to zero. The same impulse does not mean the same amount of force or the same amount of time; rather it means the same *product* of force and time. By hitting the haystack instead of the wall, you extend the *time during which your momentum is brought to zero.* A longer time interval reduces the force and decreases the resulting deceleration. For example, if the time interval is increased by a factor of 100, the force is reduced to a hundredth. Whenever we wish the force to be small, we extend the time of contact. Hence the reason for padded dashboards and airbags in motor vehicles.

Different forces exerted over different time intervals can produce the same impulse:

Ft or **Ft**

When you jump from an elevated position down to the ground, what happens if you keep your legs straight and stiff? Ouch! Instead, you bend your knees when your feet make contact with the ground. By doing so you extend the time during which your momentum decreases to 10 to 20 times that of a stiff-legged, abrupt landing. The resulting force on your bones is reduced by a factor of 10 to 20. A wrestler thrown to the floor tries to extend his time of impact with the mat by relaxing his muscles and spreading the impact into a series of smaller ones as his foot, knee, hip, ribs, and shoulder successively hit the mat. Of course, falling on a mat is preferable to falling on a solid floor because the mat also increases the time during which the force acts.

The safety net used by circus acrobats is a good example of how to achieve the impulse needed for a safe landing. The safety net reduces the force experienced by a fallen acrobat by substantially increasing the time interval during which the force acts.

SCREENCAST: Momentum

If you're about to catch a fast baseball with your bare hand, you extend your hand forward so you'll have plenty of room to let your hand move backward after you make contact with the ball. You extend the time of impact and thereby reduce the force of impact. Similarly, a boxer rides or rolls with the punch to reduce the force of impact (Figure 3.6).

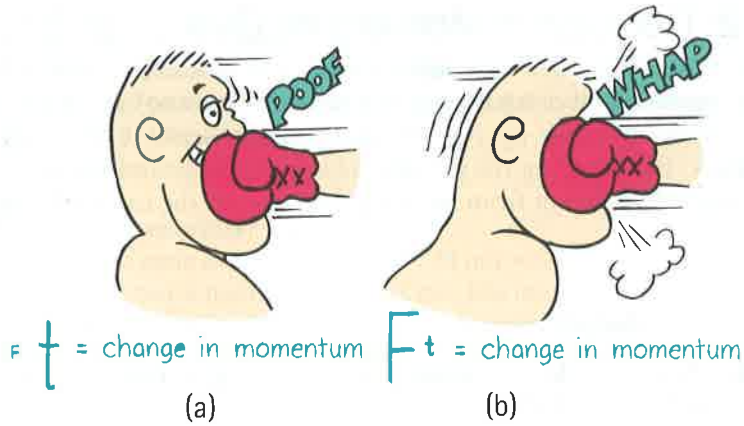

FIGURE 3.6
In both cases, the impulse provided by the boxer's jaw reduces the momentum of the punch. (a) When the boxer moves away (rides with the punch), he extends the time and diminishes the force. (b) If the boxer moves into the glove, the time is reduced and he must withstand a greater force.

Case 3: Decreasing Momentum Over a Short Time

When boxing, if you move into a punch instead of away, you're in trouble. It's the same as if you catch a high-speed baseball while your hand moves toward the ball instead of away upon contact. Or, when your car is out of control, if you drive it into a concrete wall instead of a haystack, you're really in trouble. In these cases of short impact times, the impact forces are large. Remember that for an object brought to rest, the impulse is the same no matter how it is stopped. But if the time is short, the force is large.

The idea of short time of contact explains how a karate expert can split a stack of bricks with the blow of her bare hand (Figure 3.7). She brings her arm and hand swiftly against the bricks with considerable momentum. This momentum is quickly reduced when she delivers an impulse to the bricks. The impulse is the force of her hand against the bricks multiplied by the time during which her hand makes contact with the bricks. By swift execution, she makes the time of contact very brief and correspondingly makes the force of impact huge. If her hand is made to bounce upon impact, as we will soon see, the force is even greater.

FIGURE 3.7
Cassy imparts a large impulse to the bricks in a short time and produces a considerable force.

CHECKPOINT

1. **If the boxer in Figure 3.6 increases the duration of impact to three times as long by riding with the punch, by how much is the force of impact reduced?**
2. **If the boxer instead moves *into* the punch to decrease the duration of impact by half, by how much is the force of impact increased?**
3. **A boxer being hit with a punch contrives to extend time for best results, whereas a karate expert delivers a force in a short time for best results. Isn't there a contradiction here?**

Were these your answers?

1. The force of impact is only a third of what it would have been if he hadn't pulled back.
2. The force of impact is twice what it would have been if he had held his head still. Impacts of this kind account for many knockouts.
3. There is no contradiction because the best results for each are quite different. The best result for the boxer is reduced force, accomplished by maximizing time, and the best result for the karate expert is increased force delivered in minimum time.

Bouncing

If a flowerpot falls from a shelf onto your head, you may be in trouble. If it bounces from your head, you may be in more serious trouble. Why? Because impulses are greater when an object bounces. The impulse required to bring an object to a stop and then to "throw it back again" is greater than the impulse required merely to bring the object to a stop. Suppose, for example, that you catch the falling pot with your hands. You provide an impulse to reduce its momentum to zero. If

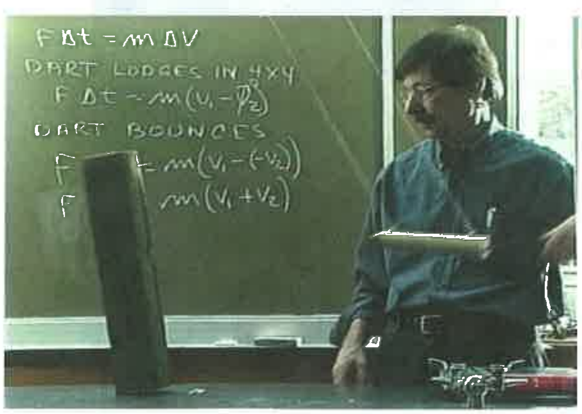

FIGURE 3.8
Howie Brand shows that the block topples when the swinging dart bounces from it. When he removes the rubber head of the dart so it doesn't bounce when it hits the block, no tipping occurs.

FIGURING PHYSICAL SCIENCE

Problem Solving

SAMPLE PROBLEM 1

An 8-kg bowling ball rolling at 2 m/s bumps into a padded guardrail and stops.
(a) What is the momentum of the ball just before hitting the guardrail?
(b) How much impulse acts on the ball?
(c) How much impulse acts on the guardrail?

Solution:

(a) The momentum of the ball is $mv = (8\text{ kg})(2\text{ m/s}) = 16\text{ kg}\cdot\text{m/s}$.
(b) In accord with the impulse–momentum relationship, the impulse on the ball is equal to its change in momentum. The momentum changes from 16 kg·m/s to zero. So $Ft = \Delta mv = (16\text{ kg}\cdot\text{m/s}) - 0 = 16\text{ kg}\cdot\text{m/s} = 16\text{ N}\cdot\text{s}$. (Note that the units kg·m/s and N·s are equivalent.)
(c) In accord with Newton's third law, the force of the ball on the padded guardrail is equal and oppositely directed to the force of the guardrail on the ball. Because the time of the interaction is the same for both the ball and the guardrail, the impulses are also equal and opposite. So the amount of impulse on the guardrail is 16 N·s.

SAMPLE PROBLEM 2

An ostrich egg of mass *m* is thrown at a speed *v* into a sagging bedsheet and is brought to rest in time *t*.
(a) Show that the average force of egg impact is *mv*/*t*.
(b) If the mass of the egg is 1.0 kg, its speed when it hits the sheet is 2.0 m/s, and it is brought to rest in 0.2 s, show that the average force that acts is 10 N.
(c) Why is breakage less likely with a sagging sheet than with a taut one?

Solution:

(a) From the impulse–momentum equation, $Ft = \Delta mv$, where in this case the egg ends up at rest, $\Delta mv = mv$, and simple algebraic rearrangement gives $F = mv/t$.

(b) $$F = \frac{mv}{t} = \frac{(1.0\text{ kg})\left(2.0\frac{\text{m}}{\text{s}}\right)}{(0.2\text{ s})}$$

$$= 10\text{ kg}\cdot\frac{\text{m}}{\text{s}^2} = 10\text{ N}$$

(c) The time during which the tossed egg's momentum goes to zero is extended when it hits a sagging sheet. Extended time means less force in the impulse that brings the egg to a halt. Less force means less chance of breakage.

you throw the pot upward again, you have to provide additional impulse. This increased amount of impulse is the same that your head supplies if the flowerpot bounces from it.

The fact that impulses are greater when bouncing occurs was used with great success during the California gold rush. The waterwheels used in gold-mining operations were not very effective. A man named Lester A. Pelton recognized a problem with the flat paddles on the waterwheels. He designed a curved paddle that caused the incoming water to make a U-turn upon impact with the paddle. Because the water "bounced," the impulse exerted on the waterwheel was increased. Pelton patented his idea, and he probably made more money from his invention, the Pelton wheel, than any of the gold miners earned. Physics can indeed enrich your life in more ways than one.

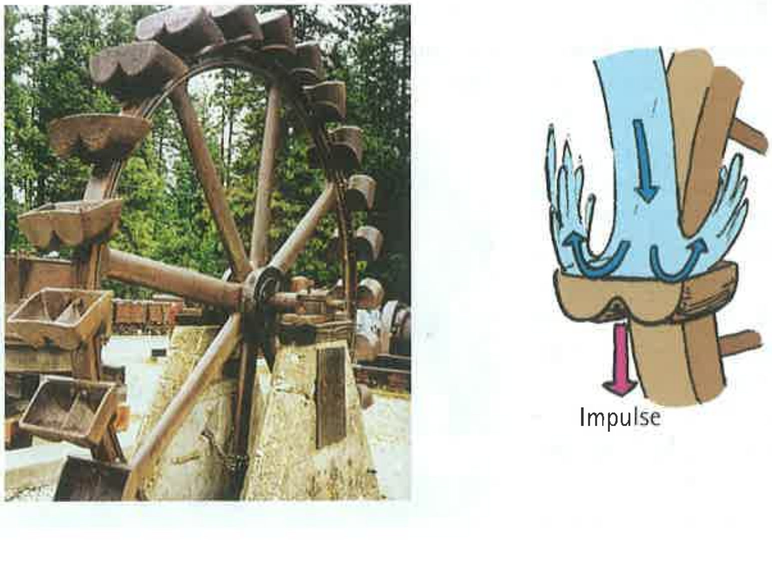

FIGURE 3.9
The Pelton wheel. The curved blades cause water to bounce and make a U-turn, which produces a greater impulse to turn the wheel.

CHECKPOINT

1. **In Figure 3.7, how does the force that Cassy exerts on the bricks compare with the force exerted on her hand?**
2. **How does the impulse resulting from the impact differ if her hand bounces back upon striking the bricks?**

Were these your answers?

1. In accordance with Newton's third law, the forces are equal. Only the resilience of the human hand and the training she has undergone to toughen her hand allow this feat to be performed without broken bones.
2. The impulse is greater if her hand bounces back from the bricks upon impact. If the time of impact is not correspondingly increased, a greater force is then exerted on the bricks (and her hand!).

3.3 Conservation of Momentum

EXPLAIN THIS What stays the same when a pool ball stops after hitting another ball at rest?

Only an impulse external to a system can change the momentum of a system. Internal forces and impulses won't work. For example, consider the cannon being fired in Figure 3.10. The force on the cannonball inside the cannon barrel is equal and opposite to the force causing the cannon to recoil. Because these forces act for the same amount of time, the impulses are also equal and opposite. Recall Newton's third law about action and reaction forces. It applies to impulses, too. These impulses are internal to the system comprising the cannon and the cannonball, so they don't change the momentum of the cannon–cannonball system. Before the firing, the system is at rest and the momentum is zero. After the firing, the net momentum, or total momentum, is *still* zero. Net momentum is neither gained nor lost.

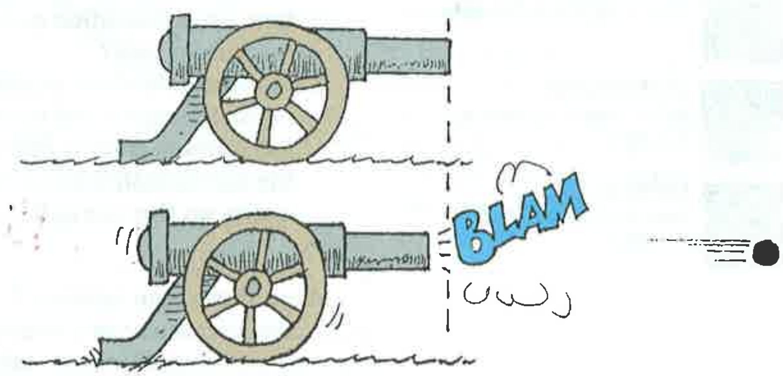

FIGURE 3.10
INTERACTIVE FIGURE MP

The net momentum before firing is zero. After firing, the net momentum is still zero, because the momentum of the cannon is equal and opposite to the momentum of the cannonball.

Momentum, like the quantities velocity and force, has both direction and magnitude. It is a *vector quantity*. Like velocity and force, momentum can be canceled. So although the cannonball in the preceding example gains momentum when fired and the recoiling cannon gains momentum in the opposite direction, there is no gain in the cannon–cannonball *system*. The momenta (plural form of *momentum*) of the cannonball and the cannon are equal in magnitude and opposite in direction.* They cancel to zero for the system as a whole. If no

fyi

- In Figure 3.10, most of the cannonball's momentum is in speed; most of the recoiling cannon's momentum is in mass. Therefore:

$$mV = \mathbf{m}v$$

* Here we neglect the momentum of ejected gases from the exploding gunpowder, which can be considerable. Firing a gun with blanks at close range is a definite no-no because of the considerable momentum of ejecting gases. More than one person has been killed by close-range firing of blanks. In 1998, a minister in Jacksonville, Florida, dramatizing his sermon before several hundred parishioners, including his family, shot himself in the head with a blank round from a .357-caliber Magnum. Although no slug emerged from the gun, exhaust gases did—enough to be lethal. So, strictly speaking, the momentum of the bullet (if any) + the momentum of the exhaust gases is equal to the opposite momentum of the recoiling gun.

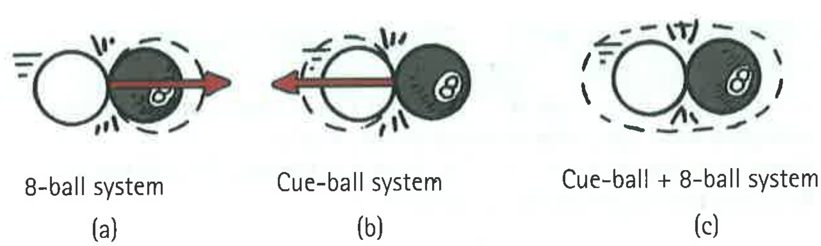

FIGURE 3.11
A cue ball hits an eight ball head-on. Consider this event in three systems: (a) An external force acts on the eight-ball system, and its momentum increases. (b) An external force acts on the cue-ball system, and its momentum decreases. (c) No external force acts on the cue-ball + eight-ball system, and momentum is conserved (simply transferred from one part of the system to the other).

net force or net impulse acts on a system, the momentum of that system cannot change.

When momentum, or any quantity in physics, does not change, we say it is *conserved.* The idea that momentum is conserved when no external force acts is elevated to a central law of mechanics called the **law of conservation of momentum:**

> **In the absence of an external force, the momentum of a system remains unchanged.**

For any system in which all forces are internal—as, for example, cars colliding, atomic nuclei undergoing radioactive decay, or stars exploding—the net momentum of the system before and after the event is the same.

SCREENCAST: Conservation of Momentum

SCREENCAST: Fish-Lunch Momentum Problem

SCREENCAST: Freddy-Frog Momentum Problem

CHECKPOINT

1. **Newton's second law states that if no net force is exerted on a system, no acceleration occurs. Does it follow that no change in momentum occurs?**
2. **Newton's third law states that the force a cannon exerts on a cannonball is equal and opposite to the force the cannonball exerts on the cannon. Does it follow that the *impulse* the cannon exerts on the cannonball is equal and opposite to the *impulse* the cannonball exerts on the cannon?**

Were these your answers?

1. Yes, because no acceleration means that no change occurs in velocity or in momentum (mass × velocity) of the system. Another line of reasoning is simply that no net force means there is no net impulse and thus no change in momentum.
2. Yes, because the interaction between both occurs during the same *time* interval. Because time is equal and the forces are equal and opposite, the impulses, *Ft,* are also equal and opposite. Impulse is a vector quantity and can be canceled.

Collisions

The collision of objects clearly illustrates the conservation of momentum. Whenever objects collide in the absence of external forces, the net momentum of both objects before the collision equals the net momentum of both objects after the collision.

$$\text{net momentum}_{\text{before collision}} = \text{net momentum}_{\text{after collision}}$$

This is true no matter how the objects might be moving before they collide.

Momentum is conserved for all collisions, elastic and inelastic (whenever external forces don't interfere).

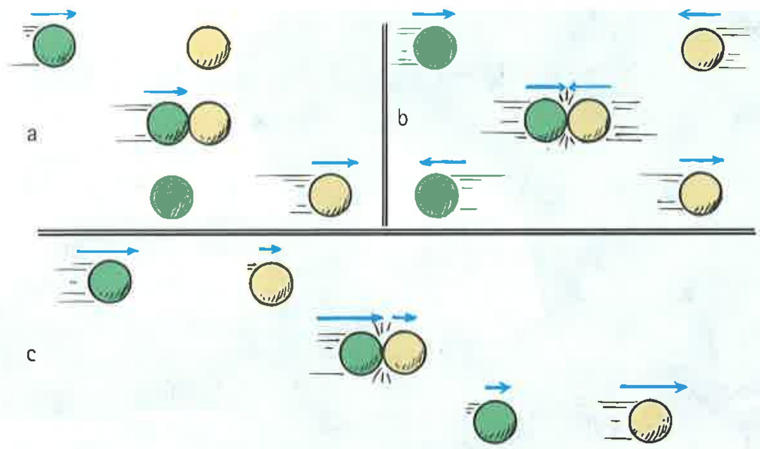

FIGURE 3.12
INTERACTIVE FIGURE MP

Elastic collisions of equally massive balls. (a) A green ball strikes a yellow ball at rest. (b) A head-on collision. (c) A collision of balls moving in the same direction. In each case, momentum is transferred from one ball to the other.

When a moving billiard ball has a head-on collision with another billiard ball at rest, the moving ball comes to rest and the other ball moves with the speed of the colliding ball. We call this an **elastic collision;** ideally, the colliding objects rebound without lasting deformation or the generation of heat (Figure 3.12). But momentum is conserved even when the colliding objects become entangled during the collision. This is an **inelastic collision,** characterized by deformation, or the generation of heat, or both. In a perfectly inelastic collision, the objects stick together. Consider, for example, the case of a freight car moving along a track and colliding with another freight car at rest (Figure 3.13). If the freight cars are of equal mass and are coupled by the collision, can we predict the velocity of the coupled cars after impact?

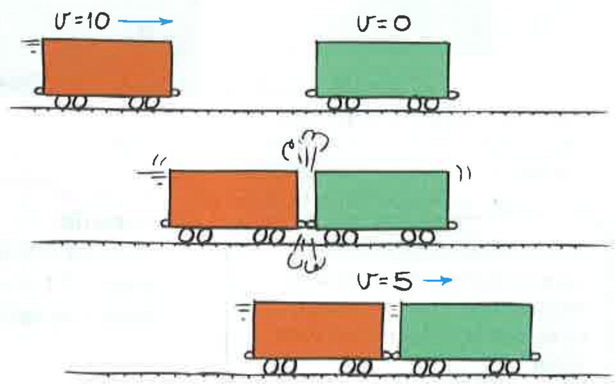

FIGURE 3.13
INTERACTIVE FIGURE MP

Inelastic collision. The momentum of the freight car on the left is shared with the same-mass freight car on the right after collision.

Suppose the single car is moving at 10 m/s, and we consider the mass of each car to be m. Then, from the conservation of momentum,

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$
$$(m \times 10 \text{ m/s})_{\text{before}} = (2m \times V)_{\text{after}}$$

By simple algebra, $V = 5$ m/s. This makes sense: because twice as much mass is moving after the collision, the velocity must be half as much as the velocity before the collision. Both sides of the equation are then equal.

CONSERVATION LAWS

A conservation law specifies that certain quantities in a system remain precisely constant, regardless of what changes may occur within the system. It is a law of constancy during change. In this chapter, we see that momentum is unchanged during collisions. We say that momentum is conserved. We'll soon learn that energy is conserved as it transforms—the amount of energy in light, for example, transforms completely to thermal energy when the light is absorbed. In Appendix A we'll see that angular momentum is conserved—whatever the rotational motion of a planetary system, its angular momentum remains unchanged so long as it is free of outside influences. In Chapter 8, we'll learn that electric charge also is conserved, which means that it can be neither created nor destroyed. When we study nuclear physics, we'll see that these and other conservation laws rule in the submicroscopic world. Conservation laws are a source of deep insights into the simple regularity of nature and are often considered the most fundamental of physical laws. Can you think of things in your own life that remain constant as other things change?

FIGURE 3.14
Will Maynez demonstrates his air track. Blasts of air from tiny holes provide a friction-free surface for the carts to glide on.

Galileo worked hard to produce smooth surfaces to minimize friction. How he would have loved to experiment with today's air tracks!

CHECKPOINT

Consider the air track in Figure 3.14. Suppose a gliding cart with a mass of 0.5 kg bumps into, and sticks to, a stationary cart that has a mass of 1.5 kg. If the speed of the gliding cart before impact is v_{before}, how fast will the coupled carts glide after collision?

Was this your answer?
According to momentum conservation, the momentum of the 0.5-kg cart before the collision = momentum of both carts stuck together afterward.

$$(0.5\text{ kg})\, v_{\text{before}} = (0.5\text{ kg} + 1.5\text{ kg})\, v_{\text{after}}$$

$$v_{\text{after}} = \frac{0.5\text{ kg}\, v_{\text{before}}}{(0.5\text{ kg} + 1.5\text{ kg})} = \frac{0.5\text{ kg}\, v_{\text{before}}}{2\text{ kg}} = \frac{v_{\text{before}}}{4}$$

This makes sense, because four times as much mass will be moving after the collision, so the coupled carts will glide more slowly. The same momentum means that four times the mass glides $\frac{1}{4}$ as fast.

So we see that changes in an object's motion depend both on force and on how long the force acts. When "how long" means time, we refer to the quantity *force* × *time* as impulse. But "how long" can mean distance also. When we consider the quantity *force* × *distance,* we are talking about something entirely different—the concept of *energy.*

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Energy

3.4 Energy and Work

EXPLAIN THIS How much faster will you hit the ground if you fall from twice the height?

Perhaps the concept most central to all of science is energy. The combination of energy and matter makes up the universe: matter is substance, and energy is the mover of substance. The idea of matter is easy to grasp.

Matter is stuff that we can see, smell, and feel. Matter has mass and occupies space. Energy, on the other hand, is abstract. We cannot see, smell, or feel most forms of energy. Surprisingly, the idea of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Although energy is familiar to us, it is difficult to define, because it is not only a "thing" but also both a thing and a process—similar to being both a noun and a verb. Persons, places, and things have energy, but we usually observe energy only when it is being transferred or being transformed. It appears in the form of electromagnetic waves from the Sun, and we feel it as thermal energy; it is captured by plants and binds molecules of matter together; it is in the foods we eat, and we receive it by digestion. Even matter itself is condensed, bottled-up energy, as set forth in Einstein's famous formula, $E = mc^2$, which we'll return to in the last part of this text. In general, **energy** is the property of a system that enables it to do *work*.

SCREENCAST: Work and Potential Energy

FIGURE 3.15
Bob may expend energy when he pushes on the wall, but if the wall doesn't move, no work is done on the wall. Instead, the energy expended becomes thermal energy.

When you push a crate across a floor you're doing work. By definition, *force* × *distance* equals the concept we call **work.**

When we lift a load against Earth's gravity, work is done. The heavier the load or the higher we lift the load, the more work is being done. Two things enter the picture whenever work is done: (1) application of a force and (2) the movement of something by that force. For the simplest case, in which the force is constant and the motion is in a straight line in the direction of the force,* we define the work done on an object by an applied force as the product of the force and the distance through which the object is moved. In shorter form:

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

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

The word *work,* in common usage, means physical or mental exertion. Don't confuse the physics definition of work with the everyday notion of work.

We see that the definition of work involves both a force and a distance. A weightlifter who holds a barbell weighing 1000 N overhead does no work on the barbell. She may get really tired holding the barbell, but if it is not moved by the force she exerts, she does no work *on the barbell.* Work may be done on the muscles by stretching and contracting, which is force times distance on a biological scale, but this work is not done on the barbell. Lifting the barbell, however, is a different story. When the weightlifter raises the barbell from the floor, she does work on it.

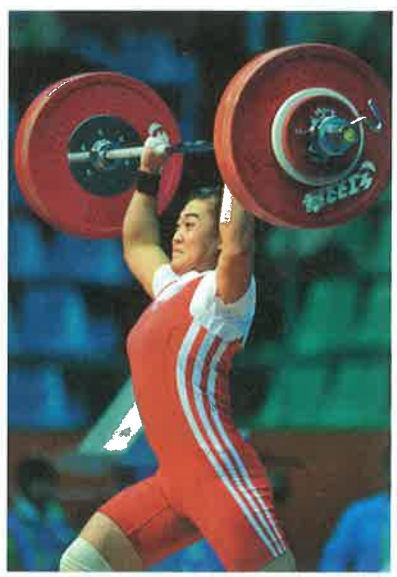


FIGURE 3.16
Work is done in lifting the barbell.

The unit of measurement for work combines a unit of force (N) with a unit of distance (m); the unit of work is the newton-meter (N·m), also called the *joule* (J), which rhymes with *cool.* One joule of work is done when a force of 1 N is exerted over a distance of 1 m, as in lifting a small apple over your head. For larger values, we speak of kilojoules (kJ, thousands of joules), or megajoules (MJ, millions of joules). The weightlifter in Figure 3.16 does work in kilojoules. To stop a loaded truck moving at 100 km/h requires megajoules of work.

* More generally, work is the product of only the component of force that acts in the direction of motion and the distance moved. For example, if a force acts at an angle to the motion, the component of force parallel to the motion is multiplied by the distance moved. When a force acts at right angles to the direction of motion, with no force component in the direction of motion, no work is done. A common example is a satellite in a circular orbit; the force of gravity is at right angles to its circular path, and no work is done on the satellite. Hence, it orbits with no change in speed.

FIGURE 3.17
The potential energy of Tenny's drawn bow equals the work (average force × distance) that she did in drawing the bow into position. When the arrow is released, most of the potential energy of the drawn bow will become the kinetic energy of the arrow.

fyi

- Your heart uses slightly more than 1 W of power in pumping blood through your body.

FIGURE 3.18
The Atlas V541 rocket that launched Curiosity to Mars in 2011 illustrates concepts such as thrust (force), work (force × distance), energy (fuel consumption), and power (the rate at which energy is expended).

CHECKPOINT

Assuming you have average strength, can you lift a 160-kg object with your bare hands? Can you do 1600 J of work on it?

Were these your answers?

An object with a mass of 160 kg weighs 1600 N, or 352 lb (the weight of a large refrigerator). So no, you cannot lift it without the use of some type of machine. If you can't move it, you can't do work on it. You'd do 1600 J of work on it if you could lift it a vertical distance of 1 m.

Power

The definition of work says nothing about how long it takes to do the work. The same amount of work is done when carrying a bag of groceries up a flight of stairs, whether we walk up or run up. So why are we more out of breath after running upstairs in a few seconds than after walking upstairs in a few minutes? To understand this difference, we need to talk about a measure of how fast the work is done—*power*. **Power** is equal to the amount of work done per time it takes to do it:

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

The work done in climbing stairs requires more power when the worker is running up rapidly than it does when the worker is climbing slowly. A high-power automobile engine does work rapidly. An engine that delivers twice the power of another, however, does not necessarily move a car twice as fast or twice as far. Twice the power means that the engine can do twice the work in the same amount of time—or it can do the same amount of work in half the time. A powerful engine can produce greater acceleration.

Power is also the rate at which energy is changed from one form to another. The unit of power is the joule per second, called the *watt*. This unit was named in honor of James Watt, the 18th-century developer of the steam engine. One watt (W) of power is used when 1 J of work is done in 1 s. One kilowatt (kW) equals 1000 W. One megawatt (MW) equals 1 million watts.

Potential Energy

An object may store energy by virtue of its position. The energy that is stored and held in readiness is called **potential energy** (PE) because in the stored state it has the potential for doing work. A stretched or compressed spring, for example, has the potential for doing work. When a bow is drawn, energy is stored in the bow. The bow can do work on the arrow. A stretched rubber band has potential energy because of the relative position of its parts. If the rubber band is part of a slingshot, it is capable of doing work.

The chemical energy in fuels is also potential energy. It is actually energy of position at the submicroscopic level. This energy is available when the positions of electric charges within and between molecules are altered—that is, when a chemical change occurs. Any substance that can do work through chemical action possesses potential energy. Potential energy is found in fossil fuels, electric batteries, and the foods we consume.

Work is required to elevate objects against Earth's gravity. The potential energy due to elevated positions is called *gravitational potential energy*. Water in an elevated reservoir and the raised ram of a pile driver both have gravitational potential energy. Whenever work is done, energy is exchanged.

The amount of gravitational potential energy possessed by an elevated object is equal to the work done against gravity in lifting it. The work done equals the

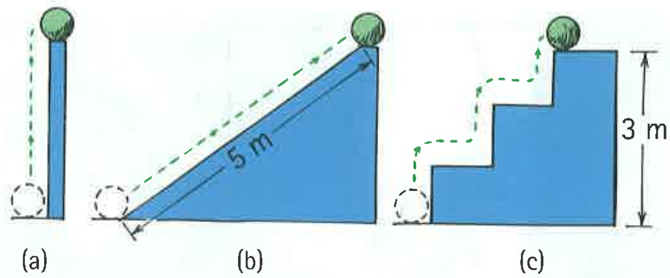


FIGURE 3.19
The potential energy of the 10-N ball is the same (30 J) in all three cases because the work done in elevating it 3 m is the same whether it is (a) lifted with 10 N of force, (b) pushed with 6 N of force up the 5-m incline, or (c) lifted with 10 N up each 1-m step. No work is done in moving it horizontally (neglecting friction).

force required to move it upward multiplied by the vertical distance it is moved (remember $W = Fd$). The upward force required while moving at constant velocity is equal to the weight, mg, of the object, so the work done in lifting it through a height h is the product mgh:

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

Note that the height is the distance above some chosen reference level, such as the ground or the floor of a building. The gravitational potential energy, mgh, is relative to that level and depends only on mg and h. We can see, in Figure 3.19, that the potential energy of the elevated ball does not depend on the path taken to get it there.

A small apple weighs 1 N. When it is held 1 m above ground, then relative to the ground, it has a PE of 1 J.

FIGURE 3.20
He raises a block of ice by lifting it vertically. She pushes an identical block of ice up the ramp. Can you see that they do equal amounts of work? And can you see that when both blocks are raised to the same vertical height, they possess the same potential energy?

Kinetic Energy

If you push on an object, you can set it in motion. If an object is moving, then it is capable of doing work. It has energy of motion. We say it has *kinetic energy* (KE). The **kinetic energy** of an object depends on the mass of the object as well as its speed. It is equal to the mass multiplied by the square of the speed, multiplied by the constant $\frac{1}{2}$:

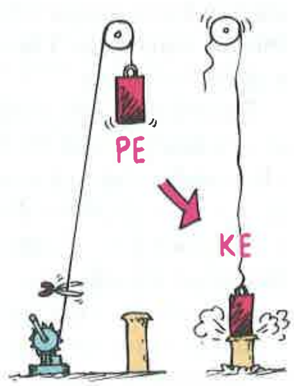
$$\text{Kinetic energy} = \tfrac{1}{2}\,\text{mass} \times \text{speed}^2$$
$$\text{KE} = \tfrac{1}{2}\,mv^2$$

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

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

or, in equation notation,

$$Fd = \tfrac{1}{2}\,mv^2$$



Gravitational potential energy always involves *two* interacting objects—one relative to the other. The ram of a pile driver, for example, interacts via gravitational force with Earth.

FIGURE 3.21
The potential energy of the elevated ram of the pile driver is converted to kinetic energy during its fall.

Note that the speed is squared, so if the speed of an object is doubled, its kinetic energy is quadrupled ($2^2 = 4$). Consequently, four times the work is required to double the speed. Likewise, nine times the work is required to triple the speed ($3^2 = 9$). The fact that speed or velocity is squared for kinetic energy clearly distinguishes the concepts of kinetic energy and momentum. What we can say is that in all interactions, whenever work is done, some form of energy increases. Whenever work is done, energy changes.

SCREENCAST: Potential and Kinetic Energy

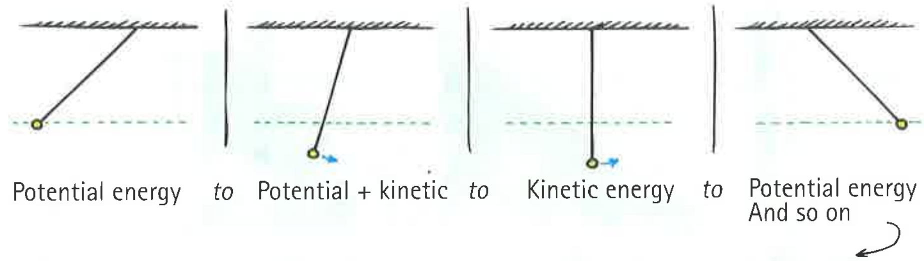


FIGURE 3.22
Energy transitions in a pendulum. PE is relative to the lowest point of the pendulum, when it is vertical.

SCREENCAST: Work-Energy Theorem

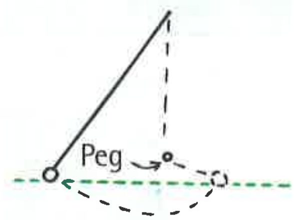


FIGURE 3.23
INTERACTIVE FIGURE MP

The pendulum bob will swing to its original height whether or not the peg is present.

FIGURE 3.24
The downhill "fall" of the roller coaster results in its roaring speed in the dip, and this kinetic energy sends it up the steep track to the next summit.

3.5 Work–Energy Theorem

EXPLAIN THIS How much farther will you skid on wet grass if you run twice as fast?

When a car speeds up, its gain in kinetic energy comes from the work done on it. Or, when a moving car slows, work is done to reduce its kinetic energy. We can say*

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

Work equals *change* in kinetic energy. This is the **work–energy theorem.**

The work–energy theorem emphasizes the role of change. Some forces can change potential energy. Recall our example of the weightlifter raising the barbell. While he exerts a force through a distance, he does work on the barbell and changes its potential energy. And when the barbell is held stationary, no further work is done and there is no further change in energy. Now if the weightlifter drops the barbell, gravity does work as the barbell is pulled down, increasing its kinetic energy.

If you push against a box on a floor and the box doesn't slide, then no change in its energy tells you that you are not doing work on the box. If you then push harder and the box slides, you are doing work on it. You push in one direction and friction acts in the other direction. The difference is a net force that does work to give the box its kinetic energy.

The work–energy theorem applies to decreasing speed as well. Energy is required to reduce the speed of a moving object or to bring it to a halt. When we apply the brakes to slow a moving car, we do work on it. This work is the friction force supplied by the brakes multiplied by the distance over which the friction force acts. The more kinetic energy something has, the more work is required to stop it.

Interestingly, the friction supplied by the brakes is the same whether the car moves slowly or quickly. Friction between solid surfaces doesn't depend on speed. The variable that makes a difference is the braking distance. A car moving at twice the speed of another takes four times ($2^2 = 4$) as much work to stop. Therefore, it takes four times as much distance to stop. Accident investigators are well aware that an automobile going 100 km/h has four times the kinetic energy it would have at 50 km/h. So a car going 100 km/h skids four times as far when its brakes are locked as it does when going 50 km/h. Kinetic energy depends on speed *squared.*

Automobile brakes convert kinetic energy to heat. Professional drivers are familiar with another way to slow a vehicle—shift to low gear to allow the

* This can be derived as follows: If we multiply both sides of $F = ma$ (Newton's second law) by d, we get $Fd = mad$. Recall from Chapter 2 that, for constant acceleration, $d = \frac{1}{2}at^2$, so we can say $Fd = ma\left(\frac{1}{2}at^2\right) = \frac{1}{2}maat^2 = \frac{1}{2}m(at)^2$; and substituting $v = at$, we get $Fd = \frac{1}{2}mv^2$. That is, work = KE, or, more specifically, $W = \Delta\text{KE}$.

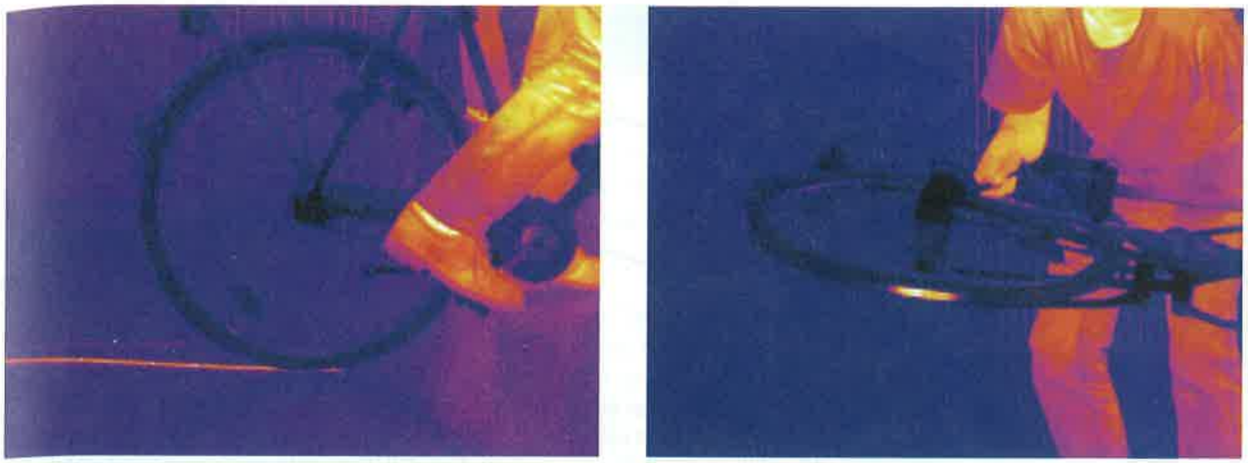


FIGURE 3.25
Because of friction, energy is transferred both into the floor and into the tire when the bicycle skids to a stop. An infrared camera reveals the heated tire track (the red streak on the floor, left) and the warmth of the tire (right). (Courtesy of Michael Vollmer.)

engine to do the braking. Today's hybrid cars do the same and divert braking energy to electrical storage batteries, where it is used to complement the energy produced by gasoline combustion (Chapter 9 treats how they accomplish this).

Kinetic energy and potential energy are two of the many forms of energy, and they underlie other forms of energy, such as chemical energy, nuclear energy, sound, and light. Kinetic energy of random molecular motion is related to temperature; potential energies of electric charges account for voltage; and kinetic and potential energies of vibrating air define sound intensity. Even light energy originates from the motion of electrons within atoms. Every form of energy can be transformed into every other form.

CHECKPOINT

1. **When you are driving at 90 km/h, how much more distance do you need to stop than if you were driving at 30 km/h?**
2. **For the same force, why does a longer cannon impart more speed to a cannonball?**

Were these your answers?

1. Nine times as much distance. The car has nine times as much kinetic energy when it travels three times as fast: $\frac{1}{2}m(3v)^2 = \frac{1}{2}m9v^2 = 9\left(\frac{1}{2}mv^2\right)$. The friction force is ordinarily the same in either case; therefore, nine times as much work requires nine times as much distance.
2. As learned earlier, a longer barrel imparts more impulse because of the longer *time* during which the force acts. The work–energy theorem similarly tells us that the longer the *distance* over which the force acts, the greater the change in kinetic energy. So we see two reasons for cannons with long barrels producing greater cannonball speeds.

Energy is nature's way of keeping score. Scams that sell energy-making machines rely on funding from deep pockets and shallow brains!

Kinetic Energy and Momentum Compared

Momentum and kinetic energy are properties of moving things, but they differ from each other. Like velocity, momentum is a vector quantity and is therefore directional and capable of being canceled entirely. But kinetic energy is a nonvector (scalar) quantity, like mass, and can never be canceled. The momenta of

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- Scientists have to be open to new ideas. That's how science grows. But a body of established knowledge exists that can't be easily overthrown. That includes energy conservation, which is woven into every branch of science and supported by countless experiments from the atomic to the cosmic scale. Yet no concept has inspired more "junk science" than energy. Wouldn't it be wonderful if we could get energy for nothing, to possess a machine that gives out more energy than is put into it? That's what many practitioners of junk science offer. Gullible investors put their money into some of these schemes. But none of them pass the test of being real science. Perhaps someday a flaw in the law of energy conservation will be discovered. If it ever is, scientists will rejoice at the breakthrough. But so far, energy conservation is as solid as any knowledge we have. Don't bet against it.

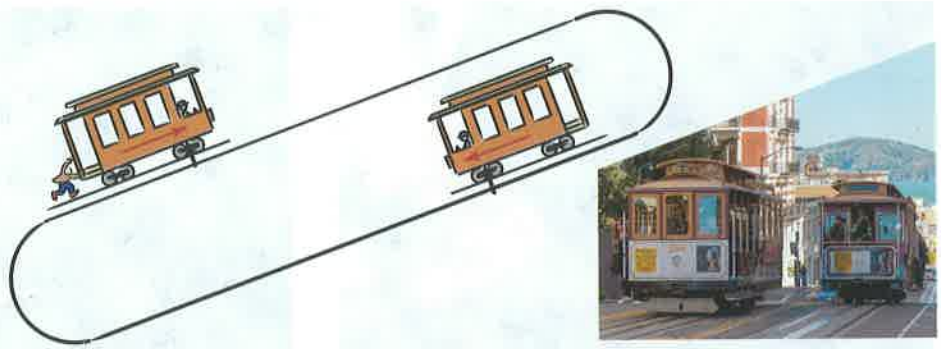


FIGURE 3.26
Cable cars on the steep hills of San Francisco nicely transfer energy to one another via the cable beneath the street. The cable forms a complete loop that connects cars going both downhill and uphill. In this way a car moving downhill does work on a car moving uphill. So the increased gravitational PE of an uphill car is due to the decreased gravitational PE of a car moving downhill.

two firecrackers approaching each other may cancel, but when they explode, there is no way their energies can cancel. Energies transform to other forms; momenta do not. Another difference is the velocity dependence of the two. Whereas momentum depends on velocity (mv), kinetic energy depends on the square of velocity $\left(\frac{1}{2}mv^2\right)$. An object that moves with twice the velocity of another object of the same mass has twice the momentum but four times the kinetic energy. So when a car traveling twice as fast crashes, it crashes with four times the energy.

If the distinction between momentum and kinetic energy isn't really clear to you, you're in good company. Failure to make this distinction resulted in disagreements and arguments between the best British and French physicists for almost two centuries.

3.6 Conservation of Energy

EXPLAIN THIS What is the energy score before and after galaxies collide?

Whenever energy is transformed or transferred, none is lost and none is gained. In the absence of work input or output or other energy exchanges, the total energy of a system before some process or event is equal to the total energy after.

Consider the changes in energy in the operation of the pile driver back in Figure 3.21. Work done to raise the ram, giving it potential energy, becomes kinetic energy when the ram is released. This energy transfers to the piling below. The distance the piling penetrates into the ground multiplied by the average force of impact is almost equal to the initial potential energy of the ram. We say *almost* because some energy goes into heating the ground and ram during penetration. Taking heat energy into account, we find that energy transforms without net loss or net gain. Quite remarkable!

The study of various forms of energy and their transformations has led to one of the greatest generalizations in physics—the **law of conservation of energy:**

> **Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.**

VIDEO: Bowling Ball and Conservation of Energy

VIDEO: Conservation of Momentum: Numerical Example

SCREENCAST: Conservation of Energy

SCREENCAST: Energy of Acrobats

FIGURING PHYSICAL SCIENCE

Problem Solving

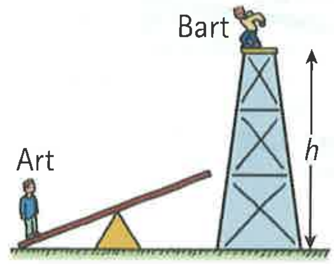
SAMPLE PROBLEM

Acrobat Art of mass m stands on the left end of a seesaw. Acrobat Bart of mass M jumps from a height h onto the right end of the seesaw, thus propelling Art into the air.

(a) Neglecting inefficiencies, how does the PE of Art at the top of his trajectory compare with the PE of Bart just before Bart jumps?

(b) Show that ideally Art reaches a height $\frac{M}{m}h$.

(c) If Art's mass is 40 kg, Bart's mass is 70 kg, and the height of the initial jump was 4 m, show that Art rises a vertical distance of 7 m.



Solution:

(a) Neglecting inefficiencies, the entire initial PE of Bart before he drops goes into the PE of Art rising to his peak—that is, at Art's moment of zero KE.

(b) $PE_{Bart} = PE_{Art}$

$Mgh_{Bart} = mgh_{Art}$

$h_{Art} = \frac{M}{m}h.$

(c) $h_{Art} = \frac{M}{m}h = \left(\frac{70\text{ kg}}{40\text{ kg}}\right)4\text{ m} = 7\text{ m}.$

When we consider any system in its entirety, whether it be as simple as a swinging pendulum or as complex as an exploding supernova, one quantity isn't created or destroyed: energy. It may change form or it may simply be transferred from one place to another, but the total energy score stays the same. This energy score takes into account the fact that the atoms that make up matter are themselves concentrated bundles of energy. When the nuclei (cores) of atoms rearrange themselves, enormous amounts of energy can be released. The Sun shines because some of this nuclear energy is transformed into radiant energy.

Enormous compression due to gravity and extremely high temperatures in the deep interior of the Sun fuse the nuclei of hydrogen atoms together to form helium nuclei. This is *thermonuclear fusion,* a process that releases radiant energy, a small part of which reaches Earth. Part of the energy reaching Earth falls on plants (and on other photosynthetic organisms), and part of this, in turn, is later stored in the form of coal. Another part supports life in the food chain that begins with plants (and other photosynthesizers), and part of this energy later is stored in oil. Part of the energy from the Sun goes into the evaporation of water from the ocean, and part of this returns to Earth in rain that may be trapped behind a dam. By virtue of its elevated position, the water behind a dam has energy that may be used to power a generating plant below, where it is transformed to electric energy. The energy travels through wires to homes, where it is used for lighting, heating, cooking, and operating electrical gadgets. How wonderful that energy transforms from one form to another!

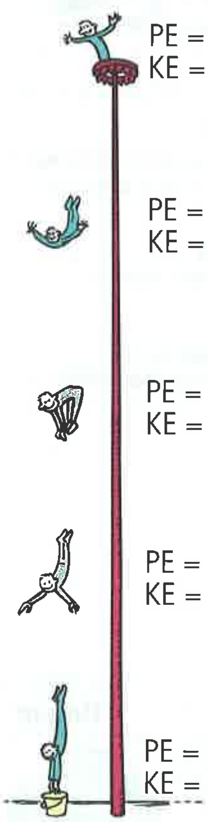


FIGURE 3.27
INTERACTIVE FIGURE MP

A circus diver at the top of a pole has a potential energy of 10,000 J. As he dives, his potential energy converts to kinetic energy. Note that, at successive positions one-fourth, one-half, three-fourths, and all the way down, the total energy is constant.

3.7 Machines

EXPLAIN THIS Why should or shouldn't you invest in a machine that creates energy?

A **machine** is a device for multiplying forces or simply changing the direction of forces. The principle underlying every machine is conservation of energy. Consider one of the simplest machines, the **lever** (Figure 3.28).

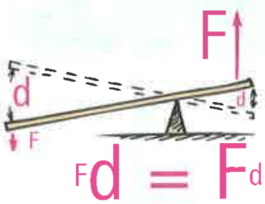


FIGURE 3.28
The lever.

At the same time that we do work on one end of the lever, the other end does work on the load. We see that the direction of force is changed: if we push down, the load is lifted up. If the little work done by friction forces is small enough to neglect, the work input equals the work output:

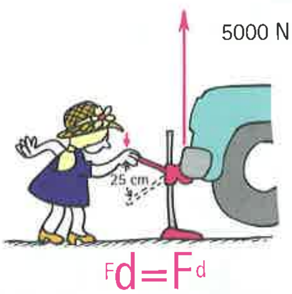
$$\text{Work input} = \text{work output}$$

Because work equals force times distance, **conservation of energy for machines** tells us that *input force* × *input distance* = *output force* × *output distance.*

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

The point of support on which a lever rotates is called the *fulcrum.* When the fulcrum of a lever is relatively close to the load, a small input force produces a large output force. This is because the input force is exerted through a large distance and the load is moved through a correspondingly short distance. So a lever can be a force multiplier. But no machine can multiply work or multiply energy. That's a conservation-of-energy no-no!

Today, a child can use the principle of the lever to jack up the front end of an automobile. By exerting a small force through a large distance, she can provide a large force that acts through a small distance. Consider the ideal example illustrated in Figure 3.29. Every time she pushes the jack handle down 25 cm, the car rises only a hundredth as far but with 100 times the force.



50 N × 25 cm = 5000 N × 0.25 cm

FIGURE 3.29
Applied force × applied distance = output force × output distance.

VIDEO:
Machines: Pulleys

SCREENCAST:
Machines and Energy

Another simple machine is a pulley. Can you see that it is a lever "in disguise"? When used as in Figure 3.30, it changes only the direction of the force; but, when used as in Figure 3.31, the output force is doubled. Force is increased and distance is decreased. As with any machine, forces can change while work input and work output are unchanged.

A block and tackle is a system of pulleys that multiplies force more than a single pulley can. With the ideal pulley system shown in Figure 3.32, the man pulls 7 m of rope with a force of 50 N and lifts a load of 500 N through a vertical distance of 0.7 m. The energy the man expends in pulling the rope is numerically equal to the increased potential energy of the 500-N block. Energy is transferred from the man to the load.

Any machine that multiplies force does so at the expense of distance. Likewise, any machine that multiplies distance, such as your forearm and elbow,

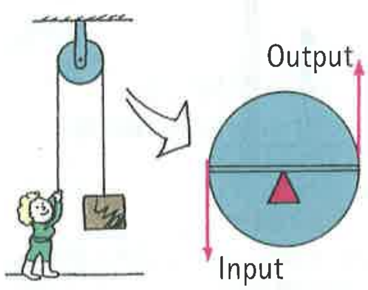


FIGURE 3.30
This pulley acts like a lever with equal arms. It changes only the direction of the input force.

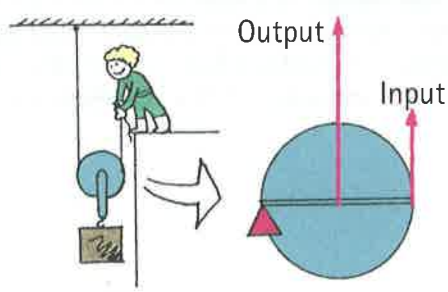


FIGURE 3.31
In this arrangement, a load can be lifted with half the input force. Note that the "fulcrum" is at the left end rather than in the center (as is the case in Figure 3.30).

FIGURE 3.32
Applied force × applied distance = output force × output distance.

does so at the expense of force. No machine or device can put out more energy than is put into it. No machine can create energy; it can only transfer energy or transform it from one form to another.

3.8 Efficiency

EXPLAIN THIS What is meant by an *ideal machine*?

The three previous examples were of *ideal machines;* 100% of the work input appeared as work output. An ideal machine would operate at 100% efficiency. In practice, this doesn't happen, and we can never expect it to happen. In any transformation, some energy is dissipated to molecular kinetic energy—thermal energy. This makes the machine and its surroundings warmer.

Efficiency can be expressed by the ratio

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

Even a lever converts a small fraction of input energy into heat when it rotates about its fulcrum. We may do 100 J of work but get out only 98 J. The lever is then 98% efficient, and we waste 2 J of work input as heat. In a pulley system, a larger fraction of input energy goes into heat. If we do 100 J of work, the forces of friction acting through the distances through which the pulleys turn and rub about their axles may dissipate 60 J of energy as heat. So the work output is only 40 J, and the pulley system has an efficiency of 40%. The lower the efficiency of a machine, the greater the amount of energy wasted as heat.*

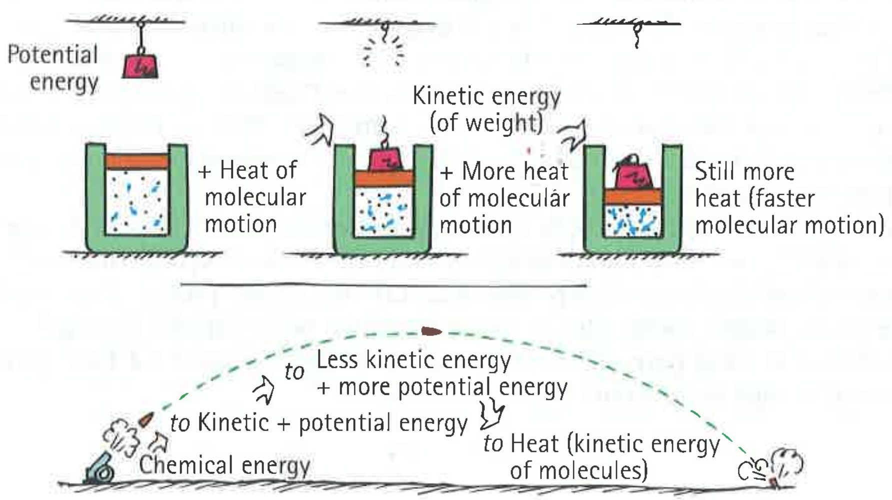


FIGURE 3.33
Energy transitions. The graveyard of mechanical energy is thermal energy.

CHECKPOINT

Consider an imaginary miracle car that has a 100% efficient internal combustion engine and burns fuel that has an energy content of 40 megajoules per liter (MJ/L). If the air resistance and overall frictional forces on the car traveling at highway speed are 500 N, show that the distance the car could travel per liter at this speed is 80 km/L.

* When you study thermodynamics in Chapter 6, you'll learn that an internal combustion engine *must* transform some of its fuel energy into thermal energy. A fuel cell, on the other hand, doesn't have this limitation. Watch for fuel cell–powered vehicles in the future!

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- The principle of the lever was understood by Archimedes, a famous Greek scientist in the third century BC. He said, "Give me a place to stand, and I will move the Earth."

fyi

- Building a perpetual motion machine (a device that can do work without energy input) is a no-no. But perpetual motion itself is a yes-yes. Atoms and their electrons, and stars and their planets, for example, are in a state of perpetual motion. Perpetual motion is the natural order of things.

A machine can multiply force but never energy—no way!

fyi

- Comparing transportation efficiencies, the most efficient is the human on a bicycle—far more efficient than train and car travel, and even that of fish and animals. Hooray for bicycles and cyclists who use them!

Inventors take heed: When introducing a new idea, first be sure it is in context with what is presently known. For example, it should be consistent with the conservation of energy.

Was this your answer?

From the definition that *work* = *force* × *distance*, simple rearrangement gives *distance* = *work/force*. If all 40 million J of energy in 1 L were used to do the work of overcoming the air resistance and frictional forces, the distance would be

$$\text{Distance} = \frac{\text{work}}{\text{force}} = \frac{40{,}000{,}000\ \text{J/L}}{500\ \text{N}} = 80{,}000\ \text{m/L} = 80\ \text{km/L}$$

(This is about 190 miles per gallon [mpg].) The important point here is that, even with a hypothetically perfect engine, there is an upper limit of fuel economy dictated by the conservation of energy.

3.9 Sources of Energy

EXPLAIN THIS How can the Sun be the source of hydroelectric, wind, and fossil-fuel power?

Except for nuclear power, practically all our energy is derived from the Sun. Even the energy we obtain from petroleum, coal, natural gas, and wood originally came from the Sun. That's because these fuels were created by photosynthesis—the process by which plants trap solar energy and store it as plant tissue.

Sunlight evaporates water, which later falls as rain; rainwater flows into rivers and over waterfalls and up against dams, where it is directed to turbines that generate electricity. Then it evaporates or returns to the sea, and the cycle continues. Even the wind, caused by unequal warming of Earth's surface, gets its energy from the Sun. Giant wind turbines, capturing wind energy, are now familiar sites around the country and offshore. Because wind power can't be turned on and off at will, it usually supplements other means of power production.

Energy in sunlight is directly converted to electric energy in photovoltaic solar cells (Figure 3.34). Photovoltaic cells vary from the small ones that power calculators to large arrays that power cities. Like the energy produced via wind generators, electric energy obtained by solar cells is pollution free. Solar power is seasonal in most parts of the world, which suggests a need for long-term seasonal storage in a medium such as hydrogen.

fyi

- Because the energy density of petroleum isn't going to be replaced soon, and no current alternative fuel can fly jet aircraft, wisdom suggests restricting petrol fuels to needs such as powering jet aircraft, where concentrated energy is vital, and using alternative fuels for heating and powering automobiles, trucks, and trains.

fyi

- Another source of energy is tidal power. In certain locations, the twice-daily tidal surges turn turbines to produce power. Interestingly, this form of energy is neither nuclear nor derived from the Sun. It comes from the rotational energy of our planet.

FIGURE 3.34
Most space crafts operating in the inner solar system rely on the use of solar panels to derive electricity from sunlight. Likewise on many rooftops on Earth below.

Although hydrogen is the most plentiful element in the universe, here on Earth hydrogen is bound to other elements, mainly oxygen and carbon. Most hydrogen in America is produced from natural gas, in a process that uses high temperatures and pressures to separate hydrogen from hydrocarbon molecules. One drawback to separating hydrogen from carbon compounds is the unavoidable production of carbon dioxide, a greenhouse gas. A simpler and cleaner method that doesn't produce greenhouse gases is *electrolysis*—electrically splitting water into its constituent parts. Figure 3.35 shows how you can perform this in the lab or at home: Place two wires that are connected to the terminals of an ordinary battery into a glass of salted water. Be sure the wires don't touch each other. Bubbles of hydrogen form on one wire, and bubbles of oxygen form on the other. For large-scale production of hydrogen, the battery is replaced with banks of photovoltaic solar cells.

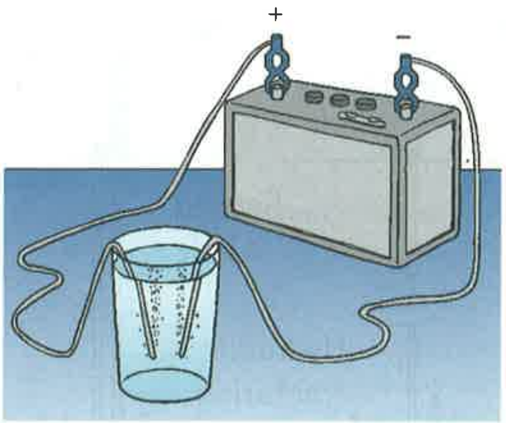

FIGURE 3.35
When electric current passes through conducting water, bubbles of hydrogen form at one wire, and bubbles of oxygen form at the other. This is *electrolysis*. A fuel cell does the opposite—hydrogen and oxygen enter the fuel cell and are combined to produce electricity and water.

A **fuel cell** is similar to the electrolysis process but runs in the opposite direction. Hydrogen and oxygen gas are combined at electrodes, and electric current is produced. The by-product of fuel cells is pure water. The former space shuttles used fuel cells to meet their electrical needs, while producing drinking water for the astronauts.

Here on Earth fuel cells of various kinds power a variety of vehicles, from forklifts to trains. In a hydrogen fuel cell, hydrogen gas combines with oxygen from the air to produce electric current that can power electric motors (Figure 3.36). Hydrogen is the least polluting of all fuels. Although we speak of hydrogen fuel, it is important to note that because energy is needed to separate it from water or hydrocarbons, hydrogen itself is not an energy source. As with electricity, the production of hydrogen requires an external energy source; the hydrogen thus produced provides a way of storing and/or transporting energy. Again, for emphasis, hydrogen is *not* an energy source. But watch for hydrogen to become society's "energy currency."

FIGURE 3.36
David Vasquez exhibits three fuel-cell "stacks" that produce electricity to power motor vehicles, the smallest for a scooter and the larger ones for automobiles. Because of zero greenhouse gas emissions, zero toxic chemicals, quick refueling times, and long driving range, major car companies are introducing hydrogen-fuel-cell cars to the mass market.

The most concentrated source of usable energy is that stored in nuclear fuels—uranium and plutonium. For the same weight of fuel, nuclear reactions release about 1 million times more energy than chemical reactions, and the process doesn't pollute the atmosphere. Interestingly, Earth's interior is hot because of radioactivity, a form of nuclear power, which has been with us since Earth was formed.

A by-product of nuclear power in Earth's interior is geothermal energy. Geothermal energy is held in underground reservoirs of hot water. Geothermal energy is largely limited to areas of volcanic activity, such as Iceland, New Zealand, Japan, and Hawaii. In these locations, heated water near Earth's surface is tapped to provide steam for driving turbogenerators.

In locations where heat from volcanic activity is near the surface and groundwater is absent, another method holds promise for producing electricity: dry-rock geothermal power (Figure 3.37, next page). With this method, water is put into cavities in deep, dry, hot rock. When the water turns to steam, it is piped to a turbine at the surface. After turning the turbine, it is returned to the cavity for reuse. This means of producing electricity produces no carbon.

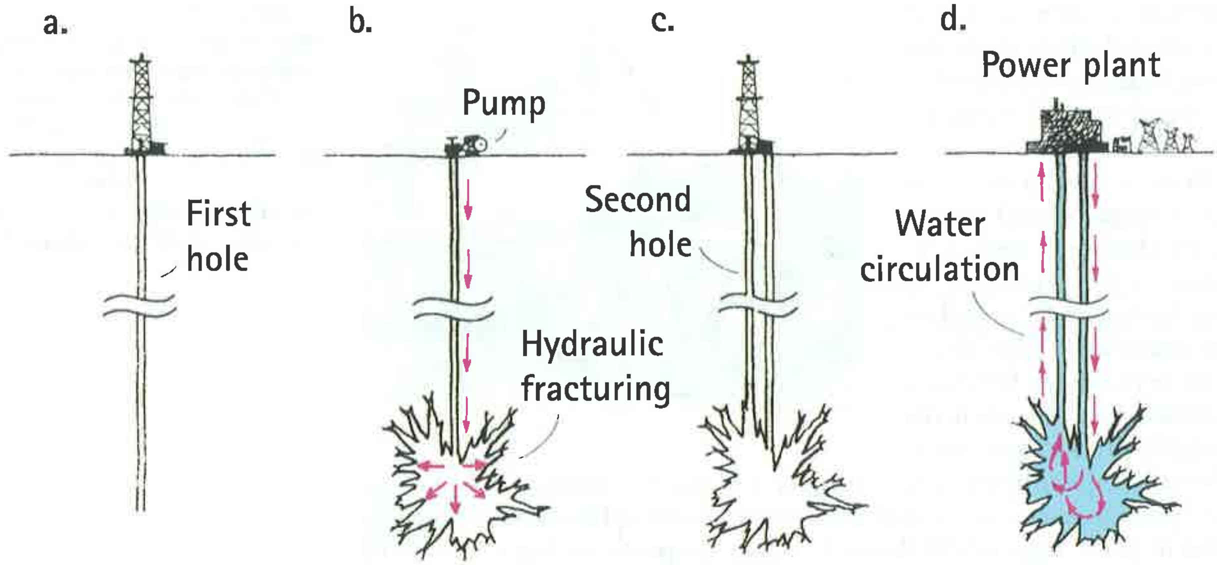

FIGURE 3.37
Dry-rock geothermal power. (a) A hole is sunk several kilometers into dry granite. (b) Water is pumped into the hole at high pressure and fractures the surrounding rock to form a cavity with increased surface area. (c) A second hole is sunk to intercept the cavity. (d) Water is circulated down one hole and through the cavity, where it is superheated before rising through the second hole. After driving a turbine, it is recirculated into the hot cavity again, making a closed cycle.

Another form of what is often called geothermal energy harnesses the temperature difference between Earth's surface and the subsurface just a few meters down, where the steady temperature is warmer than the temperature at the surface in winter and cooler than that at the surface in summer.

As the world population increases, so does our need for energy, especially because per-capita demand is also growing. With the rules of physics to guide them, technologists are presently researching newer and cleaner ways to develop energy sources. But they struggle to keep ahead of a growing world population and greater demand in the developing world. Unfortunately, as long as controlling population is politically and religiously incorrect, human misery becomes the check to unrestrained population growth. As H. G. Wells wrote (in *The Outline of History*), "Human history becomes more and more a race between education and catastrophe."

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SUMMARY OF TERMS (KNOWLEDGE)

Conservation of energy Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.

Conservation of energy for machines The work output of any machine cannot exceed the work input. In an ideal machine, where no energy is transformed into thermal energy,

$$\text{work}_{\text{input}} = \text{work}_{\text{output}};\ (Fd)_{\text{input}} = (Fd)_{\text{output}}$$

Efficiency The percentage of the work put into a machine that is converted into useful work output.

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

Elastic collision A collision in which colliding objects rebound without lasting deformation or the generation of heat.

Energy The property of a system that enables it to do work.

Fuel cell A device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent.

Impulse The product of the force acting on an object and the time during which that force acts on that object.

Inelastic collision A collision in which the colliding objects become distorted, generate heat, and may even stick together.

Kinetic energy Energy of motion, quantified by the relationship

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

Law of conservation of momentum In the absence of an external force, the momentum of a system remains unchanged. Hence, the momentum before an event involving only internal forces is equal to the momentum after the event:

$$(mv)_{\text{before}} = (mv)_{\text{after}}$$

Lever A simple machine consisting of a rigid rod pivoted at a fixed point called the fulcrum.

Machine A device, such as a lever or pulley, that increases (or decreases) a force or simply changes the direction of a force.

Momentum Inertia in motion, given by the product of the mass of an object and its velocity.

Potential energy The energy that matter possesses due to its position:

$$\text{Gravitational PE} = mgh$$

Power The rate of doing work:

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

(More generally, power is the rate at which energy is expended.)

Relationship of impulse and momentum Impulse is equal to the change in the momentum of an object that the impulse acts on. In symbol notation,

$$Ft = \Delta mv$$

Work The product of the force and the distance moved by the force:

$$W = Fd$$

(More generally, work is the component of force in the direction of motion multiplied by the distance moved.)

Work–energy theorem The net work done on an object equals the change in kinetic energy of the object.

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

READING CHECK QUESTIONS (UNDERSTANDING)

3.1 Momentum and Impulse

1. Which has greater momentum: an automobile at rest or a moving skateboard?
2. When a ball is hit with a given force, why does contact over a long time impart more speed to the ball than contact over a short time?

3.2 Impulse Changes Momentum

3. Why is it a good idea to extend your bare hand forward when you are getting ready to catch a fast-moving baseball?
4. Why is it poor judgment to have the back of your hand up against the outfield wall when you catch a long fly ball?
5. Why is it advantageous, in karate, to apply a force for a short time?
6. In boxing, why is it advantageous to roll with the punch?
7. If a ball has the same speed just before being caught and just after being thrown, in which case does the ball undergo the greatest change in momentum: (1) When it is caught, (2) when it is thrown, or (3) when it is caught and then thrown back?
8. In which of cases (1), (2), and (3) in Question 7 is the greatest impulse required?

3.3 Conservation of Momentum

9. What does it mean to say that momentum (or any quantity) is *conserved*?
10. When a cannonball is fired, momentum is conserved for the *system* of cannon + cannonball. Would momentum be conserved for the system if momentum were not a vector quantity? Explain.
11. Railroad car A rolls at a certain speed and makes a perfectly elastic collision with car B of the same mass. After the collision, car A is observed to be at rest. How does the speed of car B compare with the initial speed of car A?
12. If the equally massive railroad cars of Question 11 couple together after colliding inelastically, how does their speed after the collision compare with the initial speed of car A?

3.4 Energy and Work

13. When is energy most evident?
14. Cite an example in which a force is exerted on an object without doing work on the object.
15. Which requires more work: lifting a 50-kg sack a vertical distance of 2 m or lifting a 25-kg sack a vertical distance of 4 m?

16. A car is raised a certain distance in a service station lift and therefore has potential energy relative to the floor. If it were raised twice as high, how much potential energy would it have compared with what it had in the first case?
17. Two cars are raised to the same elevation on service station lifts. If one car is twice as massive as the other, how do their potential energies compare?
18. If a moving car speeds up until it is going three times as fast as it was, how much kinetic energy does it have compared with its initial kinetic energy?
19. What is the relationship between work and power?

3.5 Work–Energy Theorem

20. What is the relationship between the gain in kinetic energy and the work when work is done?
21. Compared with the work that the brakes must supply to stop a car moving at some original speed, how much more work must the brakes supply to stop that car if it is moving four times as fast as the original speed? How do the respective stopping distances compare?

3.6 Conservation of Energy

22. What will be the kinetic energy of the ram of a pile driver when it suddenly undergoes a 10-kJ decrease in potential energy?
23. An apple hanging from a limb has potential energy because of its height. If the apple falls, what becomes of this energy just before the apple hits the ground? When it hits the ground?

3.7 Machines

24. Can a machine multiply input force? Input distance? Input energy? (If your three answers are the same, seek help, because this is an important question.)
25. If a machine multiplies force by a factor of 4, what other quantity is diminished, and by how much?

3.8 Efficiency

26. What is the efficiency of a machine that miraculously converts all the input energy to useful output energy?
27. What becomes of energy when efficiency is lowered in a machine?

3.9 Sources of Energy

28. What is the ultimate source of the energy supplied by fossil fuels, dams, and windmills?
29. What is the ultimate source of geothermal energy?
30. Can we correctly say that hydrogen is a relatively new source of energy? Why or why not?

ACTIVITIES (HANDS-ON APPLICATION)

31. If your instructor has an air table or air track, play around with carts or air pucks. Most important, predict what will happen before you initiate collisions.

32. When you get a bit ahead in your studies, cut classes some afternoon and visit your local pool or billiards parlor to bone up on momentum conservation. Note that, no matter how complicated the collision of balls, the momentum along the line of action of the cue ball before impact is the same as the combined momentum of all the balls along this direction after impact, and that the components of momenta perpendicular to this line of action cancel to zero after impact, the same value as before impact in this direction. You'll see both the vector nature of momentum and its conservation more clearly when rotational skidding ("English") is not imparted to the cue ball. When English is imparted by striking the cue ball off center, rotational momentum, which is also conserved, somewhat complicates analysis. But regardless of how the cue ball is struck, in the absence of external forces, both linear and rotational momentum are always conserved. Both pool and billiards offer a first-rate exhibition of momentum conservation in action.

33. Pour some dry sand into a tin can with a cover. Compare the temperature of the sand before and after you vigorously shake the can for a couple of minutes. Predict what occurs. What is your explanation?

34. Place a small rubber ball on top of a basketball or soccer ball, and then drop them together. If vertical alignment remains as they fall to the floor, you'll see that the small ball bounces unusually high. Can you reconcile this with energy conservation?

PLUG AND CHUG (FORMULA FAMILIARIZATION)

Momentum = *mv*

35. Show that the momentum for a 2-kg brick parachuting straight downward at a constant speed of 8 m/s is 16 kg · m/s.

Impulse = *Ft*

36. Show that the impulse on a baseball that is hit with 100 N of force in a time of 0.5 s is 50 N.s.

Impulse = change in momentum; *Ft* = Δ*mv*

37. Show that when a 10-kg cart undergoes a 2.0-m/s increase in speed, the impulse on the cart is 20 N · s. (The unit N · s is equivalent to kg · m/s.)

38. Show that when an impulse produced by a 12-N force acts over 2.0 s on an ice puck initially at rest on an air table, the change in momentum is 24 kg · m/s.

Work = force × distance; $W = Fd$

39. Show that 2.4 J of work is done when a force of 2.0 N moves a book 1.2 m. (1 N · m = 1 J)
40. Calculate the work done when a 20-N force pushes a cart 3.5 m.

Gravitational potential energy = mass × acceleration due to gravity × height; PE = mgh

41. Show that when a 3.0-kg book is lifted 2.0 m, its increase in gravitational potential energy is 60 J.
42. Show that the gravitational potential energy of a 1000-kg boulder raised 5 m above ground level is 50,000 J. (You can express g in units of N/kg, because m/s^2 is equivalent to N/kg.)

Kinetic energy = ½mass × velocity^2; KE = $\frac{1}{2}mv^2$

43. Show that the kinetic energy of a 1.0-kg book tossed across the room at a speed of 3.0 m/s is 4.5 J. (1 J is equivalent to 1 kg(m/s)^2.)
44. Calculate the kinetic energy of a 84-kg scooter moving at 10 m/s.

Work-energy theorem; $W = \Delta$KE

45. Show that 24 J of work is done when a 3.0-kg block of ice is moved from rest to a speed of 4.0 m/s.
46. Show that a 2,500,000-J change in kinetic energy occurs for an airplane that is moved 500 m in takeoff by a sustained force of 5000 N.

$$\textbf{Power} = \frac{\textbf{work}}{\textbf{time}} = \frac{W}{t}$$

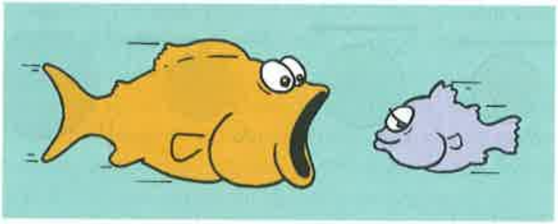
47. Show that 50 W of power is required to give a brick 100 J of PE in a time of 2 s.
48. Show that nearly 786 W of power is expended when a 500-N barbell is lifted 2.2 m above the floor in 1.4 s.

$$\textbf{Efficiency} = \frac{\textbf{useful energy output}}{\textbf{total energy input}}$$

49. Show that the efficiency of a machine that has an input of 100 J and an output of 40 J is 0.40.

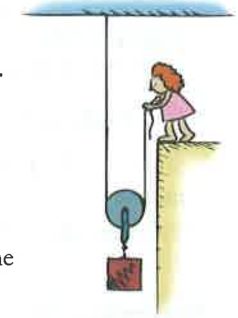
THINK AND SOLVE (MATHEMATICAL MANIPULATION)

50. In Chapter 1 we learned that acceleration $a = \frac{\Delta v}{\Delta t}$, and in Chapter 2 we learned that the cause of acceleration involves net force, where $a = \frac{F}{m}$. Equate these two equations for acceleration and show that, for constant mass, $F\Delta t = \Delta(mv)$.
51. A 10-kg bag of groceries is tossed onto a table at 3 m/s and slides to a stop in 2 s. Begin with the equation you derived in Problem 50, and show that the force of friction is 15 N.
52. An ostrich egg of mass m is tossed at a speed v into a sagging bed sheet and is brought to rest in a time t.
    (a) Show that the force acting on the egg when it hits the sheet is $\frac{mv}{t}$.
    (b) Show that if the mass of the egg is 1 kg, its initial speed is 2 m/s, and the time to stop is 1 s, then the average force on the egg is 2 N.
53. A 6-kg ball rolling at 3 m/s bumps into a pillow and stops in 0.5 s.
    (a) Show that the force exerted by the pillow is 36 N.
    (b) How much force does the ball exert on the pillow?
54. At a baseball game, a ball of mass $m = 0.15$ kg moving at a speed $v = 30$ m/s is caught by a fan.
    (a) Show that the impulse supplied to bring the ball to rest is 4.5 N · s.
    (b) Show that if the ball is stopped in 0.02 s, then the average force of the ball on the catcher's hand is 225 N.
55. Jeannie Beanie (mass 40 kg), standing on slippery ice, catches her leaping dog, Daisy (mass 20 kg), who leapt into her arms after running across an adjacent field at 6 m/s. Use the conservation of momentum to show that the speed of Jeannie and her dog after the catch is 2 m/s.
56. A railroad diesel engine weighs four times as much as a freight car. The diesel engine coasts at 5 km/h into a freight car that is initially at rest. Use the conservation of momentum to show that after they couple together, the engine + car coast at 4 km/h.
57. A 5-kg fish swimming at 1 m/s swallows an absent-minded 1-kg fish swimming toward it at a velocity that brings both fish to a halt. Show that the speed of the smaller fish before lunch was 5 m/s.



58. Little Hudson (next page) holds the 10-kg barbell 0.3 m above the floor.
    (a) What is the PE of the barbell relative to the floor?
    (b) How much additional work will Hudson do when he lifts the barbell to a height 1.0 m above the floor?
    (c) If Hudson then drops the barbell, what will be its KE of impact with the floor?

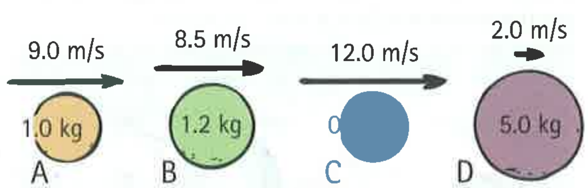
59. If you push a crate horizontally with a force of 100 N across a 10-m factory floor, and the friction force between the crate and the floor is a steady 70 N, how much kinetic energy is gained by the crate?
60. A simple lever is used to lift a heavy load. When a 60-N force pushes one end of the lever downward 1.2 m, the load rises 0.2 m. Show that the weight of the load is 360 N.
61. The following questions refer to Problem 60: (a) How much work is done by the 60-N force? (b) What is the gain in PE of the load? (c) How does the work done compare with the increased PE of the load?
62. In raising a 6000-N piano with a pulley system, the movers note that for every 2 m of rope pulled down, the piano rises 0.2 m. Show that, ideally, the force required to lift the piano is 600 N.



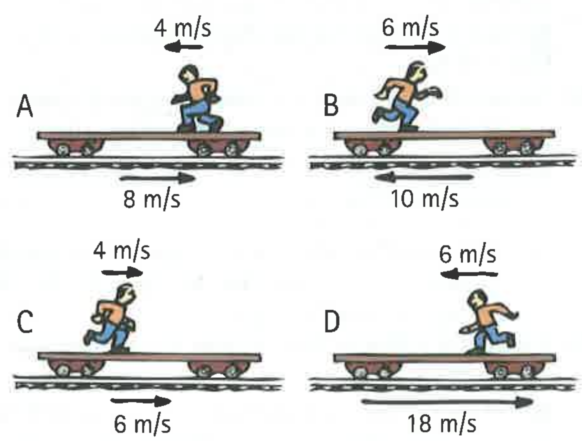
63. The girl steadily pulls her end of the rope upward a distance of 0.4 m with a constant force of 50 N. By how much does the PE of the block increase? Show that the mass of the block is 10 kg.
64. How many watts of power do you expend when you exert a force of 6 N that moves a book 2 m in a time interval of 3 s?
65. Show that 480 W of power is expended by a weightlifter who lifts a 60-kg barbell a vertical distance of 1.2 m in a time interval of 1.5 s.
66. When an average force F is exerted over a certain distance on a shopping cart of mass m, its kinetic energy increases by $\frac{1}{2}mv^2$.
    (a) Use the work–energy theorem to show that the distance over which the force acts is $\frac{mv^2}{2F}$.
    (b) If twice the force is exerted over twice the distance, how does the resulting increase in kinetic energy compare with the original increase in kinetic energy?
67. Emily holds a banana of mass m over the edge of a bridge of height h. She drops the banana, and it falls to the river below. Use the conservation of energy to show that the speed of the banana just before hitting the water is $v = \sqrt{(2gh)}$.
68. Starting from rest, Megan zooms down a frictionless slide from an initial height of 4.0 m. Show that her speed at the bottom of the slide is $\sqrt{80}$ m/s, or 8.9 m/s.

THINK AND RANK (ANALYSIS)

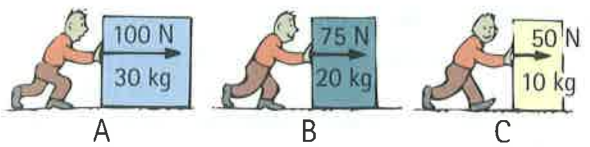
69. The balls have different masses and speeds. Rank the following from greatest to least: (a) Momentum. (b) The impulses needed to stop the balls.



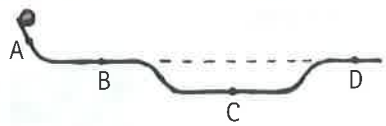
70. Jogging Jake runs along a train flatcar that moves at the velocities shown. In each case, Jake's velocity is given relative to the car. Call direction to the right positive. Rank the following from greatest to least: (a) The magnitude of Jake's momentum relative to the flatcar. (b) Jake's momentum relative to an observer at rest on the ground.



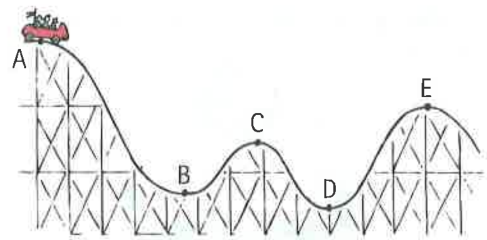
71. Starting from rest, Marshall pushes crates across the floor of his classroom for 3 seconds with a net force as shown. For each crate, rank the following from greatest to least: (a) Impulse delivered. (b) Change in momentum. (c) Final speed. (d) Momentum at the end of 3 seconds.



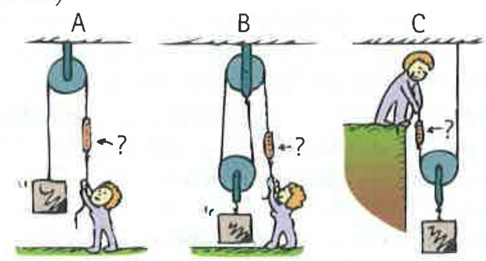
72. A ball is released from rest at the left of the metal track shown. Assume it has only enough friction to roll rather than to slide, but not enough to lessen its speed. Rank, from greatest to least, the following quantities at each point: (a) Momentum. (b) KE. (c)PE.



73. The roller coaster ride starts from rest at point A. Rank, from greatest to least, the following quantities at each point: (a) Speed. (b) KE. (c) PE.



74. Rank the scale readings from greatest to least. (Ignore friction.)



EXERCISES (SYNTHESIS)

3.1 Momentum and Impulse

75. A lunar vehicle is tested on Earth at a speed of 12 km/h. When it travels at that same speed on the Moon, is its momentum more, less, or the same?
76. In terms of impulse and momentum, why do airbags in cars reduce the chances of injury in accidents?
77. Why are today's autos designed to crumple upon impact?

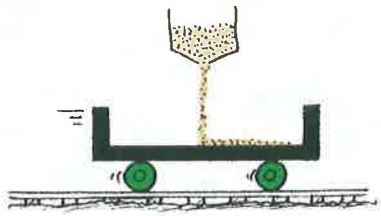
3.2 Impulse Changes Momentum

78. If you throw a raw egg against a wall, you'll break it; but if you throw it with the same speed into a sagging sheet, the egg won't break. Explain, using concepts from this chapter.
79. In terms of impulse and momentum, when a boxer is being hit, why is it important that he or she move away from the punch? Why is it disadvantageous to move into an oncoming punch?
80. To throw a ball, do you exert an impulse on it? Do you exert an impulse to catch it if it's traveling at the same speed? About how much impulse do you exert, in comparison, if you catch it and immediately throw it back again? (Imagine yourself on a skateboard.)

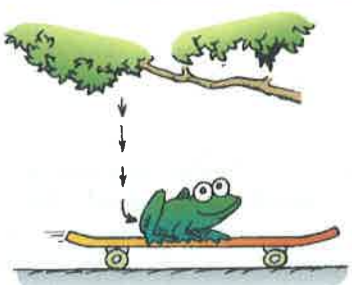
3.3 Conservation of Momentum

81. Bronco dives from a hovering helicopter and finds his momentum increasing. Does this violate the conservation of momentum? Explain.
82. A pair of skaters who are initially at rest push against each other so that they move in opposite directions. What is the total momentum of the two skaters as they move apart? Is there a different answer if their masses are not the same?
83. When you are traveling in your car at highway speed, the momentum of a bug is suddenly changed as it splatters onto your windshield. Compared with the change in momentum of the bug, by how much does the momentum of your car change?
84. You are at the front of a floating canoe near a dock. You leap, expecting to land on the dock easily. Instead you land in the water. Explain in terms of momentum conservation.
85. If you throw a ball horizontally while standing on a skateboard, you roll backward with a momentum that matches that of the ball. Will you roll backward if you hold on to the ball while going through the motions of throwing it? Explain in terms of momentum conservation.
86. A fully dressed person is at rest in the middle of a pond on perfectly frictionless ice and must get to shore. How can this be accomplished? Explain in terms of momentum conservation.
87. The examples of Exercises 84, 85, and 86 can be explained in terms of momentum conservation. Now explain them in terms of Newton's third law.
88. In the previous chapter, rocket propulsion was explained in terms of Newton's third law. That is, the force that propels a rocket is from the exhaust gases pushing against the rocket, the reaction to the force that the rocket exerts on the exhaust gases. Now explain rocket propulsion in terms of momentum conservation.
89. When vertically falling sand lands in a horizontally moving cart, the cart slows. Ignore any friction between the cart and the tracks. Give two reasons for the slowing of the cart, one in terms of a horizontal force

acting on the cart, and one in terms of momentum conservation.



90. In a movie, the hero jumps straight down from a bridge onto a small boat that continues to move with no change in velocity. What physics is being violated here?
91. Freddy Frog drops vertically from a tree onto a horizontally moving skateboard. The skateboard slows. Give two reasons for the slowing, one in terms of a horizontal friction force between Freddy's feet and the skateboard, and one in terms of momentum conservation.



3.4 Energy and Work

92. If your friend pushes a stroller four times as far as you do while exerting only half the force, which one of you does more work? How much more?
93. Which requires more work: stretching a strong spring a certain distance or stretching a weak spring the same distance? Defend your answer.
94. Two people of the same weight climb a flight of stairs. The first person climbs the stairs in 30 s, and the second person climbs them in 40 s. Which person does more work? Which uses more power?
95. Why do you run out of breath when running up the stairs but not when walking up the stairs?

3.5 Work–Energy Theorem

96. A friend says that when twice as much work is done on a wagon, it will gain twice as much kinetic energy. Another friend say it will gain four times as much kinetic energy. Which friend do you agree with?
97. Compared with a pickup truck moving at a certain speed and braking to a stop, how much work must the brakes do to stop the truck when it is moving at twice that speed?
98. When a cannon with a long barrel is fired, the force of expanding gases acts on the cannonball for a long distance. What effect does this have on the velocity of the emerging cannonball? (Do you see why long-range cannons have such long barrels?)

3.6 Conservation of Energy

99. At what point in its motion is the KE of a pendulum bob at a maximum? At what point is its PE at a maximum? When its KE is at half its maximum value, how much PE does it possess?
100. A physics instructor demonstrates energy conservation by releasing a heavy pendulum bob, as shown, allowing it to swing to and fro. What would happen if, in his exuberance, he gave the bob a slight shove as it left his nose? Explain.

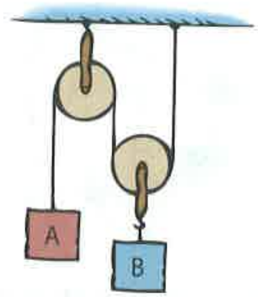
101. On a playground slide, a child has potential energy that decreases by 1000 J while her kinetic energy increases by 900 J. What other form of energy is involved, and how much?
102. Consider the identical balls released from rest on tracks A and B, as shown. When they reach the right ends of the tracks, which will have the greater speed? Why is this question easier to answer than the similar one (Discussion Question 107) in Chapter 1?

103. If a golf ball and a Ping-Pong ball both move with the same kinetic energy, can you say which has the greater speed? Explain in terms of the definition of KE. Similarly, in a gaseous mixture of heavy molecules and light molecules with the same average KE, can you say which have the greater speed?
104. In the absence of air resistance, a snowball thrown vertically upward with a certain initial KE returns to its original level with the same KE. When air resistance is a factor affecting the snowball, does it return to its original level with the same, less, or more KE? Does your answer contradict the law of energy conservation?
105. You're on a rooftop and you throw one snowball downward to the ground below and another upward. The second snowball, after rising, falls and also strikes the ground below. If air resistance can be neglected, and if downward and upward initial speeds are the same, how do the speeds of the snowballs upon striking the ground compare? (Use energy conservation to arrive at your answer.)
106. When a driver applies the brakes to keep a car going downhill at constant speed and constant kinetic energy, the potential energy of the car decreases. Where does this energy go? Where does most of it appear in a hybrid vehicle?
107. When the mass of a moving object is doubled, with no change in speed, by what factor is its momentum changed? By what factor is its kinetic energy changed?

108. When the velocity of an object is doubled, by what factor is its momentum changed? By what factor is its kinetic energy changed?
109. Which, if either, has greater momentum: a 1-kg ball moving at 2 m/s or a 2-kg ball moving at 1 m/s? Which has greater kinetic energy?
110. If an object's kinetic energy is zero, what is its momentum?
111. If your momentum is zero, is your kinetic energy necessarily zero also?
112. Two lumps of clay with equal and opposite momenta have a head-on collision and come to rest. Is momentum conserved? Is kinetic energy conserved? Why are your answers the same (or different)?
113. Consider Andrea's swinging-balls apparatus. If two balls are lifted and released, momentum is conserved because at impact, two balls pop out the other side with the same speed as the released balls. But momentum would also be conserved if one ball popped out at twice the speed. Explain why this never happens.

3.7 Machines

114. Discuss the physics that explains how the girl in Figure 3.29 can jack up a car while applying so little force.
115. Why bother using a machine if it cannot multiply work input to achieve greater work output?
116. In the pulley system shown, Block A has a mass of 10 kg and is suspended precariously at rest. Assume that the pulleys and string are massless and there is no friction. No friction means that the tension in one part of the supporting string is the same as in any other part. Discuss why the mass of Block B is 20 kg.



3.8 Efficiency

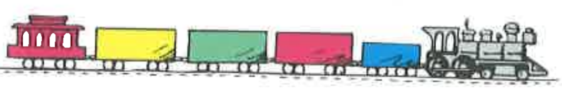
117. If an automobile had a 100% efficient engine, transferring all of the fuel's energy to work, would the engine be warm to your touch? Would its exhaust heat the surrounding air? Would it make any noise? Would it vibrate? Would any of its fuel go unused? Discuss.
118. The energy we need to live comes from chemically stored potential energy in food, which is transformed into other energy forms during the metabolism process. What happens to a person whose combined work and heat output is less than the energy consumed? What happens when the person's combined work and heat output is greater than the energy consumed? Can an undernourished person perform extra work without extra food? Discuss and defend your answers.
119. To combat wasteful habits, we often speak of "conserving energy" by turning off lights, heating or cooling systems, and hot water when these are not being used. In this chapter, we also speak of "energy conservation." Distinguish between these two uses of the term *conservation*.

3.9 Sources of Energy

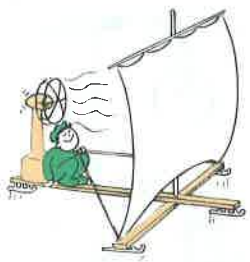
120. What is the argument that dry-rock geothermal power is a form of nuclear power?
121. What is the argument that the energy provided by a hydrogen fuel cell is actually solar energy?
122. What is the fuel that powers a fuel cell in forklifts, busses, and trains?
123. Imagine that you're in a completely dark room with no windows except a 1-ft^2 round hole in the roof. When the Sun is high in the sky, about 100 W of solar power enters the hole. On the floor where the light hits, you place a beach ball covered with aluminum foil, with the shiny side out. Discuss the illumination in your room compared with that of a 100-W incandescent light bulb.

DISCUSSION QUESTIONS (EVALUATION)

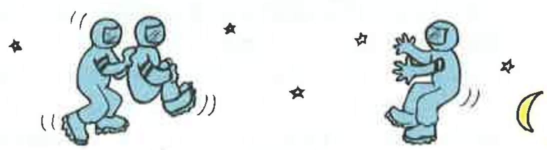
124. Railroad cars are loosely coupled so that there is a noticeable delay between the time the first car is moved and the time the last car is moved from rest by the locomotive. Discuss the advisability of this loose coupling and slack between cars from the point of view of impulse and momentum.



125. Your friend says that the law of momentum conservation is violated when a ball rolls down a hill and gains momentum. Your friend wants to discuss this. What do you say?
126. An ice sailcraft is stalled on a frozen lake on a windless day. The skipper sets up a fan as shown on the next page. If all the wind bounces backward from the sail, discuss whether or not the craft will be set in motion. If so, in what direction?

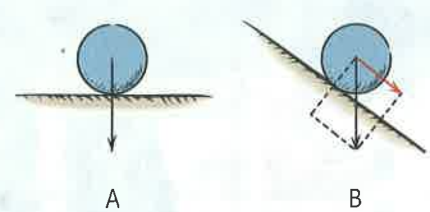


127. Will your answer to Question 126 be different if the air is brought to a halt by the sail without bouncing? Discuss.
128. Discuss the advisability of simply removing the sail in the situation discussed in Questions 126 and 127.
129. Suppose that three astronauts outside a spaceship decide to play catch. All three equally strong astronauts have the same mass. The first astronaut throws the second astronaut toward the third one and the game begins. Describe the motion of the astronauts as the game proceeds. How long will the game last?

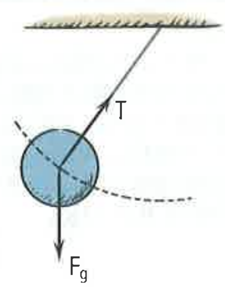


130. Discuss whether something can have energy without having momentum. Discuss whether something can have momentum without having energy.
131. Arrange the following four energy-transforming devices or processes in the correct order for converting solar energy to the kinetic energy of vehicles: (1) fuel cell, (2) electrolysis, (3) electric motor, (4) photovoltaic cell.
132. What are the roles of water, energy, hydrogen, and oxygen in (a) electrolysis, (b) operation of a fuel cell?
133. Does a car burn more fuel when its lights are turned on? Does the overall consumption of fuel depend on whether the engine is running while the lights are on? Discuss and defend your answers.
134. This may seem like an easy question for a physics buff to answer: With what force does a 10-N rock strike the ground if it is dropped from a rest position 10 m high? In fact, the question cannot be answered unless you have more information. What information is needed to answer this question, and why?
135. Your friend says that one way to improve air quality in a city is to synchronize traffic lights so that motorists can travel long distances at constant speed. Discuss the physics that supports this claim.
136. Does the electric power produced by wind-powered generators affect the speed of the wind? That is, would locations behind the wind blades be windier if the generators weren't there?

137. A red ball of mass m and a blue ball of mass $2m$ have the same kinetic energy. Explain which of the two has the larger momentum, letting equations guide your discussion.
138. No work is done by gravity on a bowling ball resting or moving on a bowling alley, because the force of gravity on the ball acts perpendicular to the surface. But on an incline, the force of gravity has a vector component parallel to the alley, as sketch b shows. Discuss two ways in which this component (a) accounts for acceleration of the ball, and (b) accounts for work done on the ball to change its kinetic energy.



139. Consider a bob attached by a string—a simple pendulum—that swings to and fro. (a) Why does the tension force in the string not do work on the pendulum? (b) Explain, however, why the force due to gravity on the pendulum at nearly every point *does* do work on the pendulum. (c) Where is the single position of the pendulum where "no work by gravity" occurs?



140. Consider a satellite in a circular orbit above Earth's surface. In Chapter 4 we will learn that the force of gravity changes the direction of motion of a satellite (and keeps it in a circle) but does NOT change its speed. Work done on the satellite by the gravitational force is zero. What is your explanation?

READINESS ASSURANCE TEST (RAT)

If you have a good handle on this chapter, then you should be able to score at least 7 out of 10 on this RAT. If you score less than 7, you need to study further before moving on.

Choose the BEST answer to the question or the BEST way to complete the statement.

1. A freight train rolls along a track with considerable momentum. If it then rolls at the same speed but has twice as much mass, its momentum is now
   (a) zero.
   (b) twice as large.
   (c) four times as large.
   (d) unchanged.
2. In the absence of external forces, momentum is conserved in
   (a) an elastic collision.
   (b) an inelastic collision.
   (c) either an elastic or an inelastic collision.
   (d) neither an elastic nor an inelastic collision.
3. If the running speed of Fast Freda doubles, what also doubles is her
   (a) momentum.
   (b) kinetic energy.
   (c) both of these
   (d) neither of these
4. Which of the following equations best illustrates the usefulness of automobile airbags?
   (a) $F = ma$
   (b) $Ft = \Delta mv$
   (c) $KE = \frac{1}{2}mv^2$
   (d) $Fd = \Delta \frac{1}{2}mv^2$
5. Which of the following equations is most useful for solving a problem that asks for the distance that a fast-moving box slides across a Post Office floor before coming to a stop?
   (a) $F = ma$
   (b) $Ft = \Delta mv$
   (c) $KE = \frac{1}{2}mv^2$
   (d) $Fd = \Delta \frac{1}{2}mv^2$
6. How much work is done on a 200-kg crate that is hoisted 2 m in a time of 4 s?
   (a) 400 J
   (b) 1000 J
   (c) 1600 J
   (d) 4000 J
7. A circus diver drops from a high pole into water far below. When he is halfway down,
   (a) his potential energy is halved.
   (b) he has gained an amount of kinetic energy equal to half his initial potential energy.
   (c) his kinetic energy and potential energy are equal.
   (d) all of these
8. A bicycle that travels twice as fast as another when braking to a stop will skid
   (a) twice as far.
   (b) four times as far.
   (c) eight times as far.
   (d) depends on the bike's mass.
9. The initial source of energy for wind power, fossil fuels, and biomass is
   (a) nuclear.
   (b) matter itself.
   (c) solar.
   (d) photovoltaic.
10. A machine cannot multiply
   (a) force.
   (b) distance.
   (c) energy.
   (d) none of these; that is, it can multiply all of them.

Answers to RAT

1. b, 2. c, 3. a, 4. b, 5. d, 6. d, 7. d, 8. b, 9. c, 10. c