

# 2

## CHAPTER TWO

# Motion



Information about the mass of a hot air balloon and forces on the balloon will enable you to predict if it is going to move up, down, or drift across the river. This chapter is about such relationships between force, mass, and changes in motion.

### O U T L I N E

Describing Motion  
 Measuring Motion  
     Speed  
     Velocity  
     Acceleration  
 Forces  
 Horizontal Motion on Land

Falling Objects  
*A Closer Look: A Bicycle Racer's Edge*  
 Compound Motion  
     Vertical Projectiles  
     Horizontal Projectiles

Laws of Motion  
 Newton's First Law of Motion  
 Newton's Second Law of Motion  
 Weight and Mass  
 Newton's Third Law of Motion

Momentum  
     Conservation of Momentum  
     Impulse  
 Forces and Circular Motion  
 Newton's Law of Gravitation  
*A Closer Look: Space Station Weightlessness*

### Physics Connections

- Mechanical work is the product of a force and the distance an object moves as a result of the force (Ch 3).
- Resonance occurs when the frequency of an applied force matches a natural frequency (Ch 5).

### Life Science Connections

- Biomechanics is the application of principles of motion to living things (Ch 20).

## Core Concept

### A net force is required for any change in a state of motion.

Inertia is the tendency of an object to remain in unchanging motion when the net force is zero (p 32).

The force of gravity uniformly accelerates falling objects (p 34).

Every object retains its state of rest or straight-line motion unless acted upon by an unbalanced force (p 37).

All objects in the universe are attracted to all other objects in the universe (p 45).

### Astronomy Connections

- Gravity pulls clouds of gas together in space to form stars (Ch 12).
- The solar system may have formed when gas, dust, and elements from a previously existing star were pulled together by gravity into a large disk (Ch 12).

### Earth Science Connections

- Earth's surface is made up of large, rigid plates that move from applied forces.

## O V E R V I E W

In chapter 1, you learned some “tools and rules” and some techniques for finding order in your surroundings. Order is often found in the form of patterns, or relationships between quantities that are expressed as equations. Equations can be used to (1) describe properties, (2) define concepts, and (3) describe how quantities change relative to one another. In all three uses, patterns are quantified, conceptualized, and used to gain a general understanding about what is happening in nature.

In the study of science, certain parts of nature are often considered and studied together for convenience. One of the more obvious groupings involves *movement*. Most objects around you appear to spend a great deal of time sitting quietly without motion. Buildings, rocks,

utility poles, and trees rarely, if ever, move from one place to another. Even things that do move from time to time sit still for a great deal of time. This includes you, automobiles, and bicycles (figure 2.1). On the other hand, the Sun, the Moon, and starry heavens always seem to move, never standing still. Why do things stand still? Why do things move?

Questions about motion have captured the attention of people for thousands of years. But the ancient people answered questions about motion with stories of mysticism and spirits that lived in objects. It was during the classic Greek culture, between 600 B.C. and 300 B.C., that people began to look beyond magic and spirits. One particular Greek philosopher, Aristotle, wrote a theory about the universe that offered

not only explanations about things such as motion but also offered a sense of beauty, order, and perfection. The theory seemed to fit with other ideas that people had and was held to be correct for nearly two thousand years after it was written. It was not until the work of Galileo and Newton during the 1600s that a new, correct understanding about motion was developed. The development of ideas about motion is an amazing and absorbing story. You will learn in this chapter how to describe and use some properties of motion. This will provide some basic understandings about motion and will be very helpful in understanding some important aspects of astronomy and the earth sciences, as well as the movement of living things.

## DESCRIBING MOTION

Motion is one of the more common events in your surroundings. You can see motion in natural events such as clouds moving, rain and snow falling, and streams of water, all moving in a never-ending cycle. Motion can also be seen in the activities of people who walk, jog, or drive various machines from place to place. Motion is so common that you would think everyone would intuitively understand the concepts of motion, but history indicates that it was only during the past three hundred years or so that people began to understand motion correctly. Perhaps the correct concepts are subtle and contrary to common sense, requiring a search for simple, clear concepts in an otherwise complex situation. The process of finding such order in a multitude of sensory impressions by taking measurable data, and then inventing a concept to describe what is happening, is the activity called *science*. We will now apply this process to motion.

What is motion? Consider a ball that you notice one morning in the middle of a lawn. Later in the afternoon, you notice that the ball is at the edge of the lawn, against a fence, and you wonder if the wind or some person moved the ball. You do not know if the wind blew it at a steady rate, if many gusts of wind moved it, or even if some children kicked it all over the yard. All you know for sure is that the ball has been moved because it is in a different position after some time passed. These are the two important aspects of motion: (1) a change of position and (2) the passage of time.

If you did happen to see the ball rolling across the lawn in the wind, you would see more than the ball at just two locations. You would see the ball moving continuously. You could consider, however, the ball in continuous motion to be a series of individual locations with very small time intervals. Moving involves a change of position during some time period. Motion is the act or process of something changing position.



**Figure 2.1**  
The motion of this windsurfer, and of other moving objects, can be described in terms of the distance covered during a certain time period.

The motion of an object is usually described with respect to something else that is considered to be not moving. (Such a stationary object is said to be “at rest.”) Imagine that you are traveling in an automobile with another person. You know that you are moving across the land outside the car since your location on the highway changes from one moment to another. Observing

your fellow passenger, however, reveals no change of position. You are in motion relative to the highway outside the car. You are not in motion relative to your fellow passenger. Your motion, and the motion of any other object or body, is the process of a change in position *relative* to some reference object or location. Thus *motion* can be defined as the act or process of changing position relative to some reference during a period of time.

## MEASURING MOTION

You have learned that objects can be described by measuring certain fundamental properties such as mass and length. Since motion involves (1) a change of position and (2) the passage of *time*, the motion of objects can be described by using combinations of the fundamental properties of length and time. Combinations of these measurements describe three properties of motion: *speed*, *velocity*, and *acceleration*.

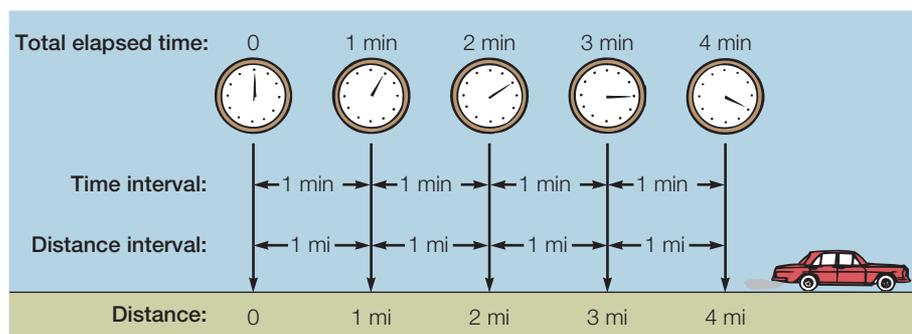
### Speed

Suppose you are in a car that is moving over a straight road. How could you describe your motion? You need at least two measurements: (1) the distance you have traveled and (2) the time that has elapsed while you covered this distance. Such a distance and time can be expressed as a ratio that describes your motion. This ratio is a property of motion called **speed**, which is a measure of how fast you are moving. Speed is defined as distance per unit of time, or

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

The units used to describe speed are usually miles/hour (mi/h), kilometers/hour (km/h), or meters/second (m/s).

Let’s go back to your car that is moving over a straight highway and imagine you are driving to cover equal distances in equal periods of time (figure 2.2). If you use a stopwatch to measure the time required to cover the distance between highway mile markers (those little signs with numbers along major highways), the time intervals will all be equal. You might find, for example, that one minute lapses between each mile marker. Such a uniform straight-line motion that covers equal distances in equal periods of time is the simplest kind of motion.



**Figure 2.2**  
This car is moving in a straight line over a distance of 1 mi each minute. Therefore, the car moves 60 mi in 60 min and has a speed of 60 mi/h.

If your car were moving over equal distances in equal periods of time, it would have a *constant speed*. This means that the car is neither speeding up nor slowing down. It is usually difficult to maintain a constant speed. Other cars and distractions such as interesting scenery cause you to reduce your speed. At other times you increase your speed. If you calculate your speed over an entire trip, you are considering a large distance between two places and the total time that elapsed. The increases and decreases in speed would be averaged. Therefore, most speed calculations are for an *average speed*. The speed at any specific instant is called the *instantaneous speed*. To calculate the instantaneous speed, you would need to consider a very short time interval—one that approaches zero. An easier way would be to use the speedometer, which shows the speed at any instant.

It is easier to study the relationships between quantities if you use symbols instead of writing out the whole word. The letter  $v$  can be used to stand for speed when dealing with straight-line motion, which is the only kind of motion that will be considered in the problems in this text. A bar over the  $v$  ( $\bar{v}$ ) is a symbol that means average (it is read “ $v$ -bar” or “ $v$ -average”). The letter  $d$  can be used to stand for distance and the letter  $t$  to stand for time. The relationship between average speed, distance, and time is therefore

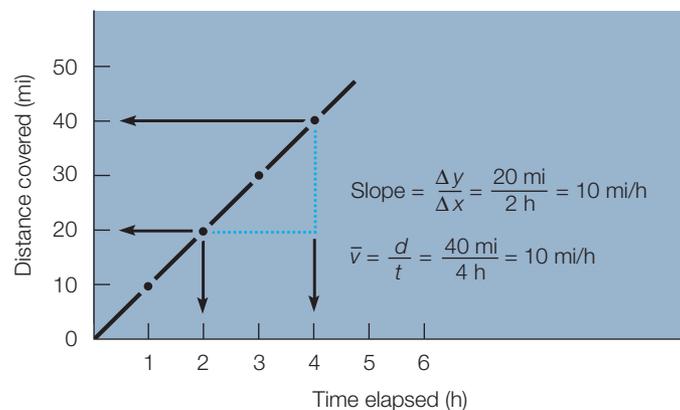
$$\bar{v} = \frac{d}{t} \quad \text{equation 2.1}$$

This is one of the three types of equations that were discussed earlier, and in this case, the equation defines a motion property (figure 2.3).

Constant, instantaneous, or average speeds can be measured with any distance and time units. Common units in the English system are miles/hour and feet/second. Metric units for speed are commonly kilometers/hour and meters/second. The ratio of any distance/time is usually read as distance per time, such as miles per hour.

## Velocity

The word *velocity* is sometimes used interchangeably with the word *speed*, but there is a difference. **Velocity** describes the *speed*



**Figure 2.3**

Speed is distance per unit of time, which can be calculated from the equation or by finding the slope of a distance-versus-time graph.

and *direction* of a moving object. For example, a speed might be described as 60 km/h. A velocity might be described as 60 km/h to the west. To produce a change in velocity, either the speed or the direction is changed (or both are changed). A satellite moving with a constant speed in a circular orbit around the Earth does not have a constant velocity since its direction of movement is constantly changing. Velocities can be represented graphically with arrows. The lengths of the arrows are proportional to the speed, and the arrowheads indicate the direction (figure 2.4).

### EXAMPLE 2.1 (Optional)

The driver of a car moving at 72.0 km/h drops a road map on the floor. It takes her 3.00 seconds to locate and pick up the map. How far did she travel during this time?

### SOLUTION

The car has a speed of 72.0 km/h and the time factor is 3.00 s, so km/h must be converted to m/s. From inside the front cover of this book, the conversion factor is 1 km/h = 0.2778 m/s, so

$$\begin{aligned} \bar{v} &= \frac{0.2778 \frac{\text{m}}{\text{s}}}{\frac{\text{km}}{\text{h}}} \times 72.0 \frac{\text{km}}{\text{h}} \\ &= (0.2778)(72.0) \frac{\text{m}}{\text{s}} \times \frac{\text{h}}{\text{km}} \times \frac{\text{km}}{\text{h}} \\ &= 20.0 \frac{\text{m}}{\text{s}} \end{aligned}$$

The relationship between the three variables,  $\bar{v}$ ,  $t$ , and  $d$ , is found in equation 2.1:  $\bar{v} = d/t$

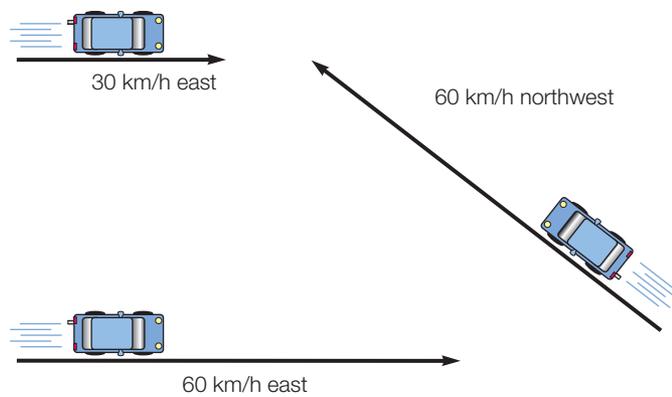
$$\begin{aligned} \bar{v} &= 20.0 \frac{\text{m}}{\text{s}} & \bar{v} &= \frac{d}{t} \\ t &= 3.00 \text{ s} & \bar{v}t &= \frac{dt}{t} \\ d &=? & d &= \bar{v}t \\ & & &= \left(20.0 \frac{\text{m}}{\text{s}}\right)(3.00 \text{ s}) \\ & & &= (20.0)(3.00) \frac{\text{m}}{\cancel{\text{s}}} \times \frac{\cancel{\text{s}}}{1} \\ & & &= \boxed{60.0 \text{ m}} \end{aligned}$$

### EXAMPLE 2.2 (optional)

A bicycle has an average speed of 8.00 km/h. How far will it travel in 10.0 seconds? (Answer: 22.2 m)

## Acceleration

Motion can be changed in three different ways: (1) by changing the speed, (2) by changing the direction of travel, or (3) by changing both the speed and direction of travel. Since velocity describes both the speed and the direction of travel, any of these three changes will result in a change of velocity. You need at least one additional measurement to describe a change of motion, which is how much time elapsed while the change was taking place. The change of velocity and time can be combined to de-


**Figure 2.4**

Velocity can be presented graphically with arrows. Here are three different velocities represented by three different arrows. The length of each arrow is proportional to the speed, and the arrowhead shows the direction of travel.

### CONCEPTS APPLIED

#### Style Speeds

Observe how many different styles of walking you can identify in students walking across the campus. Identify each style with a descriptive word or phrase.

Is there any relationship between any particular style of walking and the speed of walking? You could find the speed of walking by measuring a distance, such as the distance between two trees, then measuring the time required for a student to walk the distance. Find the average speed for each identified style of walking by averaging the walking speeds of ten people.

Report any relationships you find between styles of walking and the average speed of people with each style. Include any problems you found in measuring, collecting data, and reaching conclusions.

### CONCEPTS APPLIED

#### How Fast Is a Stream?

A stream is a moving body of water. How could you measure the speed of a stream? Would timing how long it takes a floating leaf to move a measured distance help?

What kind of relationship, if any, would you predict for the speed of a stream and a recent rainfall? Would you predict a direct relationship? Make some measurements of stream speeds and compare your findings to recent rainfall amounts.

fine the *rate* at which the motion was changed. This rate is called **acceleration**. Acceleration is defined as a change of velocity per unit time, or

$$\text{acceleration} = \frac{\text{change of velocity}}{\text{time elapsed}}$$

Another way of saying “change in velocity” is the final velocity minus the initial velocity, so the relationship can also be written as

$$\text{acceleration} = \frac{\text{final velocity} - \text{initial velocity}}{\text{time elapsed}}$$

Acceleration due to a change in speed only can be calculated as follows. Consider a car that is moving with a constant, straight-line velocity of 60 km/h when the driver accelerates to 80 km/h. Suppose it takes 4 s to increase the velocity of 60 km/h to 80 km/h. The change in velocity is therefore 80 km/h minus 60 km/h, or 20 km/h. The acceleration was

$$\begin{aligned} \text{acceleration} &= \frac{80 \frac{\text{km}}{\text{h}} - 60 \frac{\text{km}}{\text{h}}}{4\text{s}} \\ &= \frac{20 \frac{\text{km}}{\text{h}}}{4\text{s}} \\ &= 5 \frac{\text{km/h}}{\text{s}} \text{ or,} \\ &= 5 \text{ km/h/s} \end{aligned}$$

The average acceleration of the car was 5 km/h for each (“per”)second. This is another way of saying that the velocity increases an average of 5 km/h in each second. The velocity of the car was 60 km/h when the acceleration began (initial velocity). At the end of 1 s, the velocity was 65 km/h. At the end of 2 s, it was 70 km/h; at the end of 3 s, 75 km/h; and at the end of 4 s (total time elapsed), the velocity was 80 km/h (final velocity). Note how fast the velocity is changing with time. In summary,

start (initial velocity)	60 km/h
end of first second	65 km/h
end of second second	70 km/h
end of third second	75 km/h
end of fourth second (final velocity)	80 km/h

As you can see, acceleration is really a description of how fast the speed is changing (figure 2.5); in this case, it is increasing 5 km/h each second.

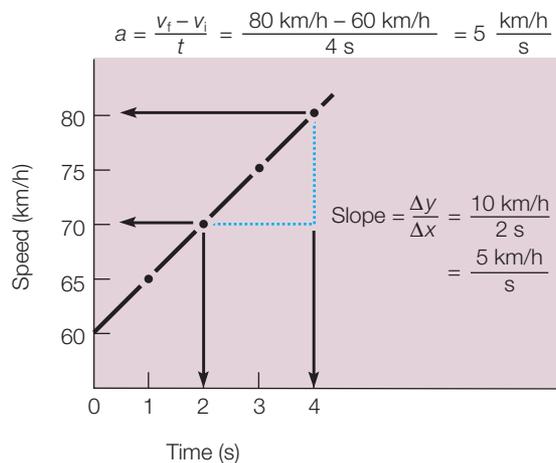
Usually, you would want all the units to be the same, so you would convert km/h to m/s. A change in velocity of 5.0 km/h converts to 1.4 m/s and the acceleration would be 1.4 m/s/s. The units m/s per s mean what change of velocity (1.4 m/s) is occurring every second. The combination m/s/s is rather cumbersome, so it is typically treated mathematically to simplify the expression (to simplify a fraction, invert the divisor and multiply, or  $\text{m/s} \times 1/\text{s} = \text{m/s}^2$ ). Remember that the expression 1.4 m/s<sup>2</sup> means the same as 1.4 m/s per s, a change of velocity in a given time period.

The relationship among the quantities involved in acceleration can be represented with the symbols  $a$  for average acceleration,  $v_f$  for final velocity,  $v_i$  for initial velocity, and  $t$  for time. The relationship is

$$a = \frac{v_f - v_i}{t}$$

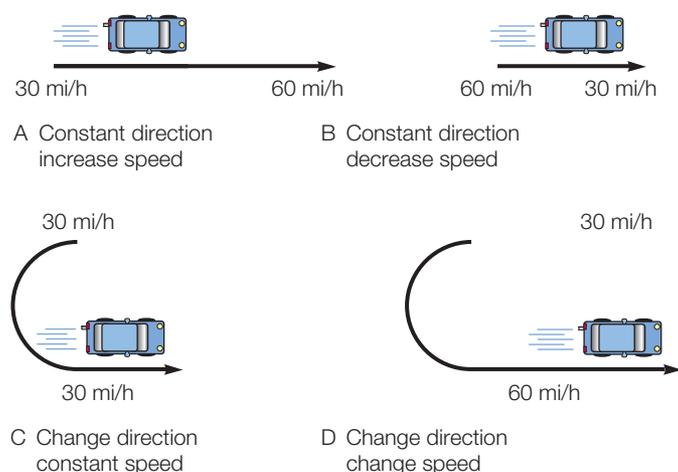
**equation 2.2**

There are also other changes in the motion of an object that are associated with acceleration. One of the more obvious is a change that results in a decreased velocity. Your car’s brakes,



**Figure 2.5**

This graph shows the speed increasing from 60 km/h to 80 km/h when moving in a straight line for 4 s. The acceleration, or change of velocity per unit of time, can be calculated either from the equation for acceleration or by calculating the slope of the straight-line graph. Both will tell you how fast the motion is changing with time.



**Figure 2.6**

Four different ways (A–D) to accelerate a car.

for example, can slow your car or bring it to a complete stop. This is *negative acceleration*, which is sometimes called *deceleration*. Another change in the motion of an object is a change of direction. Velocity encompasses both the rate of motion as well as direction, so a change of direction is an acceleration. The satellite moving with a constant speed in a circular orbit around the Earth is constantly changing its direction of movement. It is therefore constantly accelerating because of this constant change in its motion. Your automobile has three devices that could change the state of its motion. Your automobile therefore has three accelerators—the gas pedal (which can increase magnitude of velocity), the brakes (which can decrease magnitude of velocity), and the steering wheel (which can change direction of velocity). (See figure 2.6.) The important thing to remember is that acceleration results from any *change* in the motion of an object.

## Connections . . .



### Travel

The super-speed magnetic levitation (maglev) train is a completely new technology based on magnetically suspending a train 3 to 10 cm (about 1 to 4 in) above a monorail, then moving it along with a magnetic field that travels along the monorail guides. The maglev train does not have friction between wheels and the rails since it does not have wheels. This lack of resistance and the easily manipulated magnetic fields makes very short acceleration distances possible. For example, a German maglev train can accelerate from 0 to 300 km/h (about 185 mi/h) over a distance of just 5 km (about 3 mi). A conventional train with wheels requires about 30 km (about 19 mi) in order to reach the same speed from a standing start. The maglev is attractive for short runs because of its superior acceleration. It is also attractive for longer runs because of its high top speed—up to about 500 km/h (about 310 mi/h). Today, only an aircraft can match such a speed.

### CONCEPTS APPLIED

#### Acceleration Patterns

Suppose the radiator in your car has a leak and drops of coolant fall constantly, one every second. What pattern would the drops make on the pavement when you accelerate the car from a stoplight? What pattern would they make when you drive a constant speed? What pattern would you observe as the car comes to a stop? Use a marker to make dots on a sheet of paper that illustrate (1) acceleration, (2) constant speed, and (3) negative acceleration. Use words to describe the acceleration in each situation.

#### EXAMPLE 2.3 (Optional)

A bicycle moves from rest to 5 m/s in 5 s. What was the acceleration?

#### SOLUTION

$$\begin{aligned} v_i &= 0 \text{ m/s} \\ v_f &= 5 \text{ m/s} \\ t &= 5 \text{ s} \\ a &= ? \end{aligned} \qquad \begin{aligned} a &= \frac{v_f - v_i}{t} \\ &= \frac{5 \text{ m/s} - 0 \text{ m/s}}{5 \text{ s}} \\ &= \frac{5}{5} \frac{\text{m/s}}{\text{s}} \\ &= 1 \frac{\text{m}}{\text{s}} \times \frac{1}{\text{s}} \\ &= \boxed{1 \frac{\text{m}}{\text{s}^2}} \end{aligned}$$

#### EXAMPLE 2.4 (Optional)

An automobile uniformly accelerates from rest at 15 ft/s<sup>2</sup> for 6 s. What is the final velocity in ft/s? (Answer: 90 ft/s)

## FORCES

The Greek philosopher Aristotle considered some of the first ideas about the causes of motion back in the fourth century B.C. However, he had it all wrong when he reportedly stated that a dropped object falls at a constant speed that is determined by its weight. He also incorrectly thought that an object moving across Earth's surface requires a continuously applied force to continue moving. These ideas were based on observing and thinking, not measurement, and no one checked to see if they were correct. It took about two thousand years before people began to correctly understand motion.

Aristotle did recognize an association between force and motion, and this much was acceptable. It is partly correct because a force is closely associated with *any* change of motion, as you will see. This section introduces the concept of a force, which will be developed more fully when the relationship between forces and motion is considered later.

A **force** is a push or a pull that is capable of changing the state of motion of an object. Consider, for example, the movement of a ship from the pushing of two tugboats (figure 2.7). Tugboats can vary the strength of the force exerted on a ship, but they can also push in different directions. What effect does direction have on two forces acting on an object? If the tugboats were side by side, pushing in the same direction, the overall force is the sum of the two forces. If they act in exactly opposite directions, one pushing on each side of the ship, the overall force is the difference between the strength of the two forces. If they have the same strength, the overall effect is to cancel each other without producing any motion. The **net force** is the sum of all the forces acting on an object. Net force means “final,” after the forces are added (figure 2.8).

When two parallel forces act in the same direction, they can be simply added. In this case, there is a net force that is equivalent to the sum of the two forces. When two parallel forces act in opposite directions, the net force is the difference between the two forces and is in the direction of the larger force. When two forces act neither in a way that is exactly together nor exactly opposite each other, the result will be like a new, different force having a new direction and strength.

Forces have a strength and direction that can be represented by force arrows. The tail of the arrow is placed on the object that feels the force, and the arrowhead points in the direction in which the force is exerted. The length of the arrow is proportional to the strength of the force. The use of force arrows helps you visualize and understand all the forces and how they contribute to the net force.

There are four **fundamental forces** that *cannot* be explained in terms of any other force. They are gravitational, electromagnetic, weak, and the strong nuclear force. Gravitational forces act between all objects in the universe—between you and Earth, between Earth and the Sun, between the planets in the solar systems and, in fact, hold stars in large groups called galaxies. Switching scales from the very large galaxy to inside an atom, we find electromagnetic forces acting between electrically charged parts of atoms, such as electrons and protons. Electromagnetic forces are responsible for the structure of atoms, chemical

## Connections . . .



### Weather

Classification schemes are imaginative mental constructions used to show similarities and differences in objects or events. For example, the following describes two schemes used to help us classify storms that are not associated with weather fronts.

What is the difference between a tropical depression, tropical storm, and a hurricane? They are classified according to the *speed* of the maximum sustained surface winds. In the United States, the maximum sustained surface wind is measured by averaging the wind speed over a 1-minute period. Here is the classification scheme:

**Tropical Depression.** This is a center of low pressure around which the winds are generally moving 55 km/h (about 35 mi/h) or less. The tropical depression might dissolve into nothing, or it might develop into a more intense disturbance.

**Tropical Storm.** This is a more intense, highly organized center of low pressure with winds between 56 and 120 km/h (about 35 to 75 mi/h).

**Hurricane.** This is an intense low-pressure center with winds greater than 120 km/h (about 75 mi/h). A strong storm of this type is called a “hurricane” if it occurs over the Atlantic Ocean or the Pacific Ocean east of the international date line. It is called a “typhoon” if it occurs over the North Pacific Ocean west of the international date line. Hurricanes are further classified according to category and damage to be expected. Here is the classification scheme:

Category	Damage	Winds
1	minimal	120–153 km/h (75–95 mi/h)
2	moderate	154–177 km/h (96–110 mi/h)
3	extensive	178–210 km/h (111–130 mi/h)
4	extreme	211–250 km/h (131–155 mi/h)
5	catastrophic	>250 km/h (>155 mi/h)

change, and electricity and magnetism. Weak and strong forces act inside the nucleus of an atom, so they are not as easily observed at work as are gravitational and electromagnetic forces. The weak force is involved in certain nuclear reactions. The strong nuclear force is involved in close-range holding of the nucleus together. In general, the strong nuclear force between particles inside a nucleus is about  $10^2$  times stronger than the electromagnetic force and about  $10^{39}$  times stronger than the gravitational force. The fundamental forces are responsible for everything that happens in the universe, and we will learn more about them in chapters on electricity, light, nuclear energy, chemistry, geology, and astronomy.

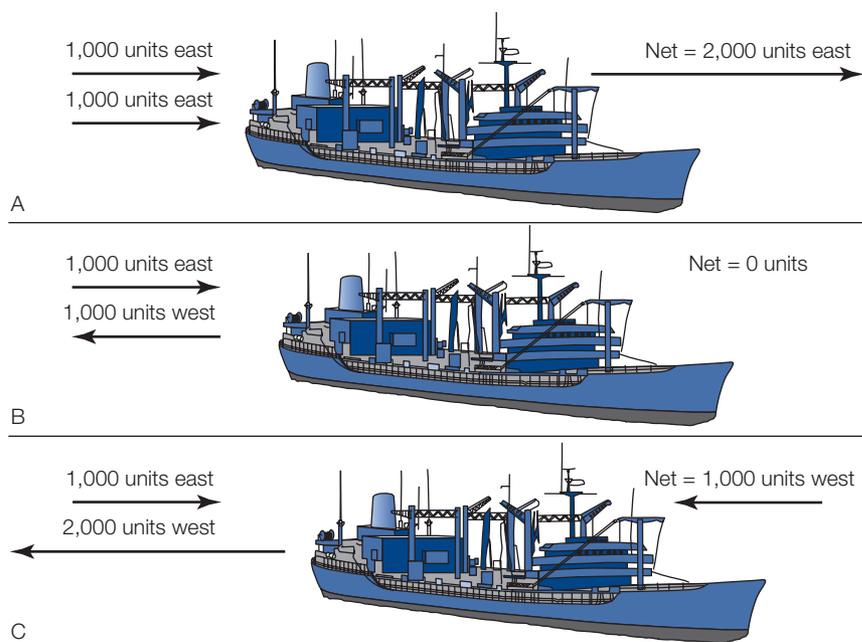
## HORIZONTAL MOTION ON LAND

Everyday experience seems to indicate that Aristotle's idea about horizontal motion on the Earth's surface is correct. After all, moving objects that are not pushed or pulled do come to rest in



**Figure 2.7**

The rate of movement and the direction of movement of this ship are determined by a combination of direction and size of force from each of the tugboats. Which direction are the two tugboats pushing? What evidence would indicate that one tugboat is pushing with a greater force? If the tugboat by the numbers is pushing with a greater force and the back tugboat is keeping the back of the ship from moving, what will happen?



**Figure 2.8**

(A) When two parallel forces are acting on the ship in the same direction, the net force is the two forces added together. (B) When two forces are opposite and of equal size, the net force is zero. (C) When two parallel forces are not of equal size, the net force is the difference in the direction of the larger force.

a short period of time. It would seem that an object keeps moving only if a force continues to push it. A moving automobile will slow and come to rest if you turn off the ignition. Likewise, a ball that you roll along the floor will slow until it comes to rest. Is the natural state of an object to be at rest, and is a force necessary to keep an object in motion? This is exactly what people thought until Galileo (figure 2.9) published his book *Two New Sciences* in 1638, which described his findings about motion.

The book had three parts that dealt with uniform motion, accelerated motion, and projectile motion. Galileo described details of simple experiments, measurements, calculations, and thought experiments as he developed definitions and concepts of motion. In one of his thought experiments, Galileo presented an argument against Aristotle's view that a force is needed to keep an object in motion. Galileo imagined an object (such as a ball) moving over a horizontal surface without the force of friction. He concluded that the object would move forever with a constant velocity as long as there was no unbalanced force acting to change the motion.

Why does a rolling ball slow to a stop? You know that a ball will roll farther across a smooth, waxed floor such as a bowling lane than it will across floor covered with carpet. The rough car-

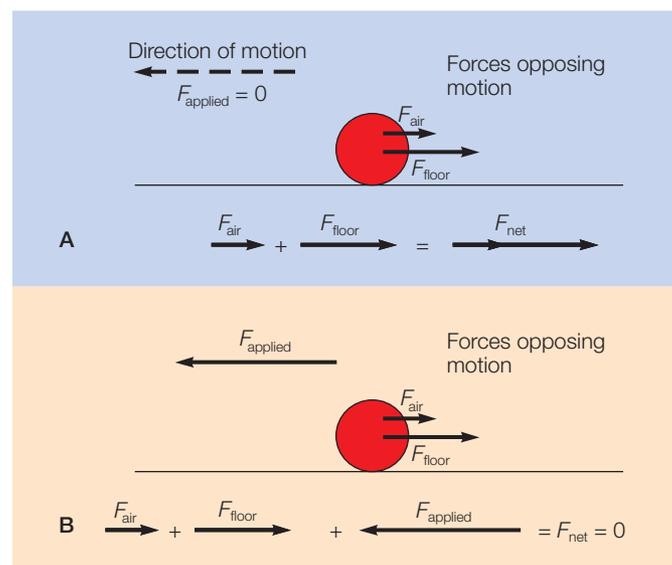


**Figure 2.9**

Galileo (left) challenged the Aristotelian view of motion and focused attention on the concepts of distance, time, velocity, and acceleration.

pet offers more resistance to the rolling ball. The resistance of the floor friction is shown by a force arrow,  $F_{\text{floor}}$ , in figure 2.10. This force, along with the force arrow for air resistance,  $F_{\text{air}}$ , oppose the forward movement of the ball. Notice the dashed line arrow in part A of figure 2.10. There is no other force applied to the ball, so the rolling speed decreases until the ball finally comes to a complete stop. Now imagine what force you would need to exert by pushing with your hand, moving along with the ball to keep it rolling at a uniform rate. An examination of the forces in part B of figure 2.10 can help you determine the amount of force. The force you apply,  $F_{\text{applied}}$ , must counteract the resistance forces. It opposes the forces that are slowing down the ball as illustrated by the direction of the arrows. To determine how much force you should apply, look at the arrow equation.  $F_{\text{applied}}$  has the same length as the sum of the two resistance forces, but it is in the opposite direction of the resistance forces. Therefore, the overall force,  $F_{\text{net}}$ , is zero. The ball continues to roll at a uniform rate when you *balance* the force opposing its motion. It is reasonable, then, that if there were no opposing forces, you would not need to apply a force to keep it rolling. This was the kind of reasoning that Galileo did when he discredited the Aristotelian view that a force was necessary to keep an object moving. Galileo concluded that a moving object would continue moving with a constant velocity if no unbalanced forces were applied; that is, if the net force were zero.

It could be argued that the difference in Aristotle's and Galileo's views of forced motion is really a degree of analysis. After all, moving objects on the Earth do come to rest unless continuously pushed or pulled. But Galileo's conclusion describes *why* they must be pushed or pulled and reveals the true nature



**Figure 2.10**

(A) This ball is rolling to your left with no forces in the direction of motion. The sum of the force of floor friction ( $F_{\text{floor}}$ ) and the force of air friction ( $F_{\text{air}}$ ) results in a net force opposing the motion, so the ball slows to a stop. (B) A force is applied to the moving ball, perhaps by a hand that moves along with the ball. The force applied ( $F_{\text{applied}}$ ) equals the sum of the forces opposing the motion, so the ball continues to move with a constant velocity.

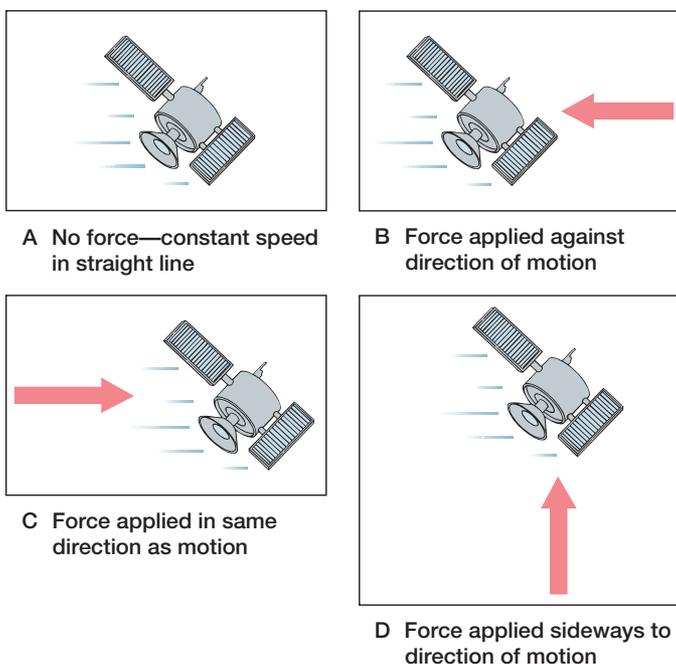
of the motion of objects. Aristotle argued that the natural state of objects is to be at rest and attempted to explain why objects move. Galileo, on the other hand, argued that it is just as natural for an object to be moving and attempted to explain why they come to rest. The behavior of matter to persist in its state of motion is called **inertia**. Inertia is the *tendency of an object to remain in unchanging motion whether actually moving or at rest, when the net force is zero*. The development of this concept changed the way people viewed the natural state of an object and opened the way for further understandings about motion. Today, it is understood that a satellite moving through free space will continue to do so with no unbalanced forces acting on it (figure 2.11A). An unbalanced force is needed to slow the satellite (figure 2.11B), increase its speed (figure 2.11C), or change its direction of travel (figure 2.11D).

### MYTHS, MISTAKES, AND MISUNDERSTANDINGS Walk or Run in Rain?

Is it a mistake to run in rain if you want to stay drier? One idea is that you should run because you spend less time in the rain so you will stay drier. On the other hand, this is true only if the rain lands only on the top of your head and shoulders. If you run, you will end up running into more raindrops on the larger surface area of your face, chest, and front of your legs.

Two North Carolina researchers looked into this question with one walking and the other running over a measured distance while wearing cotton sweatsuits. They then weighed their clothing and found that the walking person's sweatsuit weighed more. This means you should run to stay drier.

You can check this result by using the online calculator at [www.dctech.com/physics/features/physics\\_0600a.html](http://www.dctech.com/physics/features/physics_0600a.html).



**Figure 2.11**

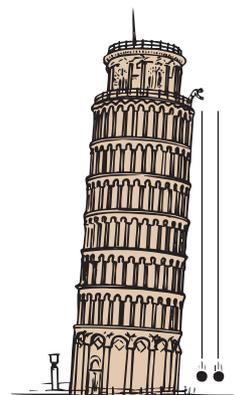
Explain how the combination of drawings (A–D) illustrates inertia.

## FALLING OBJECTS

Did you ever wonder what happens to a falling rock during its fall? Aristotle reportedly thought that a rock falls at a uniform speed that is proportional to its weight. Thus, a heavy rock would fall at a faster uniform speed than a lighter rock. As stated in a popular story, Galileo discredited Aristotle's conclusion by dropping a solid iron ball and a solid wooden ball simultaneously from the top of the Leaning Tower of Pisa (figure 2.12). Both balls, according to the story, hit the ground nearly at the same time. To do this, they would have to fall with the same velocity. In other words, the velocity of a falling object does not depend on its weight. Any difference in freely falling bodies is explainable by air resistance. Soon after the time of Galileo, the air pump was invented. The air pump could be used to remove the air from a glass tube. The effect of air resistance on falling objects could then be demonstrated by comparing how objects fall in the air with how they fall in an evacuated glass tube. You know that a coin falls faster than a feather when they are dropped together in the air. A feather and heavy coin will fall together in the near vacuum of an evacuated glass tube because the effect of air resistance on the feather has been removed. When objects fall toward Earth without considering air resistance, they are said to be in **free fall**. Free fall considers only gravity and neglects air resistance.

Galileo concluded that light and heavy objects fall together in free fall, but he also wanted to know the details of what was going on while they fell. He now knew that the velocity of an object in free fall was *not* proportional to the weight of the object. He observed that the velocity of an object in free fall *increased* as the object fell and reasoned from this that the velocity of the falling object would have to be (1) somehow proportional to the *time* of fall and (2) somehow proportional to the *distance* the object fell. If the time and distance were both related to the velocity of a falling object at a given time and distance, how were they related to one another?

Galileo reasoned that a freely falling object should cover a distance *proportional to the square of the time of the fall* ( $d \propto t^2$ ).



**Figure 2.12**

According to a widespread story, Galileo dropped two objects with different weights from the Leaning Tower of Pisa. They reportedly hit the ground at about the same time, discrediting Aristotle's view that the speed during the fall is proportional to weight.

## A Closer Look A Bicycle Racer's Edge



Galileo was one of the first to recognize the role of friction in opposing motion. As shown in figure 2.10, friction with the surface and air friction combine to produce a net force that works against anything that is moving on the surface. This article is about air friction and some techniques that bike riders use to reduce that opposing force—perhaps giving them an edge in a close race.

The bike riders in box figure 2.1 are forming a single-file line, called a *paceline*, because the slipstream reduces the air resistance for a closely trailing rider. Cyclists say that riding in the slipstream of another cyclist will save much of their energy. In fact, the cyclists will be able to move 5 mi/h faster than they would expending the same energy while riding alone.

In a sense, riding in a slipstream means that you do not have to push as much air out of your way. It has been estimated that at 20 mi/h a cyclist must move a little less than half a ton of air out of the way every minute. One of the earliest demonstrations of how a slipstream can help a cyclist was done back about the turn of the century. Charles Murphy had a special bicycle trail built down the middle of a railroad track. Riding very close behind a special train caboose, Murphy was able to reach a speed of over 60



### Box Figure 2.1

**The object of the race is to be in the front, to finish first. If this is true, why are these racers forming a single-file line?**

mi/h for a one-mile course. More recently, cyclists have reached over 125 mi/h by following close in the slipstream of a race car.

Along with the problem of moving about a half-ton of air out of the way every minute, there are two basic factors related to air resistance. These are (1) a turbulent versus a smooth flow of air and (2) the problem of frictional drag. A turbulent flow of air contributes to air resistance because it causes the air to separate slightly on the back side, which increases the pressure on the front of the moving object. This is why

racing cars, airplanes, boats, and other racing vehicles are streamlined to a teardrop-like shape. This shape is not as likely to have the lower-pressure-producing air turbulence behind (and resulting greater pressure in front) because it smooths or streamlines the air flow.

The frictional drag of air is similar to the frictional drag that occurs when you push a book across a rough tabletop. You know that smoothing the rough tabletop will reduce the frictional drag on the book. Likewise, the smoothing of a surface exposed to moving air will reduce air friction. Cyclists accomplish this “smoothing” by wearing smooth spandex clothing and by shaving hair from arm and leg surfaces that are exposed to moving air. Each hair contributes to the overall frictional drag, and removal of the arm and leg hair can thus result in seconds saved. This might provide enough of an edge to win a close race. Shaving legs and arms, together with the wearing of spandex or some other tight, smooth-fitting garments, are just a few of the things a cyclist can do to gain an edge. Perhaps you will be able to think of more ways to reduce the forces that oppose motion.

## Connections . . .

### Sports

There are two different meanings for the term *free fall*. In physics, free fall means the unconstrained motion of a body in a gravitational field, without considering air resistance. Without air resistance, all objects are assumed to accelerate toward the surface at  $9.8 \text{ m/s}^2$ .

In the sport of skydiving, free fall means falling within the atmosphere without a drag-producing device such as a parachute. Air provides a resisting force that opposes the motion of a falling object, and the net force is the difference between the downward force (weight) and the upward force of air resistance. The weight of the falling object depends on the mass and acceleration from gravity, and this is the force downward. The resisting force is determined by at least two variables: (1) the area of the object exposed to the airstream and (2) the speed of the falling object. Other variables such as streamlining, air temperature, and turbulence play a role, but the greatest effect seems to be from exposed area and the increased resistance as speed increases.

A skydiver's weight is constant, so the downward force is constant. Modern skydivers typically free-fall from about 3,650 m (about 12,000 ft) above the ground until about 750 m (about 2,500 ft), where they open their parachutes. After jumping from the plane, the diver at first accelerates toward the surface, reaching speeds up to about 185–210 km/h (about 115–130 mi/h). The air resistance increases with increased speed and the net force becomes less and less. Eventually, the downward weight force will be balanced by the upward air resistance force, and the net force becomes zero. The person now falls at a constant speed, and we say the terminal velocity has been reached. It is possible to change your body position to vary your rate of fall up or down by 32 km/h (about 20 mi/h). However, by diving or “standing up” in free fall, experienced skydivers can reach speeds of up to 290 km/h (about 180 mi/h). The record free fall speed, done without any special equipment, is 517 km/h (about 321 mi/h). Once the parachute opens, a descent rate of about 16 km/h (about 10 mi/h) is typical.



## CONCEPTS APPLIED

### Falling Bodies

Galileo concluded that all objects fall together, with the same acceleration, when the upward force of air resistance is removed. It would be most difficult to remove air from the room, but it is possible to do some experiments that provide some evidence of how air influences falling objects.

1. Take a sheet of paper and your textbook and drop them side by side from the same height. Note the result.
2. Place the sheet of paper on top of the book and drop them at the same time. Do they fall together?
3. Crumple the sheet of paper into a loose ball and drop the ball and book side by side from the same height.
4. Crumple a sheet of paper into a very tight ball and again drop the ball and book side by side from the same height.

Explain any evidence you found concerning how objects fall.

In other words, the object should fall 4 times as far in 2 s as in 1 s ( $2^2 = 4$ ), 9 times as far in 3 s ( $3^2 = 9$ ), and so on. Galileo checked this calculation by rolling balls on an inclined board with a smooth groove in it. He used the inclined board to slow the motion of descent in order to measure the distance and time relationships, a necessary requirement since he lacked the accurate timing devices that exist today. He found, as predicted, that the falling balls moved through a distance proportional to the square of the time of falling. This also means that the *velocity of the falling object increased at a constant rate*. Recall that a change of velocity during some time period is called *acceleration*. In other words, a falling object *accelerates* toward the surface of Earth.

Since the velocity of a falling object increases at a constant rate, this must mean that falling objects are *uniformly accelerated* by the force of gravity. *All objects in free fall experience a constant acceleration*. During each second of fall, the object on Earth gains 9.8 m/s (32 ft/s) in velocity. This gain is the acceleration of the falling object,  $9.8 \text{ m/s}^2$  (32 ft/s<sup>2</sup>).

The acceleration of objects falling toward Earth varies slightly from place to place on Earth's surface because of Earth's shape and spin. The acceleration of falling objects decreases from the poles to the equator and also varies from place to place because Earth's mass is not distributed equally. The value of  $9.8 \text{ m/s}^2$  (32 ft/s<sup>2</sup>) is an approximation that is fairly close to, but not exactly, the acceleration due to gravity in any particular location. The acceleration due to gravity is important in a number of situations, so the acceleration from this force is given a special symbol, **g**.

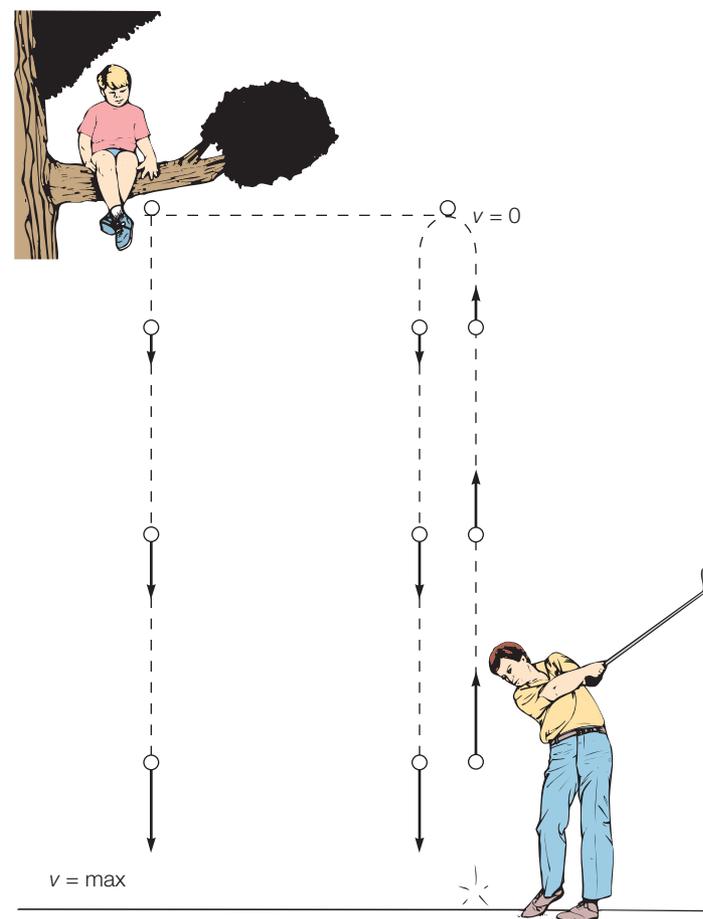
## COMPOUND MOTION

So far we have considered two types of motion: (1) the horizontal, straight-line motion of objects moving on the surface of Earth and (2) the vertical motion of dropped objects that accelerate toward the surface of Earth. A third type of motion occurs when an object is thrown, or projected, into the air. Essentially, such a projectile (rock, football, bullet, golf ball, or whatever)

could be directed straight upward as a vertical projection, directed straight out as a horizontal projection, or directed at some angle between the vertical and the horizontal. Basic to understanding such compound motion is the observation that (1) gravity acts on objects *at all times*, no matter where they are, and (2) the acceleration due to gravity (**g**) is *independent of any motion* that an object may have.

## Vertical Projectiles

Consider first a ball that you throw straight upward, a vertical projection. The ball has an initial velocity but then reaches a maximum height, stops for an instant, then accelerates back toward Earth. Gravity is acting on the ball throughout its climb, stop, and fall. As it is climbing, the force of gravity is continually reducing its velocity. The overall effect during the climb is deceleration, which continues to slow the ball until the instantaneous stop. The ball then accelerates back to the surface just like a ball that has been dropped. If it were not for air resistance, the ball would return with the same velocity that it had initially. The velocity arrows for a ball thrown straight up are shown in figure 2.13.



**Figure 2.13**

On its way up, a vertical projectile such as this misdirected golf ball is slowed by the force of gravity until an instantaneous stop; then it accelerates back to the surface, just as another golf ball does when dropped from the same height. The straight up- and down-moving golf ball has been moved to the side in the sketch so we can see more clearly what is happening.

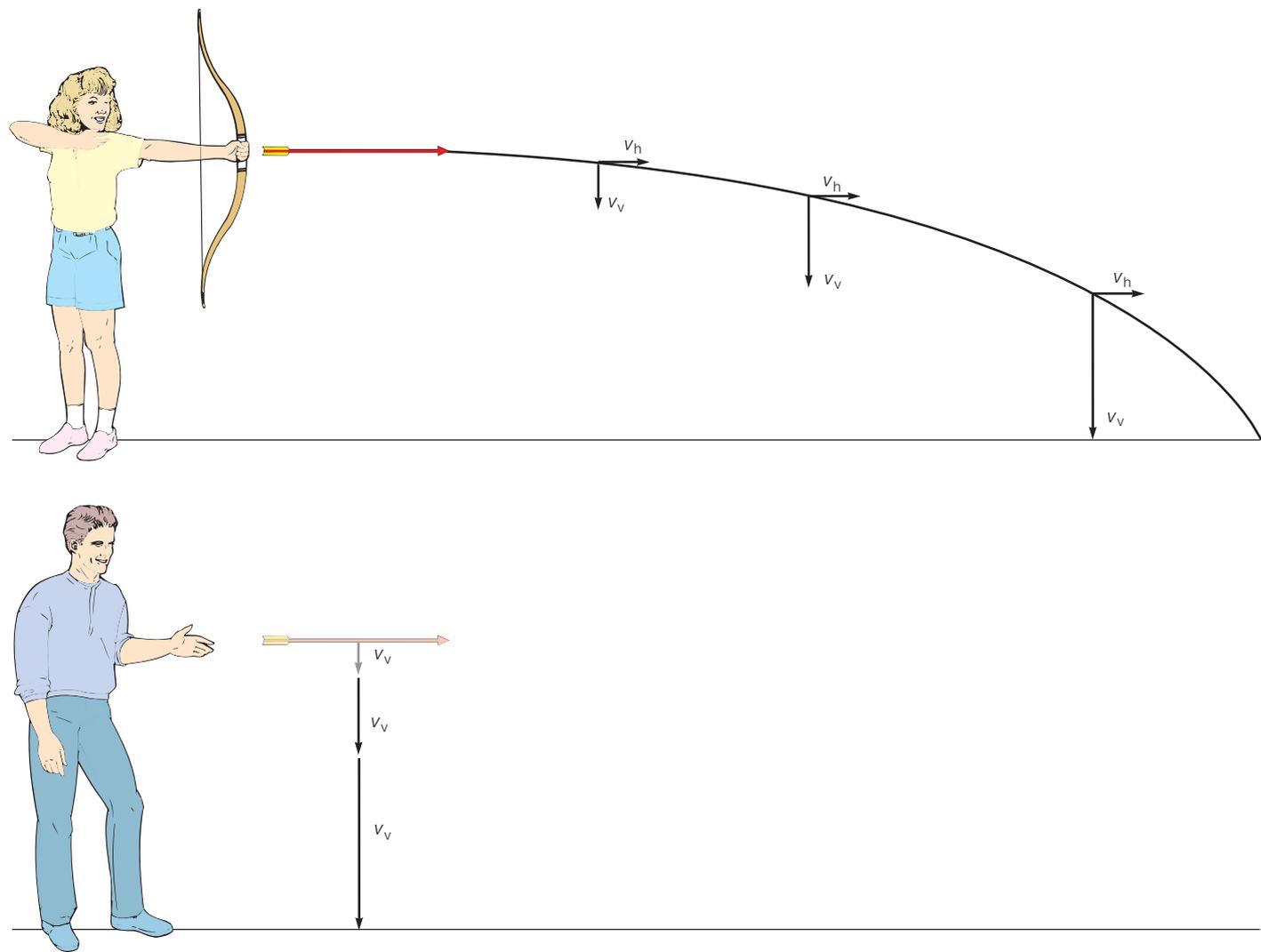
## Horizontal Projectiles

Horizontal projectiles are easier to understand if you split the complete motion into vertical and horizontal parts. Consider, for example, an arrow shot horizontally from a bow. The force of gravity accelerates the arrow downward, giving it an increasing downward velocity as it moves through the air. This increasing downward velocity is shown in figure 2.14 as increasingly longer velocity arrows ( $v_v$ ). There are no forces in the horizontal direction if you can ignore air resistance, so the horizontal velocity of the arrow remains the same as shown by the  $v_h$  velocity arrows. The combination of the increasing vertical ( $v_v$ ) motion and the unchanging horizontal ( $v_h$ ) motion causes the arrow to follow a curved path until it hits the ground.

An interesting prediction that can be made from the shot arrow analysis is that an arrow shot horizontally from a bow will hit the ground at the same time as a second arrow that is simply dropped from the same height (figure 2.14). Would this be true

of a bullet dropped at the same time as one fired horizontally from a rifle? The answer is yes; both bullets would hit the ground at the same time. Indeed, without air resistance, all the bullets and arrows should hit the ground at the same time if dropped or shot from the same height.

Golf balls, footballs, and baseballs are usually projected upward at some angle to the horizon. The horizontal motion of these projectiles is constant as before because there are no horizontal forces involved. The vertical motion is the same as that of a ball projected directly upward. The combination of these two motions causes the projectile to follow a curved path called a *parabola*, as shown in figure 2.15. The next time you have the opportunity, observe the path of a ball that has been projected at some angle (figure 2.16). Note that the second half of the path is almost a reverse copy of the first half. If it were not for air resistance, the two values of the path would be exactly the same. Also note the distance that the ball travels as compared to the angle of projection. An angle of projection of  $45^\circ$  results in the maximum distance of travel.



**Figure 2.14**

A horizontal projectile has the same horizontal velocity throughout the fall as it accelerates toward the surface, with the combined effect resulting in a curved path. Neglecting air resistance, an arrow shot horizontally will strike the ground at the same time as one dropped from the same height above the ground, as shown here by the increasing vertical velocity arrows.

# Science and Society Transportation and the Environment



Environmental science is an interdisciplinary study of Earth's environment. The concern of this study is the overall problem of human degradation of the environment and remedies for that damage. As an example of an environmental topic of study, consider the damage that results from current human activities involving the use of transportation. Researchers estimate that overall transportation activities are responsible for about one-third of the total U.S. carbon emissions that are added to the air every day. Carbon emissions are a problem because they are directly harmful in the form of carbon monoxide. They are also indirectly harmful because of the contribution of carbon dioxide to possible global warming and the consequences of climate change.

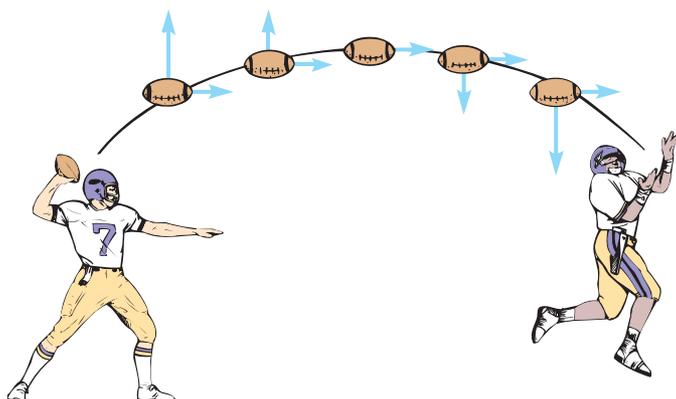
Here is a list of things that people might do to reduce the amount of environmental damage from transportation:

- A.** Use a bike, carpool, walk, or take public transportation wherever possible.
- B.** Plan to combine trips to the store, mall, and work, leaving the car parked whenever possible.
- C.** Purchase hybrid electric or fuel cell-powered cars and vehicles whenever possible.
- D.** Move to a planned community that makes the use of cars less necessary and less desirable.

## Questions to Discuss

Discuss with your group the following questions concerning connections between thought and feeling:

1. What are your positive or negative feelings associated with each item in the list?
2. Would you feel differently if you had a better understanding of the global problem?
3. Do your feelings mean that you have reached a conclusion?
4. What new items could be added to the list?



**Figure 2.15**

A football is thrown at some angle to the horizon when it is passed downfield. Neglecting air resistance, the horizontal velocity is a constant, and the vertical velocity decreases, then increases, just as in the case of a vertical projectile. The combined motion produces a parabolic path. Contrary to statements by sportscasters about the abilities of certain professional quarterbacks, it is impossible to throw a football with a “flat trajectory” because it begins to accelerate toward the surface as soon as it leaves the quarterback’s hand.

## LAWS OF MOTION

Isaac Newton (1643–1727) was a quiet farm boy who seemed more interested in mathematics and tinkering than farming. He entered Trinity College of Cambridge University at the age of eighteen, where he enrolled in mathematics. He graduated four years later, the same year that the university was closed because the bubonic plague, or Black Death, was ravaging Europe. During this time, Newton returned to his boyhood home, where he thought out most of the ideas that would later make him famous. Here, between the ages of twenty-three and twenty-four, he invented the field of mathematics called *calculus* and clarified his ideas on motion and gravitation. After the plague, he



**Figure 2.16**

Without a doubt, this baseball player is aware of the relationship between the projection angle and the maximum distance acquired for a given projection velocity.

returned to Cambridge, where he was appointed professor of mathematics at the age of twenty-six. He lectured and presented papers on optics. One paper on his theory about light and colors caused such a controversy that Newton resolved never to publish another line. Newton was a shy, introspective person who was too absorbed in his work for such controversy. In 1684, Edmund Halley (of Halley's comet fame) asked Newton to resolve a dispute involving planetary motions. Newton had already worked out the solution to this problem, in addition to other problems on gravity and motion. Halley persuaded the reluctant Newton to publish the material. Two years later, in 1687, Newton published *Principia*, which was paid for by Halley. Although he feared controversy, the book was accepted almost at once and established Newton as one of the greatest thinkers who ever lived.

Newton built his theory of motion on the previous work of Galileo and others. In fact, Newton's first law is similar to the concept of inertia described earlier by Galileo. Newton acknowledged the contribution of Galileo and others to his work, stating that if he had seen further than others "it was by standing upon the shoulders of giants."

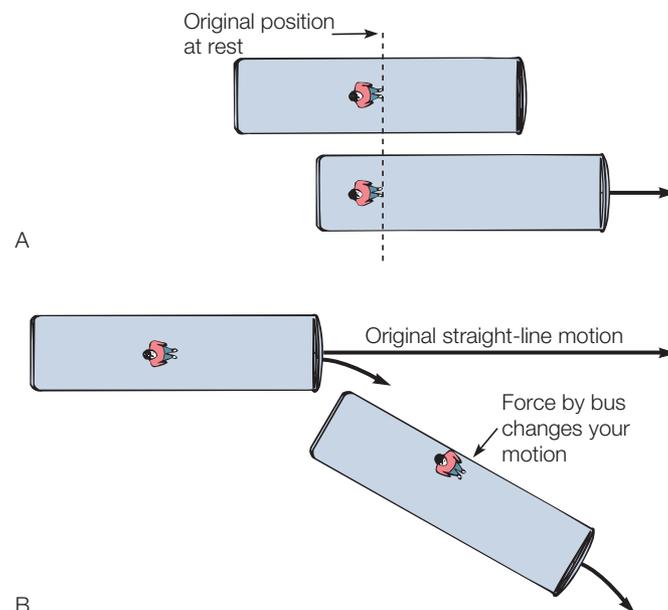
## Newton's First Law of Motion

Newton's first law of motion is also known as the *law of inertia* and is very similar to one of Galileo's findings about motion. Recall that Galileo used the term *inertia* to describe the tendency of an object to resist changes in motion. Newton's first law describes this tendency more directly. In modern terms (not Newton's words), the **first law of motion** is as follows:

**Every object retains its state of rest or its state of uniform straight-line motion unless acted upon by an unbalanced force.**

This means that an object at rest will remain at rest unless it is put into motion by an unbalanced force; that is, the net force must be greater than zero. Likewise, an object moving with uniform straight-line motion will retain that motion unless a net force causes it to speed up, slow down, or change its direction of travel. Thus, Newton's first law describes the tendency of an object to resist *any* change in its state of motion.

Think of Newton's first law of motion when you ride standing in the aisle of a bus. The bus begins to move, and you, being an independent mass, tend to remain at rest. You take a few steps back as you tend to maintain your position relative to the ground outside. You reach for a seat back or some part of the bus. Once you have a hold on some part of the bus, it supplies the forces needed to give you the same motion as the bus and you no longer find it necessary to step backward. You now have the same motion as the bus, and no forces are involved, at least until the bus goes around a curve. You now feel a tendency to move to the side of the bus. The bus has changed its straight-line motion, but you, again being an independent mass, tend to move straight ahead. The side of the seat forces you into following the curved motion of the bus. The forces you feel when the bus starts moving or turning are a result of your tendency to remain at rest or follow a straight path until forces correct your motion so that it is the same as that of the bus (figure 2.17).



**Figure 2.17**

Top view of a person standing in the aisle of a bus. (A) The bus is at rest and then starts to move forward. Inertia causes the person to remain in the original position, appearing to fall backward. (B) The bus turns to the right, but inertia causes the person to retain the original straight-line motion until forced in a new direction by the side of the bus.

## Newton's Second Law of Motion

Newton successfully used Galileo's ideas to describe the nature of motion. Newton's first law of motion explains that any object, once started in motion, will continue with a constant velocity in a straight line unless a force acts on the moving object. This law not only describes motion but establishes the role of a force as well. A change of motion is therefore *evidence* of the action of a net force. The association of forces and a change of motion is common in your everyday experience. You have felt forces on your back in an accelerating automobile, and you have felt other forces as the automobile turns or stops. You have also learned about gravitational forces that accelerate objects toward the surface of Earth. Unbalanced forces and acceleration are involved in any change of motion. Newton's second law of motion is a relationship between *net force*, *acceleration*, and *mass* that describes the cause of a change of motion.

Consider the motion of you and a bicycle you are riding. Suppose you are riding your bicycle over level ground in a straight line at 10 miles per hour. Newton's first law tells you that you will continue with a constant velocity in a straight line as long as no external, unbalanced force acts on you and the bicycle. The force that you *are* exerting on the pedals seems to equal some external force that moves you and the bicycle along (more on this later). The force exerted as you move along is needed to *balance* the resisting forces of tire friction and air resistance. If these resisting forces were removed, you would not need to exert any force at all to continue moving at a constant velocity. The net force is thus the force you are applying minus

## CONCEPTS APPLIED

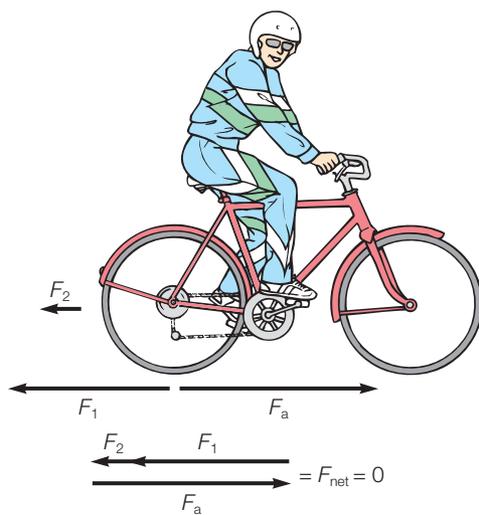
### First Law Experiment

Place a small ball on a flat part of the floor in a car, SUV, or pickup truck. First, predict what will happen to the ball in each of the following situations: (1) The vehicle moves forward from a stopped position. (2) The vehicle is moving at a constant speed. (3) The vehicle is moving at a constant speed, then turns to the right. (4) The vehicle is moving at a constant speed, then comes to a stop. Now, test your predictions, and then explain each finding in terms of Newton's first law of motion.

the forces from tire friction and air resistance. The *net force* is therefore zero when you move at a constant speed in a straight line (figure 2.18).

If you now apply a greater force on the pedals, the *extra* force you apply is unbalanced by friction and air resistance. Hence, there will be a net force greater than zero, and you will accelerate. You will accelerate during, and *only* during, the time that the net force is greater than zero. Likewise, you will slow down if you apply a force to the brakes, another kind of resisting friction. A third way to change your velocity is to apply a force on the handlebars, changing the direction of your velocity. Thus, *unbalanced forces* on you and your bicycle produce an *acceleration*.

Starting a bicycle from rest suggests a relationship between force and acceleration. You observe that the harder you push on the pedals, the greater your acceleration. If you double the net force, then you will also double the acceleration, reaching the same velocity in half the time. Likewise, if you triple the net force, you will increase the acceleration threefold. Recall that when quantities increase or decrease together in the same ratio, they are said to be *directly proportional*. The acceleration is therefore directly proportional to the force.



**Figure 2.18**

At a constant velocity the force of tire friction ( $F_1$ ) and the force of air resistance ( $F_2$ ) have a sum that equals the force applied ( $F_a$ ). The net force is therefore zero.

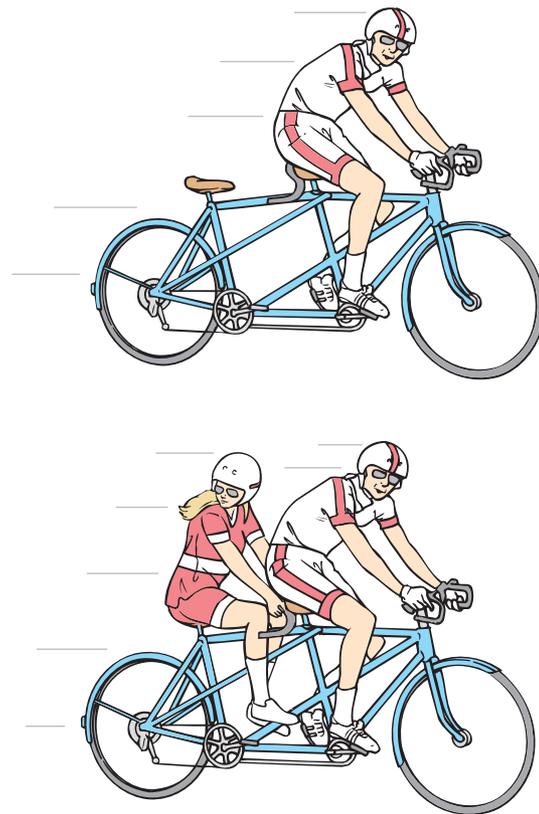
Suppose that your bicycle has two seats, and you have a friend who will ride (but not pedal) with you. Suppose also that the addition of your friend on the bicycle will double the mass of the bike and riders. If you use the same net force as before, the bicycle will undergo a much smaller acceleration. In fact, with all other factors equal, doubling the mass and applying the same extra force will produce an acceleration of only half as much (figure 2.19). An even more massive friend would reduce the acceleration even more. If you triple the mass and apply the same extra force, the acceleration will be one-third as much. Recall that when a relationship between two quantities shows that one quantity increases as another decreases, in the same ratio, the quantities are said to be *inversely proportional*.

The acceleration of an object depends on *both* the *net force applied* and the *mass* of the object. The **second law of motion** is as follows:

**The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to the mass of the object.**

If we express force in appropriate units, we can write this statement as an equation,

$$a = \frac{F}{m}$$



**Figure 2.19**

More mass results in less acceleration when the same force is applied. With the same force applied, the riders and bike with twice the mass will have half the acceleration, with all other factors constant. Note that the second rider is not pedaling.

By solving for  $F$ , we rearrange the equation into the form it is most often expressed,

$$F = ma$$

equation 2.3

In the metric system, you can see that the units for force will be the units for mass ( $m$ ) times acceleration ( $a$ ). The unit for mass is kg and the unit for acceleration is  $\text{m/s}^2$ . The combination of these units, (kg) ( $\text{m/s}^2$ ) is a unit of force called the **newton** (N), in honor of Isaac Newton. So,

$$1 \text{ newton} = 1 \text{ N} = 1 \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

Newton's second law of motion is the essential idea of his work on motion. According to this law, there is always a relationship between the acceleration, a net force, and the mass of an object. Implicit in this statement are three understandings: (1) that we are talking about the net force, meaning total external force acting on an object, (2) that the motion statement is concerned with acceleration, not velocity, and (3) that the mass does not change unless specified.

#### EXAMPLE 2.5 (Optional)

A 60 kg bicycle and rider accelerate at  $0.5 \text{ m/s}^2$ . How much extra force was applied?

#### SOLUTION

The mass ( $m$ ) of 60 kg and the acceleration ( $a$ ) of  $0.5 \text{ m/s}^2$  are given. The problem asked for the extra force ( $F$ ) needed to give the mass the acquired acceleration. The relationship is found in equation 2.5,  $F = ma$ .

$$\begin{aligned} m &= 60 \text{ kg} & F &= ma \\ a &= 0.5 \frac{\text{m}}{\text{s}^2} & &= (60 \text{ kg}) \left( 0.5 \frac{\text{m}}{\text{s}^2} \right) \\ F &=? & &= (60)(0.5) \text{ kg} \times \frac{\text{m}}{\text{s}^2} \\ & & &= 30 \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \\ & & &= \boxed{30 \text{ N}} \end{aligned}$$

An extra force of 30 N beyond that required to maintain constant speed must be applied to the pedals for the bike and rider to maintain an acceleration of  $0.5 \text{ m/s}^2$ . (Note that the units  $\text{kg} \cdot \text{m/s}^2$  form the definition of a newton of force, so the symbol N is used.)

#### EXAMPLE 2.6 (Optional)

What is the acceleration of a 20 kg cart if the net force on it is 40 N? (Answer:  $2 \text{ m/s}^2$ )

## Weight and Mass

What is the meaning of weight—is it the same concept as mass? Weight is a familiar concept to most people, and in everyday language, the word is often used as having the same meaning as mass. In physics, however, there is a basic difference between weight and mass, and this difference is very important in Newton's explanation of motion and the causes of motion.

## CONCEPTS APPLIED

### Second Law Experiment

Tie one end of a string to a book and the other end to a large rubber band. With your index finger curled in the loop of the rubber band, pull the book across a smooth tabletop. How much the rubber band stretches will provide a rough estimate of the force you are applying. (1) Pull the book with a constant velocity across the tabletop. Compare the force required for different constant velocities. (2) Accelerate the book at different rates. Compare the force required to maintain the different accelerations. (3) Use a different book with a greater mass and again accelerate the book at different rates. How does more mass change the results?

Based on your observations, can you infer a relationship between force, acceleration, and mass?

**Mass** is defined as the property that determines how much an object resists a change in its motion. The greater the mass the greater the *inertia*, or resistance to change in motion. Consider, for example, that it is easier to push a small car into motion than to push a large truck into motion. The truck has more mass and therefore more inertia. Newton originally defined mass as the “quantity of matter” in an object, and this definition is intuitively appealing. However, Newton needed to measure inertia because of its obvious role in motion and redefined mass as a measure of inertia.

You could use Newton's second law to measure a mass by exerting a force on the mass and measuring the resulting acceleration. This is not very convenient, so masses are usually measured on a balance by comparing the force of gravity acting on a standard mass compared to the force of gravity acting on the unknown mass.

The force of gravity acting on a mass is the *weight* of an object. Weight is a force and has different units (N) from those of mass (kg). Since weight is a measure of the force of gravity acting on an object, the force can be calculated from Newton's second law of motion,

$$F = ma$$

or

$$\text{downward force} = (\text{mass})(\text{acceleration due to gravity})$$

or

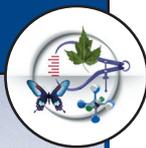
$$\text{weight} = (\text{mass})(g)$$

$$\text{or } w = mg$$

equation 2.4

You learned previously that  $g$  is the symbol used to represent acceleration due to gravity. Near Earth's surface,  $g$  has an approximate value of  $9.8 \text{ m/s}^2$ . To understand how  $g$  is applied to an object not moving, consider a ball you are holding in your hand. By supporting the weight of the ball, you hold it stationary, so the upward force of your hand and the downward force of the ball (its weight) must add to a net force of zero. When you let go of the ball, the gravitational force is the only force acting on the ball. The ball's weight is then the net force that accelerates it at  $g$ , the

# Connections . . .



## Weight on Different Planets

Planet	Acceleration of Gravity	Approximate Weight (N)	Approximate Weight (lb)
Mercury	3.72 m/s <sup>2</sup>	223 N	50 lb
Venus	8.92 m/s <sup>2</sup>	535 N	120 lb
Earth	9.80 m/s <sup>2</sup>	588 N	132 lb
Mars	3.72 m/s <sup>2</sup>	223 N	50 lb
Jupiter	24.89 m/s <sup>2</sup>	1,493 N	336 lb
Saturn	10.58 m/s <sup>2</sup>	635 N	143 lb
Uranus	8.92 m/s <sup>2</sup>	535 N	120 lb
Neptune	11.67 m/s <sup>2</sup>	700 N	157 lb
Pluto	0.59 m/s <sup>2</sup>	35 N	7.9 lb

**Table 2.1** Units of Mass and Weight in the Metric and English Systems of Measurement

	Mass	×	Acceleration	=	Force
<b>Metric system</b>	kg	×	$\frac{\text{m}}{\text{s}^2}$	=	$\frac{\text{kg} \cdot \text{m}}{\text{s}^2}$ (newton)
<b>English system</b>	$\left(\frac{\text{lb}}{\text{ft}/\text{s}^2}\right)$	×	$\frac{\text{ft}}{\text{s}^2}$	=	lb (pound)

acceleration due to gravity. Thus,  $F_{\text{net}} = w = ma = mg$ . The weight of the ball never changes in a given location, so its weight is always equal to  $w = mg$ , even if the ball is not accelerating.

An important thing to remember is that *pounds* and *newtons* are units of *force* (table 2.1). A *kilogram*, on the other hand, is a measure of *mass*. Thus the English unit of 1.0 lb is comparable to the metric unit of 4.5 N (or 0.22 lb is equivalent to 1.0 N). Conversion tables sometimes show how to convert from pounds (a unit of weight) to kilograms (a unit of mass). This is possible because weight and mass are proportional in a given location on the surface of Earth. Using conversion factors from inside the front cover of this book, see if you can express your weight in pounds and newtons and your mass in kilograms.

**EXAMPLE 2.7** (Optional)

What is the weight of a 60.0 kg person on the surface of Earth?

**SOLUTION**

A mass ( $m$ ) of 60.0 kg is given, and the acceleration due to gravity ( $g$ ) 9.8 m/s<sup>2</sup> is implied. The problem asked for the weight ( $w$ ). The relationship is found in equation 2.4,  $w = mg$ , which is a form of  $F = ma$ .

$$\begin{aligned} m &= 60.0 \text{ kg} & w &= mg \\ g &= 9.8 \text{ m/s}^2 & &= (60.0 \text{ kg}) (9.8 \frac{\text{m}}{\text{s}^2}) \\ w &=? & &= (60.0)(9.8) \text{ kg} \times \frac{\text{m}}{\text{s}^2} \end{aligned}$$

$$\begin{aligned} &= 588 \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \\ &= 588 \text{ N} \\ &= \boxed{590 \text{ N}} \end{aligned}$$

**EXAMPLE 2.8** (Optional)

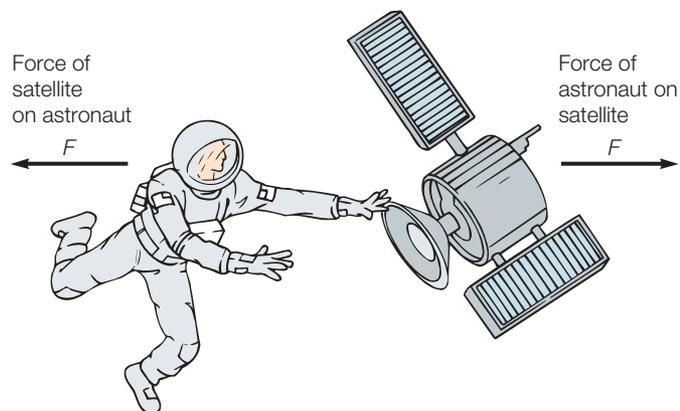
A 60.0 kg person weighs 100.0 N on the Moon. What is the value of  $g$  on the Moon? (Answer: 1.67 m/s<sup>2</sup>)

## Newton's Third Law of Motion

Newton's first law of motion states that an object retains its state of motion when the net force is zero. The second law states what happens when the net force is *not* zero, describing how an object with a known mass moves when a given force is applied. The two laws give one aspect of the concept of a force; that is, if you observe that an object starts moving, speeds up, slows down, or changes its direction of travel, you can conclude that an unbalanced force is acting on the object. Thus, any change in the state of motion of an object is *evidence* that an unbalanced force has been applied.

Newton's third law of motion is also concerned with forces. First, consider where a force comes from. A force is always produced by the interaction of two objects. Sometimes we do not know what is producing forces, but we do know that they always come in pairs. Anytime a force is exerted, there is always a matched and opposite force that occurs at the same time. For example, if you push on the wall, the wall pushes back with an equal and opposite force. The two forces are opposite and balanced, and you know this because  $F = ma$  and neither you or the wall accelerated. If the acceleration is zero, then you know from  $F = ma$  that the net force is zero (zero equals zero). Note also that the two forces were between two different objects, you and the wall. Newton's third law always describes what happens between two different objects. To simplify the many interactions that occur on Earth, consider a satellite freely floating in space. According to Newton's second law ( $F = ma$ ), a force must be applied to change the state of motion of the satellite. What is a possible source of such a force? Perhaps an astronaut pushes on the satellite for 1 second. The satellite would accelerate *during* the application of the force, then move away from the original position at some constant velocity. The astronaut would also move away from the original position, but in the opposite direction (figure 2.20). A *single force does not exist* by itself. There is always a matched and opposite force that occurs at the same time. Thus, the astronaut exerted a momentary force on the satellite, but the satellite evidently exerted a momentary force back on the astronaut as well, for the astronaut moved away from the original position in the opposite direction. Newton did not have astronauts and satellites to think about, but this is the kind of reasoning he did when he concluded that forces always occur in matched pairs that are equal and opposite. Thus, the **third law of motion** is as follows:

**Whenever two objects interact, the force exerted on one object is equal in strength and opposite in direction to the force exerted on the other object.**



**Figure 2.20**

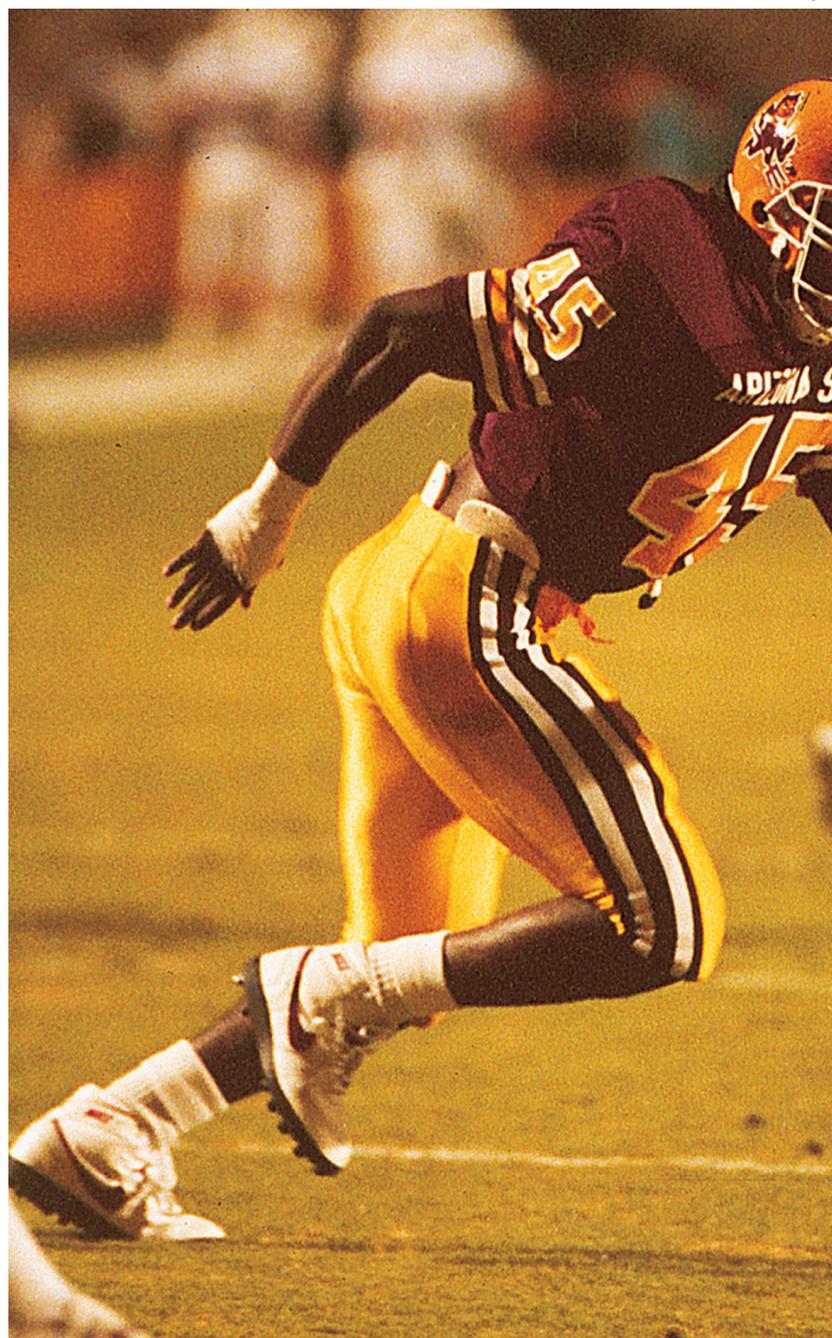
Forces occur in matched pairs that are equal in strength and opposite in direction.

The third law states that forces always occur in matched pairs that act in opposite directions and on two *different* bodies. Sometimes the third law of motion is expressed as follows: “For every action there is an equal and opposite reaction,” but this can be misleading. Neither force is the cause of the other. The forces are at every instant the cause of each other, and they appear and disappear at the same time. If you are going to describe the force exerted on a satellite by an astronaut, then you must realize that there is a simultaneous force exerted on the astronaut by the satellite. The forces (astronaut on satellite and satellite on astronaut) are equal in magnitude but opposite in direction.

Perhaps it would be more common to move a satellite with a small rocket. A satellite is maneuvered in space by firing a rocket in the direction opposite to the direction someone wants to move the satellite. Exhaust gases (or compressed gases) are accelerated in one direction and exert an equal but opposite force on the satellite that accelerates it in the opposite direction. This is another example of the third law.

Consider how the pairs of forces work on Earth’s surface. You walk by pushing your feet against the ground (figure 2.21). Of course you could not do this if it were not for friction. You would slide as on slippery ice without friction. But since friction does exist, you exert a backward horizontal force on the ground, and, as the third law explains, the ground exerts an equal and opposite force on you. You accelerate forward from the net force as explained by the second law. If Earth had the same mass as you, however, it would accelerate backward at the same rate that you were accelerated forward. Earth is much more massive than you, however, so any acceleration of Earth is a vanishingly small amount. The overall effect is that you are accelerated forward by the force the ground exerts on you.

Return now to the example of riding a bicycle that was discussed previously. What is the source of the *external* force that accelerates you and the bike? Pushing against the pedals is not external to you and the bike, so that force will *not* accelerate you and the bicycle forward. This force is transmitted through the bike mechanism to the rear tire, which pushes against the ground. It is the ground exerting an equal and opposite force against the system of you and the bike that accelerates you for-



**Figure 2.21**

The football player’s foot is pushing against the ground, but it is the ground pushing against the foot that accelerates the player forward to catch a pass.

ward. You must consider the forces that act on the system of you and the bike before you can apply  $F = ma$ . The only forces that will affect the forward motion of the bike system are the force of the ground pushing it forward and the frictional forces that oppose the forward motion. This is another example of the third law.

## MOMENTUM

Sportscasters often refer to the *momentum* of a team, and newscasters sometimes refer to an election where one of the candidates has *momentum*. Both situations describe a competition where one side is moving toward victory and it is difficult to stop. It seems appropriate to borrow this term from the physical

# Connections . . .



## Swimming Scallop

Newton's laws of motion apply to animal motion as well as that of satellites and automobiles. Consider, for example, the dilemma of a growing scallop. A scallop is the shell often seen as a logo for a certain petroleum company, a fan-shaped shell with a radiating fluted pattern (box figure 2.2). The scallop is a marine mollusk that is most unusual since it is the only clamlike mollusk that is capable of swimming. By opening and closing its shell, it is able to propel itself by forcing water from the interior of the shell in a jetlike action. The popular seafood called "scallops" is the edible muscle that the scallop uses to close its shell.

A scallop is able to swim by orienting its shell at a proper angle and maintaining a minimum acceleration to prevent sinking. For example, investigations have found that one particular species of scallop must force enough water backward to move about 6 body lengths per second with a 10 degree angle of attack to maintain level swimming. Such a swimming effort can be maintained for up to about 20 seconds, enabling the scallop to escape predation or some other disturbing condition.

A more massive body limits the swimming ability of the scallop, as a greater force is needed to give a greater mass the same acceleration (as



**Box Figure 2.2**  
A scallop shell.

you would expect from Newton's second law of motion). This problem becomes worse as the scallop grows larger and larger without developing a greater and greater jet force.

sciences because momentum is a property of movement. It takes a longer time to stop something from moving when it has a lot of momentum. The physical science concept of momentum is closely related to Newton's laws of motion. **Momentum** ( $p$ ) is defined as the product of the mass ( $m$ ) of an object and its velocity ( $v$ ),

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

or

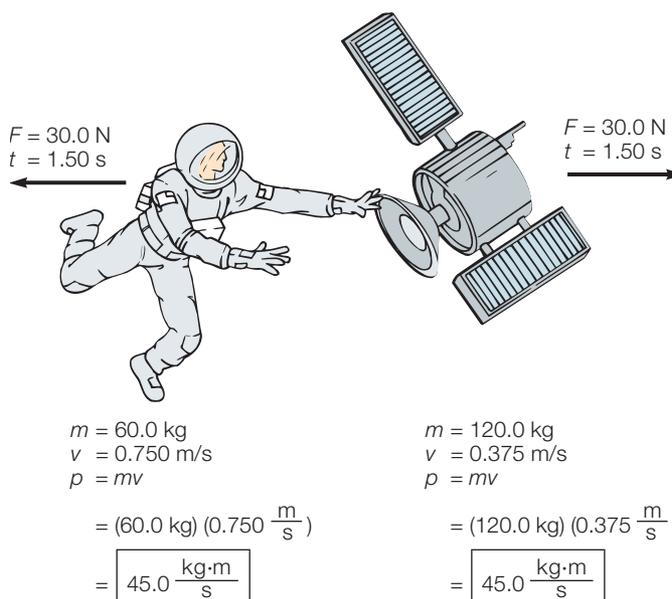
$$p = mv$$

**equation 2.5**

The astronaut in figure 2.22 has a mass of 60.0 kg and a velocity of 0.750 m/s as a result of the interaction with the satellite. The resulting momentum is therefore (60.0 kg) (0.750 m/s), or 45.0 kg·m/s. As you can see, the momentum would be greater if the astronaut had acquired a greater velocity or if the astronaut had a greater mass and acquired the same velocity. Momentum involves both the inertia and the velocity of a moving object.

## Conservation of Momentum

Notice that the momentum acquired by the satellite in figure 2.22 is *also* 45.0 kg·m/s. The astronaut gained a certain momentum in one direction, and the satellite gained the *very same momentum in the opposite direction*. Newton originally defined the second law in terms of a change of momentum being proportional to the net force acting on an object. Since the third law explains that the forces exerted on both the astronaut and satellite were equal and opposite, you would expect both objects to acquire equal momentum in the opposite direction. This result is observed any



**Figure 2.22**

Both the astronaut and the satellite receive a force of 30.0 N for 1.50 s when they pushed on each other. Both then have a momentum of 45.0 kg·m/s in the opposite direction. This is an example of the law of conservation of momentum.

time objects in a system interact and the only forces involved are those between the interacting objects (figure 2.22). This statement leads to a particular kind of relationship called a *law of conservation*. In this case, the law applies to momentum and is called the **law of conservation of momentum**:

**The total momentum of a group of interacting objects remains the same in the absence of external forces.**

Conservation of momentum, energy, and charge are among examples of conservation laws that apply to everyday situations. These situations always illustrate two understandings: (1) each conservation law is an expression that describes a physical principle that can be observed, and (2) each law holds regardless of the details of an interaction or how it took place. Since the conservation laws express something that always occurs, they tell us what might be expected to happen and what might be expected not to happen in a given situation. The conservation laws also allow unknown quantities to be found by analysis. The law of conservation of momentum, for example, is useful in analyzing motion in simple systems of collisions such as those of billiard balls, automobiles, or railroad cars. It is also useful in measuring action and reaction interactions, as in rocket propulsion, where the backward momentum of the exhaust gases equals the momentum given to the rocket in the opposite direction (figure 2.23). When this is done, momentum is always found to be conserved.



**Figure 2.23**

According to the law of conservation of momentum, the momentum of the expelled gases in one direction equals the momentum of the rocket in the other direction in the absence of external forces.

## Impulse

Have you ever heard that you should “follow through” when hitting a ball? When you follow through, the bat is in contact with the ball for a longer period of time. The force of the hit is important, of course, but both the force and how long the force is applied determine the result. The product of the force and the time of application is called **impulse**. This quantity can be expressed as

$$\text{impulse} = Ft$$

where  $F$  is the force applied during the time of contact ( $t$ ). The impulse you give the ball determines how fast the ball will move and thus how far it will travel.

Impulse is related to the change of motion of a ball of a given mass, so the change of momentum ( $mv$ ) is brought about by the impulse. This can be expressed as

$$\text{change of momentum} = (\text{applied force}) (\text{time of contact})$$

$$\Delta p = Ft$$

**equation 2.6**

where  $\Delta p$  is a change of momentum. You “follow through” while hitting a ball in order to increase the contact time. If the same force is used, a longer contact time will result in a greater impulse. A greater impulse means a greater change of momentum, and since the mass of the ball does not change, the overall result is a moving ball with a greater velocity. This means following through will result in more distance from hitting the ball with the same force. That’s why it is important to follow through when you hit the ball.

Now consider bringing a moving object to a stop by catching it. In this case, the mass and the velocity of the object are fixed at the time you catch it, and there is nothing you can do about these quantities. The change of momentum is equal to the impulse, and the force and time of force application *can* be

### CONCEPTS APPLIED Momentum Experiment

The popular novelty item of a frame with five steel balls hanging from strings can be used to observe momentum exchanges during elastic collisions. When one ball is pulled back and released, it stops as it transfers its momentum to the ball it strikes and the momentum is transferred ball to ball until the end ball swings out. Make some predictions, then do the experiment for the following. What happens when: (1) two balls are released together on one side; (2) one ball on each side is released at the same time; (3) two balls on one side are released together as two balls are simultaneously released on the other side; and (4) two balls on one side are released together as a single ball is simultaneously released on the other side? Analyze the momentum transfers down the line for each situation.

As an alternative to using the swinging balls, consider a similar experiment using a line of marbles in contact with each other in a grooved ruler. Here, you could also vary the mass of marbles in collisions.

manipulated. For example, consider how you would catch a raw egg that is tossed to you. You would probably move your hands with the egg as you catch it, increasing the contact time. Increasing the contact time has the effect of reducing the force, since  $\Delta p = Ft$ . You changed the force applied by increasing the contact time, and hopefully, you reduced the force sufficiently so the egg does not break.

Contact time is also important in safety. Automobile airbags, the padding in elbow and knee pads, and the plastic barrels off the highway in front of overpass supports are examples of designs intended to increase the contact time. Again, increasing the contact time reduces the force, since  $\Delta p = Ft$ . The impact force is reduced and so are the injuries. Think about this the next time you see a car that was crumpled and bent by a collision. The driver and passengers were probably saved from injuries that are more serious since more time was involved in stopping the car that crumpled. A car that crumples is a safer car in a collision.

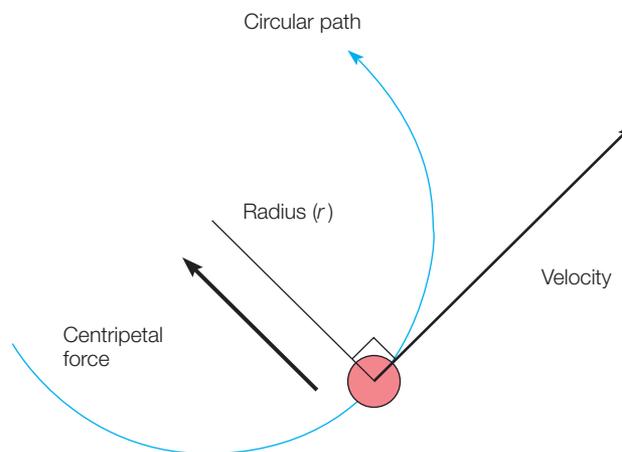
## FORCES AND CIRCULAR MOTION

Consider a communications satellite that is moving at a uniform speed around Earth in a circular orbit. According to the first law of motion, there *must be* forces acting on the satellite, since it does *not* move off in a straight line. The second law of motion also indicates forces, since an unbalanced force is required to change the motion of an object.

Recall that acceleration is defined as a rate of change in velocity and that velocity has both strength and direction. Velocity is changed by a change in speed, direction, or both speed and direction. The satellite in a circular orbit is continuously being accelerated. This means that there is a continuously acting unbalanced force on the satellite that pulls it out of a straight-line path.

The force that pulls an object out of its straight-line path and into a circular path is called a **centripetal** (center-seeking) **force**. Perhaps you have swung a ball on the end of a string in a horizontal circle over your head. Once you have the ball moving, the only unbalanced force (other than gravity) acting on the ball is the centripetal force your hand exerts on the ball through the string. This centripetal force pulls the ball from its natural straight-line path into a circular path. There are no outward forces acting on the ball. The force that you feel on the string is a consequence of the third law; the ball exerts an equal and opposite force on your hand. If you were to release the string, the ball would move away from the circular path in a *straight line* that has a right angle to the radius at the point of release (figure 2.24). When you release the string, the centripetal force ceases, and the ball then follows its natural straight-line motion. If other forces were involved, it would follow some other path. Nonetheless, the apparent outward force has been given a name just as if it were a real force. The outward tug is called a *centrifugal force*.

The magnitude of the centripetal force required to keep an object in a circular path depends on the inertia, or mass, of the object and the acceleration of the object, just as you learned in the second law of motion. The acceleration of an object moving



**Figure 2.24**

Centripetal force on the ball causes it to change direction continuously, or accelerate into a circular path. Without the force acting on it, the ball would continue in a straight line.

in a circle can be shown to be directly proportional to the square of the speed around the circle ( $v^2$ ) and inversely proportional to the radius of the circle ( $r$ ). (A smaller radius requires a greater acceleration.) Therefore, the acceleration of an object moving in uniform circular motion ( $a_c$ ) is

$$a_c = \frac{v^2}{r} \quad \text{equation 2.7}$$

The magnitude of the centripetal force of an object with a constant mass ( $m$ ) that is moving with a velocity ( $v$ ) in a circular orbit of a radius ( $r$ ) can be found by substituting equation 2.7 in  $F = ma$ , or

$$F = \frac{mv^2}{r} \quad \text{equation 2.8}$$

### EXAMPLE 2.9 (Optional)

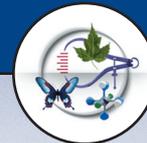
A 0.25 kg ball is attached to the end of a 0.5 m string and moved in a horizontal circle at 2.0 m/s. What net force is needed to keep the ball in its circular path?

### SOLUTION

$$\begin{aligned} m &= 0.25 \text{ kg} \\ r &= 0.5 \text{ m} \\ v &= 2.0 \text{ m/s} \\ F &= ? \end{aligned}$$

$$\begin{aligned} F &= \frac{mv^2}{r} \\ &= \frac{(0.25 \text{ kg})(2.0 \text{ m/s})^2}{0.5 \text{ m}} \\ &= \frac{(0.25 \text{ kg})(4.0 \text{ m}^2/\text{s}^2)}{0.5 \text{ m}} \\ &= \frac{(0.25)(4.0) \text{ kg} \cdot \text{m}^2}{0.5 \text{ s}^2} \times \frac{1}{\text{m}} \\ &= 2 \frac{\text{kg} \cdot \cancel{\text{m}^2}}{\cancel{\text{m}} \cdot \text{s}^2} \\ &= 2 \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \\ &= \boxed{2 \text{ N}} \end{aligned}$$

# Connections . . .



## Circular Fun

Amusement park rides are designed to accelerate your body, sometimes producing changes in the acceleration (jerk) as well. This is done by changes in speed, changes in the direction of travel, or changes in both direction and speed. Many rides move in a circular path, since such movement is a constant acceleration.

Why do people enjoy amusement park rides? It is not the high speed, since your body is not very sensitive to moving at a constant speed. Moving at a steady 600 mi/h in an airplane, for example, provides little sensation when you are seated in an aisle seat in the central cabin.

Your body is not sensitive to high-speed traveling, but it is sensitive to acceleration and changes of acceleration. Acceleration affects the fluid

in your inner ear, which controls your sense of balance. In most people, acceleration also produces a reaction that results in the release of the hormones epinephrine and norepinephrine from the adrenal medulla, located near the kidney. The heart rate increases, blood pressure rises, blood is shunted to muscles, and the breathing rate increases. You have probably experienced this reaction many times in your life, as when you nearly have an automobile accident or slip and nearly fall. In the case of an amusement park ride, your body adapts and you believe you enjoy the experience.

### EXAMPLE 2.10 (Optional)

Suppose you make the string in example 2.9 half as long, 0.25 m. What force is now needed? (Answer: 4.0 N)

## NEWTON'S LAW OF GRAVITATION

You know that if you drop an object, it always falls to the floor. You define *down* as the direction of the object's movement and *up* as the opposite direction. Objects fall because of the force of gravity, which accelerates objects on Earth at  $g = 9.8 \text{ m/s}^2$  ( $32 \text{ ft/s}^2$ ) and gives them weight,  $w = mg$ .

Gravity is an attractive force, a pull that exists between all objects in the universe. It is a mutual force that, just like all other forces, comes in matched pairs. Since Earth attracts you with a certain force, you must attract Earth with an exact opposite force. The magnitude of this force of mutual attraction depends on several variables. These variables were first described by Newton in *Principia*, his famous book on motion that was printed in 1687. Newton had, however, worked out his ideas much earlier, by the age of twenty-four, along with ideas about his laws of motion and the formula for centripetal acceleration. In a biography written by a friend in 1752, Newton stated that the notion of gravitation came to mind during a time of thinking that "was occasioned by the fall of an apple." He was thinking about why the Moon stays in orbit around Earth rather than moving off in a straight line as would be predicted by the first law of motion. Perhaps the same force that attracts the Moon toward Earth, he thought, attracts the apple to Earth. Newton developed a theoretical equation for gravitational force that explained not only the motion of the Moon but the motion of the whole solar system. Today, this relationship is known as the **universal law of gravitation**:

**Every object in the universe is attracted to every other object with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distances between them.**

In symbols,  $m_1$  and  $m_2$  can be used to represent the masses of two objects,  $d$  the distance between their centers, and  $G$  a con-

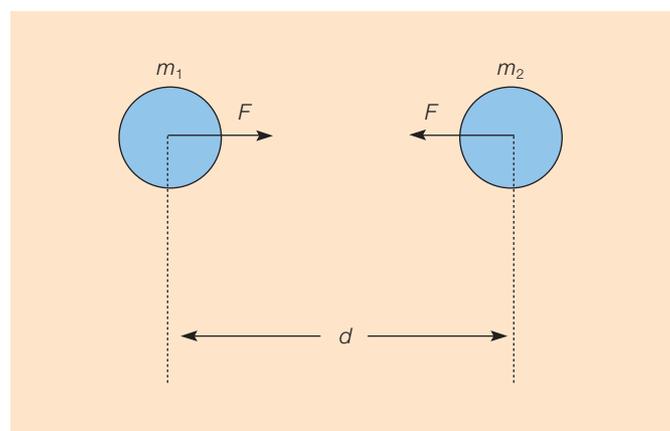
stant of proportionality. The equation for the law of universal gravitation is therefore

$$F = G \frac{m_1 m_2}{d^2}$$

equation 2.9

This equation gives the magnitude of the attractive force that each object exerts on the other. The two forces are oppositely directed. The constant  $G$  is a universal constant, since the law applies to all objects in the universe. It was first measured experimentally by Henry Cavendish in 1798. The accepted value today is  $G = 6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$ . Do not confuse  $G$ , the universal constant, with  $g$ , the acceleration due to gravity on the surface of Earth.

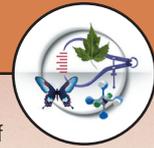
Thus, the magnitude of the force of gravitational attraction is determined by the mass of the two objects and the distance between them (figure 2.25). The law also states that *every* object is attracted to every other object. You are attracted to all the objects around you—chairs, tables, other people, and so forth. Why



**Figure 2.25**

The variables involved in gravitational attraction. The force of attraction ( $F$ ) is proportional to the product of the masses ( $m_1, m_2$ ) and inversely proportional to the square of the distance ( $d$ ) between the centers of the two masses.

## A Closer Look Space Station Weightlessness



When do astronauts experience weightlessness, or “zero gravity”? Theoretically, the gravitational field of Earth extends to the whole universe. You know that it extends to the Moon and, indeed, even to the Sun some 93 million miles away. There is a distance, however, at which the gravitational force must become immeasurably small. But even at an altitude of 20,000 miles above the surface of Earth, gravity is measurable. At 20,000 miles, the value of  $g$  is about  $1 \text{ ft/s}^2$  ( $0.3 \text{ m/s}^2$ ) compared to  $32 \text{ ft/s}^2$  ( $9.8 \text{ m/s}^2$ ) on the surface. Since gravity does exist at these distances, how can an astronaut experience “zero gravity”?

Gravity does act on astronauts in spacecraft that are in orbit around Earth. The spacecraft stays in orbit, in fact, because of the gravitational attraction and because it has the correct tangential speed. If the tangential speed were less than 5 mi/s, the spacecraft would return to Earth. Astronauts fire their retro-rockets, which slow the tangential speed, causing the spacecraft to fall down to Earth. If the tangential speed were more than 7 mi/s, the spacecraft would fly off into space. The spacecraft stays in orbit because it

has the right tangential speed to continuously “fall” around and around Earth. Gravity provides the necessary centripetal force that causes the spacecraft to fall out of its natural straightline motion.

Since gravity is acting on the astronaut and spacecraft, the term *zero gravity* is not an accurate description of what is happening. The astronaut, spacecraft, and everything in it are experiencing *apparent weightlessness* because they are continuously falling toward Earth. Everything seems to float because everything is falling together. But, strictly speaking, everything still has weight, because weight is defined as a gravitational force acting on an object ( $w = mg$ ).

Whether weightlessness is apparent or real, however, the effects on people are the same. Long-term orbital flights have provided evidence that the human body changes from the effect of weightlessness. Bones lose calcium and other minerals, the heart shrinks to a much smaller size, and leg muscles shrink so much on prolonged flights that astronauts cannot walk when they return to Earth. These changes occur because on Earth, humans are constantly sub-

jected to the force of gravity. The nature of the skeleton and the strength of the muscles are determined by how the body reacts to this force. Metabolic pathways and physiological processes that maintain strong bones and muscles evolved having to cope with a specific gravitational force. When we are suddenly subjected to a place where gravity is significantly different, these processes result in weakened systems. If we had evolved on a planet with a different gravitational force, we would have muscles and bones that were adapted to the gravity on that planet. All organisms have evolved in a world with gravity. Many kinds of organisms have been used in experiments in space to try to develop a better understanding of how their systems work.

The problems related to prolonged weightlessness must be worked out before long-term weightlessness flights can take place. One solution to these problems might be a large, uniformly spinning spacecraft. The astronauts tend to move in a straight line, and the side of the turning spacecraft (now the “floor”) exerts a force on them to make them go in a curved path. This force would act as an artificial gravity.

don’t you notice the forces between you and other objects? One or both of the interacting objects must be quite massive before a noticeable force results from the interaction. That is why you do not notice the force of gravitational attraction between you and objects that are not very massive compared to Earth. The attraction between you and Earth overwhelmingly predominates, and that is all you notice.

### EXAMPLE 2.11 (Optional)

What is the force of gravitational attraction between two 60.0 kg (132 lb) students who are standing 1.00 m apart?

#### SOLUTION

$$\begin{aligned}
 G &= 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2 \\
 m_1 &= 60.0 \text{ kg} \\
 m_2 &= 60.0 \text{ kg} \\
 d &= 1.00 \text{ m} \\
 F &= ?
 \end{aligned}
 \quad
 F = G \frac{m_1 m_2}{d^2}$$

$$\begin{aligned}
 &= \frac{(6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2)(60.0 \text{ kg})(60.0 \text{ kg})}{(1.00 \text{ m})^2} \\
 &= (6.67 \times 10^{-11})(3.60 \times 10^3) \frac{\text{Nm}^2 \text{kg}^2}{\text{kg}^2 \text{m}^2} \\
 &= 2.40 \times 10^{-7} (\text{Nm}^2) \left( \frac{1}{\text{m}^2} \right) \\
 &= 2.40 \times 10^{-7} \frac{\text{Nm}^2}{\text{m}^2} \\
 &= \boxed{2.40 \times 10^{-7} \text{ N}}
 \end{aligned}$$

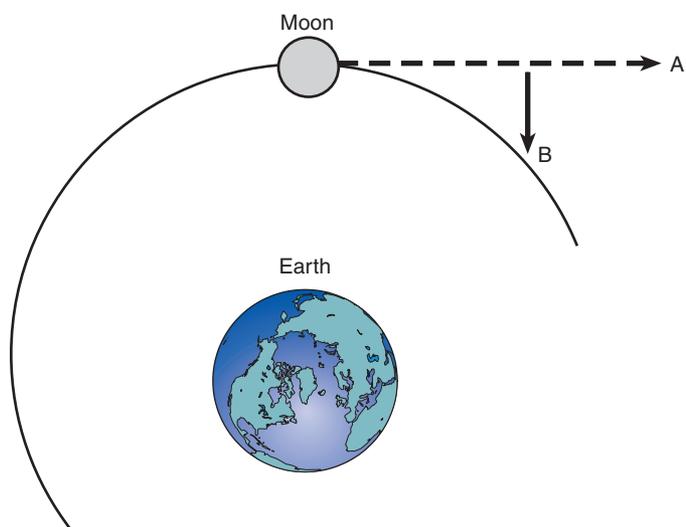
(Note: A force of  $2.40 \times 10^{-7}$  (0.00000024) N is equivalent to a force of  $5.40 \times 10^{-8}$  lb (0.00000005 lb), a force that you would not notice. In fact, it would be difficult to measure such a small force.)

### EXAMPLE 2.12 (Optional)

What would be the value of  $g$  if Earth were less dense, with the same mass and double the radius? (Answer:  $g = 2.45 \text{ m/s}^2$ )

The acceleration due to gravity,  $g$ , is about  $9.8 \text{ m/s}^2$  on Earth and is practically a constant for relatively short distances above the surface. Notice, however, that Newton’s law of gravitation is an inverse square law. This means if you double the distance, the force is  $1/(2)^2$  or  $1/4$  as great. If you triple the distance, the force is  $1/(3)^2$  or  $1/9$  as great. In other words, the force of gravitational attraction and  $g$  decrease inversely with the square of the distance from Earth’s center.

Newton was able to calculate the acceleration of the Moon toward Earth, about  $0.0027 \text{ m/s}^2$ . The Moon “falls” toward Earth because it is accelerated by the force of gravitational attraction. This attraction acts as a *centripetal force* that keeps the Moon from following a straight-line path as would be predicted from the first law. Thus, the acceleration of the Moon keeps it in a somewhat circular orbit around Earth. Figure 2.26 shows that the Moon would be in position A if it followed a straight-line path instead of “falling” to position B as it does. The Moon thus “falls” around Earth. Newton was able to analyze the motion of the Moon quantitatively as evidence that it is gravitational force that keeps the Moon in its orbit. The law of gravitation was


**Figure 2.26**

Gravitational attraction acts as a centripetal force that keeps the Moon from following the straight-line path shown by the dashed line to position A. It was pulled to position B by gravity ( $0.0027 \text{ m/s}^2$ ) and thus “fell” toward the Earth the distance from the dashed line to B, resulting in a somewhat circular path.

### CONCEPTS APPLIED

#### Apparent Weightlessness

Use a sharp pencil to make a small hole in the bottom of a Styrofoam cup. The hole should be large enough for a thin stream of water to flow from the cup, but small enough for the flow to continue for 3 or 4 seconds. Test the water flow over a sink.

Hold a finger over the hole on the cup as you fill it with water. Stand on a ladder or outside stairwell as you hold the cup out at arm’s length. Move your finger, allowing a stream of water to flow from the cup as you drop it. Observe what happens to the stream of water as the cup is falling. Explain your observations. Also predict what you would see if you were falling with the cup.

extended to the Sun, other planets, and eventually the universe. The quantitative predictions of observed relationships among the planets were strong evidence that all objects obey the same law of gravitation. In addition, the law provided a means to calculate the mass of Earth, the Moon, the planets, and the Sun. Newton’s law of gravitation, laws of motion, and work with mathematics formed the basis of most physics and technology for the next two centuries, as well as accurately describing the world of everyday experience.

## SUMMARY

Motion can be measured by speed, velocity, and acceleration. *Speed* is a measure of how fast something is moving. It is a ratio of the distance covered between two locations to the time that elapsed while moving between the two locations. The *average speed* considers the distance covered during some period of time, while the *instantaneous speed* is the speed at

some specific instant. *Velocity* is a measure of the speed and direction of a moving object. *Acceleration* is a change of velocity per unit of time.

A *force* is a push or a pull that can change the motion of an object. The *net force* is the sum of all the forces acting on an object.

Galileo determined that a continuously applied force is not necessary for motion and defined the concept of *inertia*: an object remains in unchanging motion in the absence of a net force. Galileo also determined that falling objects accelerate toward Earth’s surface independent of the weight of the object. He found the acceleration due to gravity,  $g$ , to be  $9.8 \text{ m/s}^2$  ( $32 \text{ ft/s}^2$ ), and the distance an object falls is proportional to the square of the time of free fall ( $d \propto t^2$ ).

Compound motion occurs when an object is projected into the air. Compound motion can be described by splitting the motion into vertical and horizontal parts. The acceleration due to gravity,  $g$ , is a constant that is acting at all times and acts independently of any motion that an object has. The path of an object that is projected at some angle to the horizon is therefore a parabola.

Newton’s *first law of motion* is concerned with the motion of an object and the lack of a net force. Also known as the *law of inertia*, the first law states that an object will retain its state of straight-line motion (or state of rest) unless a net force acts on it.

The *second law of motion* describes a relationship between net force, mass, and acceleration. A *newton* of force is the force needed to give a  $1.0 \text{ kg}$  mass an acceleration of  $1.0 \text{ m/s}^2$ .

*Weight* is the downward force that results from Earth’s gravity acting on the mass of an object. Weight is measured in *newtons* in the metric system and *pounds* in the English system.

Newton’s *third law of motion* states that forces are produced by the interaction of *two different* objects. These forces always occur in matched pairs that are equal in size and opposite in direction.

*Momentum* is the product of the mass of an object and its velocity. In the absence of external forces, the momentum of a group of interacting objects always remains the same. This relationship is the *law of conservation of momentum*. *Impulse* is a change of momentum equal to a force times the time of application.

An object moving in a circular path must have a force acting on it, since it does not move in a straight line. The force that pulls an object out of its straight-line path is called a *centripetal force*. The centripetal force needed to keep an object in a circular path depends on the mass of the object, its velocity, and the radius of the circle.

The *universal law of gravitation* is a relationship between the masses of two objects, the distance between the objects, and a proportionality constant. Newton was able to use this relationship to show that gravitational attraction provides the centripetal force that keeps the moon in its orbit.

### SUMMARY OF EQUATIONS

$$2.1 \quad \text{average speed} = \frac{\text{distance}}{\text{time}}$$

$$\bar{v} = \frac{d}{t}$$

$$2.2 \quad \text{acceleration} = \frac{\text{change of velocity}}{\text{time}}$$

$$= \frac{\text{final velocity} - \text{initial velocity}}{\text{time}}$$

$$a = \frac{v_f - v_i}{t}$$

2.3 force = mass  $\times$  acceleration

$$F = ma$$

2.4 weight = mass  $\times$  acceleration due to gravity

$$w = mg$$

2.5 momentum = mass  $\times$  velocity

$$p = mv$$

2.6 change of momentum = force  $\times$  time

$$\Delta p = Ft$$

2.7 centripetal acceleration =  $\frac{\text{velocity squared}}{\text{radius of circle}}$

$$a_c = \frac{v^2}{r}$$

2.8 centripetal force =  $\frac{\text{mass} \times \text{velocity squared}}{\text{radius of circle}}$

$$F = \frac{mv^2}{r}$$

2.9 gravitational force = constant  $\times \frac{\text{one mass} \times \text{another mass}}{\text{distance squared}}$

$$F = G \frac{m_1 m_2}{d^2}$$

## KEY TERMS

acceleration (p. 27)

centripetal force (p. 44)

first law of motion (p. 37)

force (p. 29)

free fall (p. 32)

fundamental forces (p. 29)

$g$  (p. 34)

impulse (p. 43)

inertia (p. 32)

law of conservation of momentum (p. 42)

mass (p. 39)

momentum (p. 42)

net force (p. 29)

newton (p. 39)

second law of motion (p. 38)

speed (p. 25)

third law of motion (p. 40)

universal law of gravitation (p. 45)

velocity (p. 26)

## APPLYING THE CONCEPTS

1. A quantity of  $5 \text{ m/s}^2$  is a measure of
  - a. metric area.
  - b. acceleration.
  - c. speed.
  - d. velocity.
2. An automobile has how many different devices that can cause it to undergo acceleration?
  - a. none
  - b. one
  - c. two
  - d. three or more
3. Ignoring air resistance, an object falling toward the surface of Earth has a *velocity* that is
  - a. constant.
  - b. increasing.
  - c. decreasing.
  - d. acquired instantaneously but dependent on the weight of the object.
4. Ignoring air resistance, an object falling near the surface of Earth has an *acceleration* that is
  - a. constant.
  - b. increasing.
  - c. decreasing.
  - d. dependent on the weight of the object.
5. Two objects are released from the same height at the same time, and one has twice the weight of the other. Ignoring air resistance,
  - a. the heavier object hits the ground first.
  - b. the lighter object hits the ground first.
  - c. they both hit at the same time.
  - d. whichever hits first depends on the distance dropped.
6. A ball rolling across the floor slows to a stop because
  - a. there is a net force acting on it.
  - b. the force that started it moving wears out.
  - c. the forces are balanced.
  - d. the net force equals zero.
7. Considering the forces on the system of you and a bicycle as you pedal the bike at a constant velocity in a horizontal straight line,
  - a. the force you are exerting on the pedal is greater than the resisting forces.
  - b. all forces are in balance, with the net force equal to zero.
  - c. the resisting forces of air and tire friction are less than the force you are exerting.
  - d. the resisting forces are greater than the force you are exerting.
8. If you double the unbalanced force on an object of a given mass, the acceleration will be
  - a. doubled.
  - b. increased fourfold.
  - c. increased by one-half.
  - d. increased by one-fourth.

9. If you double the mass of a cart while it is undergoing a constant unbalanced force, the acceleration will be
  - a. doubled.
  - b. increased fourfold.
  - c. half as much.
  - d. one-fourth as much.
10. Doubling the distance between the center of an orbiting satellite and the center of Earth will result in what change in the gravitational attraction of Earth for the satellite?
  - a. one-half as much
  - b. one-fourth as much
  - c. twice as much
  - d. four times as much
11. If a ball swinging in a circle on a string is moved twice as fast, the force on the string will be
  - a. twice as great.
  - b. four times as great.
  - c. one-half as much.
  - d. one-fourth as much.
12. A ball is swinging in a circle on a string when the string length is doubled. At the same velocity, the force on the string will be
  - a. twice as great.
  - b. four times as great.
  - c. one-half as much.
  - d. one-fourth as much.

### Answers

1. b 2. d 3. b 4. a 5. c 6. a 7. b 8. a 9. c 10. b 11. b 12. c

## QUESTIONS FOR THOUGHT

1. An insect inside a bus flies from the back toward the front at 5.0 mi/h. The bus is moving in a straight line at 50.0 mi/h. What is the speed of the insect?
2. Disregarding air friction, describe all the forces acting on a bullet shot from a rifle into the air.
3. Can gravity act in a vacuum? Explain.
4. Is it possible for a small car to have the same momentum as a large truck? Explain.
5. What net force is needed to maintain the constant velocity of a car moving in a straight line? Explain.
6. How can an unbalanced force exist if every action has an equal and opposite reaction?
7. Why should you bend your knees as you hit the ground after jumping from a roof?
8. Is it possible for your weight to change as your mass remains constant? Explain.
9. What maintains the speed of Earth as it moves in its orbit around the Sun?
10. Suppose you are standing on the ice of a frozen lake and there is no friction whatsoever. How can you get off the ice? (*Hint:* Friction is necessary to crawl or walk, so that will not get you off the ice.)
11. A rocket blasts off from a platform on a space station. An identical rocket blasts off from free space. Considering everything else to be equal, will the two rockets have the same acceleration? Explain.
12. An astronaut leaves a spaceship that is moving through free space to adjust an antenna. Will the spaceship move off and leave the astronaut behind? Explain.

## PARALLEL EXERCISES

The exercises in groups A and B cover the same concepts. Solutions to group A exercises are located in appendix D.

*Note: Neglect all frictional forces in all exercises.*

### Group A

1. How far away was a lightning strike if thunder is heard 5.00 seconds after seeing the flash? Assume that sound traveled at 350.0 m/s during the storm.
2. What is the acceleration of a car that moves from rest to 15.0 m/s in 10.0 s?
3. What is the average speed of a truck that makes a 285-mile trip in 5.0 hours?
4. What force will give a 40.0 kg grocery cart an acceleration of 2.4 m/s<sup>2</sup>?
5. An unbalanced force of 18 N will give an object an acceleration of 3 m/s<sup>2</sup>. What force will give this very same object an acceleration of 10 m/s<sup>2</sup>?
6. A rocket pack with a thrust of 100 N accelerates a weightless astronaut at 0.5 m/s<sup>2</sup> through free space. What is the mass of the astronaut and equipment?
7. What is the momentum of a 100 kg football player who is moving at 6 m/s?
8. A car weighing 13,720 N is speeding down a highway with a velocity of 91 km/h. What is the momentum of this car?
9. A 15 g bullet is fired with a velocity of 200 m/s from a 6 kg rifle. What is the recoil velocity of the rifle?
10. A net force of 5,000.0 N accelerates a car from rest to 90.0 km/h in 5.0 s. (a) What is the mass of the car? (b) What is the weight of the car?
11. How much centripetal force is needed to keep a 0.20 kg ball on a 1.50 m string moving in a circular path with a speed of 3.0 m/s?
12. On Earth, an astronaut and equipment weigh 1,960.0 N. While weightless in space, the astronaut fires a 100 N rocket backpack for 2.0 s. What is the resulting velocity of the astronaut and equipment?

### Group B

1. How many meters away is a cliff if an echo is heard one-half second after the original sound? Assume that sound traveled at 343 m/s on that day.
2. What is the acceleration of a car that moves from a speed of 5.0 m/s to a speed of 15 m/s during a time of 6.0 s?
3. What is the average speed of a car that travels 270.0 miles in 4.50 hours?
4. What force would an asphalt road have to give a 6,000 kg truck in order to accelerate it at 2.2 m/s<sup>2</sup> over a level road?
5. If a space probe weighs 39,200 N on the surface of Earth, what will be the mass of the probe on the surface of Mars?
6. On Earth, an astronaut and equipment weigh 1,960 N. Weightless in space, the motionless astronaut and equipment are accelerated by a rocket pack with a 100 N thruster that fires for 2 s. What is the resulting final velocity?
7. What is the momentum of a 30.0 kg shell fired from a cannon with a velocity of 500 m/s?
8. What is the momentum of a 39.2 N bowling ball with a velocity of 7.00 m/s?
9. A 30.0 kg shell fired from a 2,000 kg cannon will have a velocity of 500 m/s. What is the resulting velocity of the cannon?
10. A net force of 3,000.0 N accelerates a car from rest to 36.0 km/h in 5.00 s. (a) What is the mass of the car? (b) What is the weight of the car?
11. What tension must a 50.0 cm length of string support in order to whirl an attached 1,000.0 g stone in a circular path at 5.00 m/s?
12. A 200.0 kg astronaut and equipment move with a velocity of 2.00 m/s toward an orbiting spacecraft. How long will the astronaut need to fire a 100.0 N rocket backpack to stop the motion relative to the spacecraft?

## FOR FURTHER ANALYSIS

1. What are the significant similarities and differences between speed and velocity?
2. What are the significant similarities and differences between velocity and acceleration?
3. Compare your beliefs and your own reasoning about motion before and after learning Newton's three laws of motion.
4. Newton's law of gravitation explains that every object in the universe is attracted to every other object in the universe. Describe a conversation between yourself and another person who does not believe this law, as you persuade them that the law is indeed correct.
5. Why is it that your weight can change by moving from one place to another, but your mass stays the same?
6. Assess the reasoning that Newton's first law of motion tells us that centrifugal force does not exist.

## INVITATION TO INQUIRY

### THE DOMINO EFFECT

The *domino effect* is a cumulative effect produced when one event initiates a succession of similar events. In the actual case of dominoes, a row is made by standing dominoes on their end face to face in a line. When one on the end is tipped over toward the others, it will fall into its neighbor, which falls into the next one, and so on until the whole row has fallen. How should the dominoes be spaced so the row falls with maximum speed? Should one domino strike the next one as high as possible, in the center, or as low as possible? If you accept this invitation, you will need to determine how you plan to space the dominoes as well as how you will measure the speed.