PHYSICS

2 Motion

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

CORE CONCEPT

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

OUTLINE

2.1 Describing Motion
2.2 Measuring Motion
Speed
Velocity
Acceleration
Science and Society: Transportation and the Environment
Forces
2.3 Horizontal Motion on Land
2.4 Falling Objects
A Closer Look: A Bicycle Racer's Edge
2.5 Compound Motion
Vertical Projectiles
Horizontal Projectiles
A Closer Look: Free Fall
2.6 Three Laws of Motion
Newton's First Law of Motion
Newton's Second Law of Motion
Weight and Mass
Newton's Third Law of Motion
2.7 Momentum
Conservation of Momentum
Impulse
2.8 Forces and Circular Motion
2.9 Newton's Law of Gravitation
Earth Satellites
A Closer Look: Gravity Problems
Weightlessness
People Behind the Science: Isaac Newton

Forces
Inertia is the tendency of an object to remain in unchanging motion when the net force is zero.

Newton's First Law of Motion
Every object retains its state of rest or straight-line motion unless acted upon by an unbalanced force.

Newton's Third Law of Motion
A single force does not exist by itself; there is always a matched and opposite force that occurs at the same time.

Falling Objects
The force of gravity uniformly accelerates falling objects.

Newton's Second Law of Motion
The acceleration of an object depends on the net force applied and the mass of the object.

Newton's Law of Gravitation
All objects in the universe are attracted to all other objects in the universe.

OVERVIEW

In chapter 1, you learned some "tools and rules" and some techniques for finding order in your physical surroundings. Order is often found in the form of patterns, or relationships between quantities that are expressed as equations. Recall that 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 physical 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 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, bicycles, and surfboards (Figure 2.1). On the other hand, the Sun, the Moon, and starry heavens seem to always 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 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.

2.1 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 moving, all 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.

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.

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.

2.2 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. These combinations of measurement 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

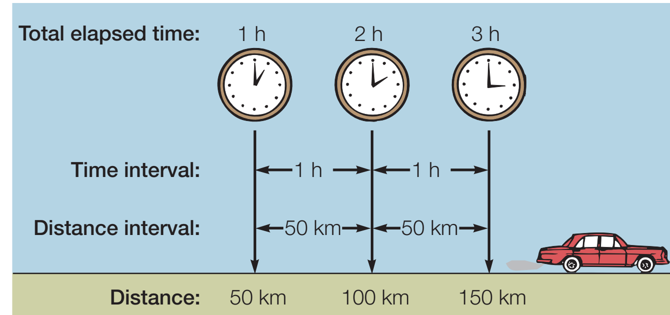

FIGURE 2.2 If you know the value of any two of the three variables of distance, time, and speed, you can find the third. What is the average speed of this car? Two ways of finding the answer are in Figure 2.3.

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. 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.

If your car were moving over equal distances in equal periods of time, it would have a *constant speed* (Figure 2.2). 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.

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 to time is usually read as distance per time, such as miles per hour. The *per* means "for each."

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, the letter d can be used to stand for distance, and the letter t to stand for time. A bar over the v ($\bar{v}$) is a symbol that means average (it is read "v-bar" or "v-average"). The relationship between average speed, distance, and time is therefore

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

equation 2.1

This is one of the three types of equations that were discussed on page 10, and in this case, the equation defines a motion property. You can use this relationship to find average speed. For example, suppose a car travels 150 km in 3 h. What was the average speed? Since $d = 150$ km and $t = 3$ h, then

$$\bar{v} = \frac{150 \text{ km}}{3 \text{ h}}$$

$$= 50\frac{\text{km}}{\text{h}}$$

As with other equations, you can mathematically solve the equation for any term as long as two variables are known (Figure 2.3). For example, suppose you know the speed and the time but want to find the distance traveled. You can solve this by first writing the relationship

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

and then multiplying both sides of the equation by t (to get d on one side by itself),

$$(\bar{v})(t) = \frac{(d)(\cancel{t})}{\cancel{t}}$$

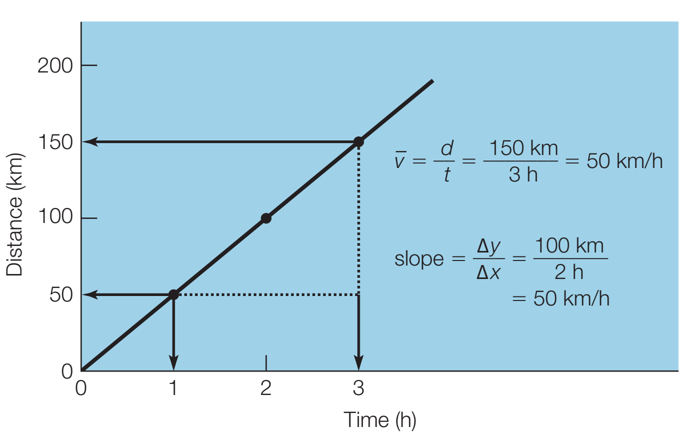

FIGURE 2.3 Speed is distance per unit of time, which can be calculated from the equation or by finding the slope of a distance-versus-time graph. This shows both ways of finding the speed of the car shown in Figure 2.2.

and the t's on the right cancel, leaving

$$\bar{v}t = d \qquad \text{or} \qquad d = \bar{v}t$$

If the $\bar{v}$ is 50 km/h and the time traveled is 2 h, then

$$d = \left(50\frac{\text{km}}{\text{h}}\right)(2 \text{ h})$$

$$= (50)(2)\left(\frac{\text{km}}{\text{h}}\right)(\text{h})$$

$$= 100\frac{(\text{km})(\cancel{\text{h}})}{\cancel{\text{h}}}$$

$$= 100 \text{ km}$$

Notice how both the numerical values and the units were treated mathematically. See "How to Solve Problems" in chapter 1 for more information.

EXAMPLE 2.1

The driver of a car moving at 72.0 km/h drops a road map on the floor. It takes him 3.00 seconds to locate and pick up the map. How far did he 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

$$\bar{v} = \frac{0.2778\frac{\text{m}}{\text{s}}}{\frac{\text{km}}{\text{h}}} \times 72.0\frac{\text{km}}{\text{h}}$$

$$= (0.2778)(72.0)\frac{\text{m}}{\text{s}} \times \frac{\text{h}}{\text{km}} \times \frac{\text{km}}{\text{h}}$$

$$= 20.0\frac{\text{m}}{\text{s}}$$

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

$\bar{v} = 20.0\frac{\text{m}}{\text{s}}$

$t = 3.00$ s

$d = ?$

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

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

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

$$= \left(20.0\frac{\text{m}}{\text{s}}\right)(3.00 \text{ s})$$

$$= (20.0)(3.00)\frac{\text{m}}{\text{s}} \times \frac{\text{s}}{1}$$

$$= \boxed{60.0 \text{ m}}$$

EXAMPLE 2.2

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

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.

VELOCITY

The word *velocity* is sometimes used interchangeably with the word speed, but there is a difference. **Velocity** describes the *speed 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 Earth does not have a constant velocity since its direction of movement is constantly changing. Velocity can be represented graphically with arrows. The lengths of the arrows are proportional to the magnitude, and the arrowheads indicate the direction (Figure 2.4).

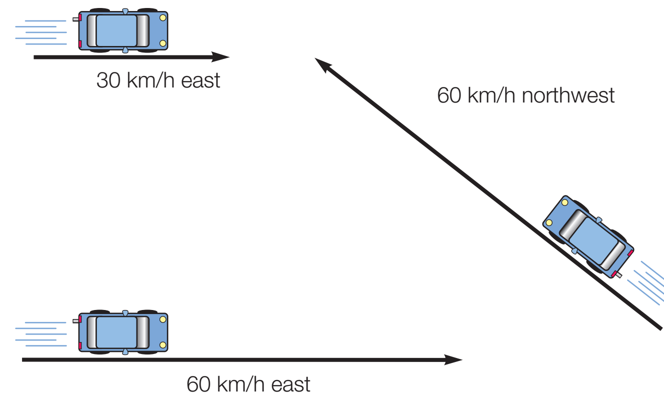

FIGURE 2.4 Here are three different velocities represented by three different arrows. The length of each arrow is proportional to the speed, and the arrowhead shows the direction of travel.

ACCELERATION

Motion can be changed in three different ways: (1) by changing the speed, (2) by changing the direction of travel, or (3) combining both of these by changing both the speed and the direction of travel at the same time. 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 define 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

$$\text{acceleration} = \frac{80\frac{\text{km}}{\text{h}} - 60\frac{\text{km}}{\text{h}}}{4\ \text{s}}$$

$$= \frac{20\frac{\text{km}}{\text{h}}}{4\ \text{s}}$$

$$= 5\frac{\text{km/h}}{\text{s}} \text{ or}$$

$$= 5\ \text{km/h/s}$$

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

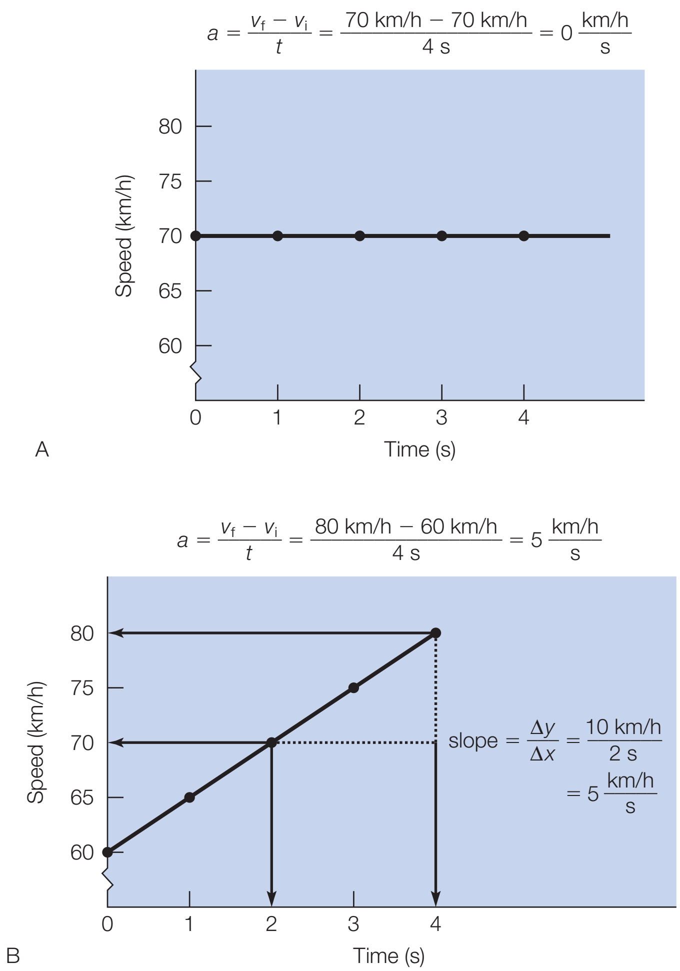

FIGURE 2.5 (*A*) This graph shows how the speed changes per unit of time while driving at a constant 70 km/h in a straight line. As you can see, the speed is constant, and for straight-line motion, the acceleration is 0. (*B*) This graph shows the speed increasing from 60 km/h to 80 km/h for 5 s. The 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.

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 that 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 m/s $\times$ 1/s = m/s^2). Remember that the expression 1.4 m/s^2 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

As in other equations, any one of these quantities can be found if the others are known. For example, solving the equation for the final velocity, v_f, yields

$$v_f = at + v_i$$

In problems where the initial velocity is equal to zero (starting from rest), the equation simplifies to

$$v_f = at$$

Recall from chapter 1 that the symbol Δ means "the change in" a value. Therefore, equation 2.1 for speed could be written

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

and equation 2.2 for acceleration could be written

$$a = \frac{\Delta v}{t}$$

This shows that both equations are a time rate of change. Speed is a time rate change of *distance*. Acceleration is a time rate change of *velocity*. The time rate of change of something is an important concept that you will meet again in chapter 3.

EXAMPLE 2.3

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

SOLUTION

$v_i = 0$ m/s

$v_f = 5$ m/s

$t = 5$ s

$a = ?$

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

$$= \frac{5 \text{ m/s} - 0 \text{ m/s}}{5 \text{ s}}$$

$$= \frac{5}{5}\frac{\text{m/s}}{\text{s}}$$

$$= 1\left(\frac{\text{m}}{\text{s}}\right)\left(\frac{1}{\text{s}}\right)$$

$$= \boxed{1 \frac{\text{m}}{\text{s}^2}}$$

EXAMPLE 2.4

An automobile uniformly accelerates from rest at 5 m/s^2 for 6 s. What is the final velocity in m/s? (Answer: 30 m/s)

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 whenever possible.

B. Combine trips to the store, mall, and work, leaving the car parked whenever possible.

C. Purchase hybrid electric or fuel cell–powered cars or 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 your feelings be different 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?

So far, you have learned only about straight-line, uniform acceleration that results in an increased velocity. 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, 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 and direction, so a change of direction is an acceleration. The satellite moving with a constant speed in a circular orbit around 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 the magnitude of velocity), the brakes (which can decrease the magnitude of velocity), and the steering wheel (which can change the direction of the velocity). (See Figure 2.6.) The important thing to remember is that acceleration results from any *change* in the motion of an object.

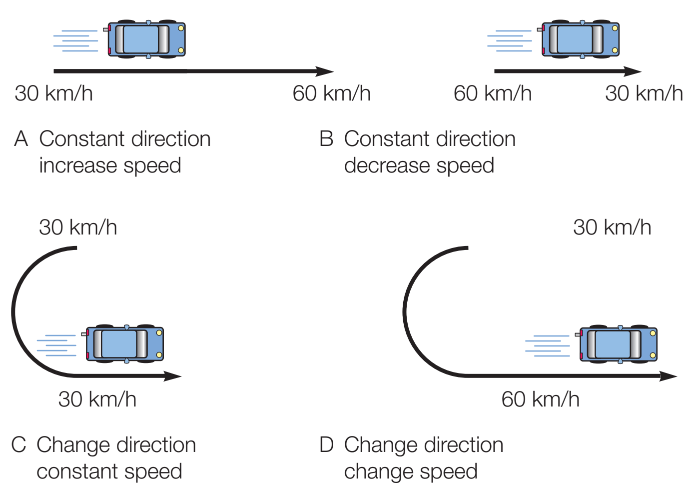

FIGURE 2.6 Four different ways (*A–D*) to accelerate a car.

The final velocity (v_f) and the initial velocity (v_i) are different variables than the average velocity ($\bar{v}$). You cannot use an initial or final velocity for an average velocity. You may, however, calculate an average velocity ($\bar{v}$) from the other two variables as long as the acceleration taking place between the initial and final velocities is uniform. An example of such a uniform change would be an automobile during a constant, straight-line acceleration. To find an average velocity *during* a uniform acceleration, you add the initial velocity and the final velocity and divide by 2. This averaging can be done for a uniform acceleration that is increasing the velocity or for one that is decreasing the velocity. In symbols,

$$\bar{v} = \frac{v_f + v_i}{2}$$

equation 2.3

EXAMPLE 2.5

An automobile moving at 25.0 m/s comes to a stop in 10.0 s when the driver slams on the brakes. How far did the car travel while stopping?

SOLUTION

The car has an initial velocity of 25.0 m/s (v_i) and the final velocity of 0 m/s (v_f) is implied. The time of 10.0 s (t) is given. The problem asked for the distance (d). The relationship given between $\bar{v}$, t, and d is given in equation 2.1, $\bar{v} = d/t$, which can be solved for d. The average velocity ($\bar{v}$), however, is not given but can be found from equation 2.3.

$$\bar{v} = \frac{v_f + v_i}{2} \qquad \bar{v} = \frac{d}{t} \quad \therefore \quad d = \bar{v} \cdot t$$

$v_i = 25.0$ m/s

$v_f = 0$ m/s

$t = 10.0$ s

$\bar{v} = ?$

$d = ?$

Since $\bar{v} = \dfrac{v_f + v_i}{2}$,

you can substitute $\left(\dfrac{v_f + v_i}{2}\right)$ for $\bar{v}$, and

$$d = \left(\frac{v_f + v_i}{2}\right)(t)$$

$$= \left(\frac{0\frac{\text{m}}{\text{s}} + 25.0\frac{\text{m}}{\text{s}}}{2}\right)(10.0 \text{ s})$$

$$= 12.5 \times 10.0 \frac{\text{m}}{\text{s}} \times \text{s}$$

$$= 125 \frac{\text{m} \cdot \cancel{\text{s}}}{\cancel{\text{s}}}$$

$$= \boxed{125 \text{ m}}$$

EXAMPLE 2.6

What was the deceleration of the automobile in example 2.5? (Answer: -2.50 m/s^2)

CONCEPTS *Applied*

Acceleration Patterns

Suppose the radiator in your car has a leak and drops of fluid fall constantly, one every second. What pattern will the drops make on the pavement when you accelerate the car from a stoplight? What pattern will they make when you drive at a constant speed? What pattern will 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.

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 would take 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.

A **force** is a push or a pull that is acting on 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 are 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 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 net 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 the gravitational, electromagnetic, weak, and strong nuclear forces. Gravitational forces act between all objects in the universe—between you and Earth, between Earth and the Sun, between the planets in the solar system—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 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

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. In 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?

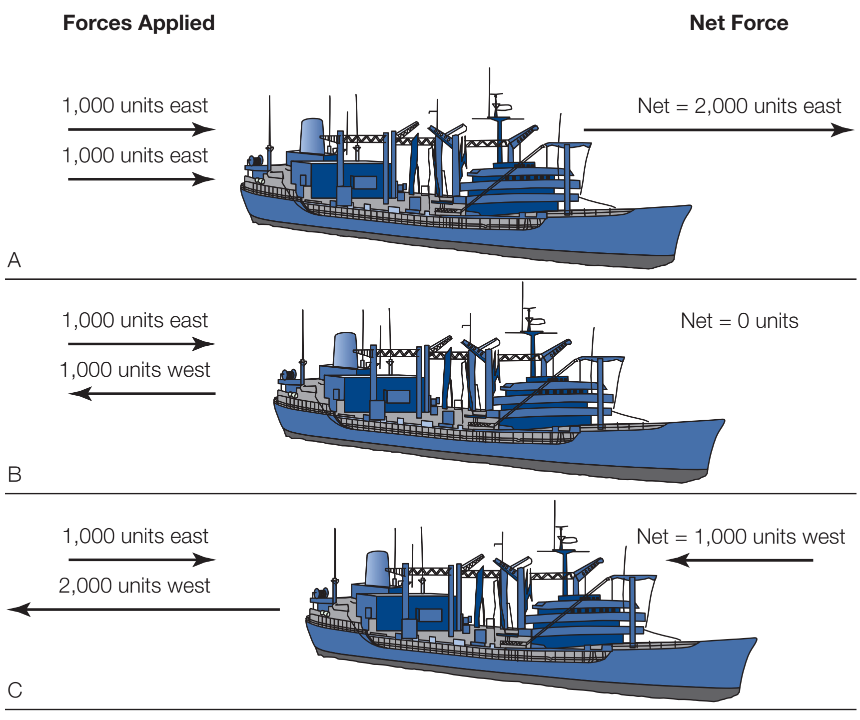

FIGURE 2.8 (*A*) When two parallel forces are acting on the ship in the same direction, the net force is the two forces added together. (*B*) When two forces are opposite and of equal size, the net force is zero. (*C*) When two parallel forces in opposite directions are not of equal size, the net force is the difference in the direction of the larger force.

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 gravitation 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.

2.3 HORIZONTAL MOTION ON LAND

Everyday experience seems to indicate that Aristotle's idea about horizontal motion on Earth's surface is correct. After all, moving objects that are not pushed or pulled do come to rest in 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 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 a floor covered with carpet. The rough carpet offers more resistance to the rolling ball. The resistance of the floor friction is shown by a force arrow, F_{floor}, in Figure 2.9. This force, along with the force arrow for air resistance, F_{air}, opposes the forward movement of the ball. Notice the dashed line arrow in part A of Figure 2.9. 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 2.9 can help you determine the amount of force. The force you apply, $F_{applied}$, 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. The force $F_{applied}$ has the same length as the sum of the two resistance forces, but it is in the opposite direction to the resistance forces. Therefore, the overall force, F_{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.

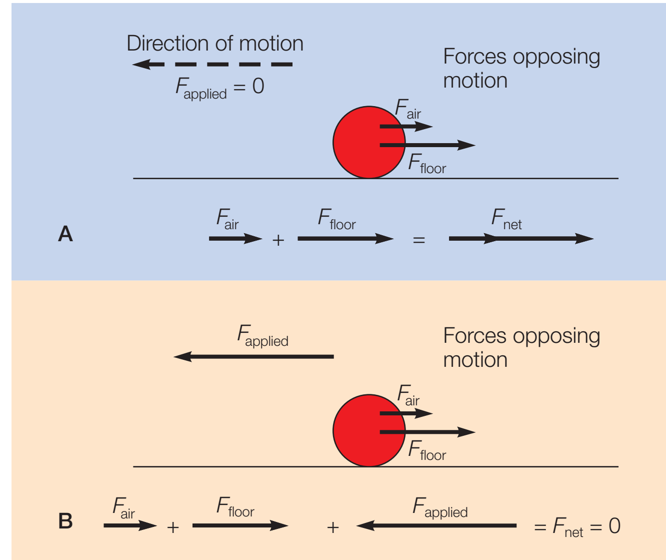

FIGURE 2.9 The following focus is on horizontal forces only: (*A*) This ball is rolling to your left with no forces in the direction of motion. The sum of the force of floor friction (F_{floor}) and the force of air friction (F_{air}) results in a net force opposing the motion, so the ball slows to a stop. (*B*) A force is applied to the moving ball, perhaps by a hand that moves along with the ball. The force applied ($F_{applied}$) equals the sum of the forces opposing the motion, so the ball continues to move with a constant velocity.

It could be argued that the difference in Aristotle's and Galileo's views of forced motion is really in degree of analysis. After all, moving objects on 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 of the motion of objects. Aristotle argued that the natural state of objects is to be at rest, and he tried to explain why objects move. Galileo, on the other hand, argued that it is just as natural for objects to be moving, and he tried to explain why they come to rest. Galileo called the behavior of matter that causes it to persist in its state of motion **inertia.** Inertia is the *tendency of an object to remain in unchanging motion whether actually at rest or moving in the absence of an unbalanced force* (friction, gravity, or whatever). 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 spacecraft moving through free space will continue to do so with no unbalanced forces acting on it (Figure 2.10A). An unbalanced force is needed to slow the spacecraft (Figure 2.10B), increase its speed (Figure 2.10C), or change its direction of travel (Figure 2.10D).

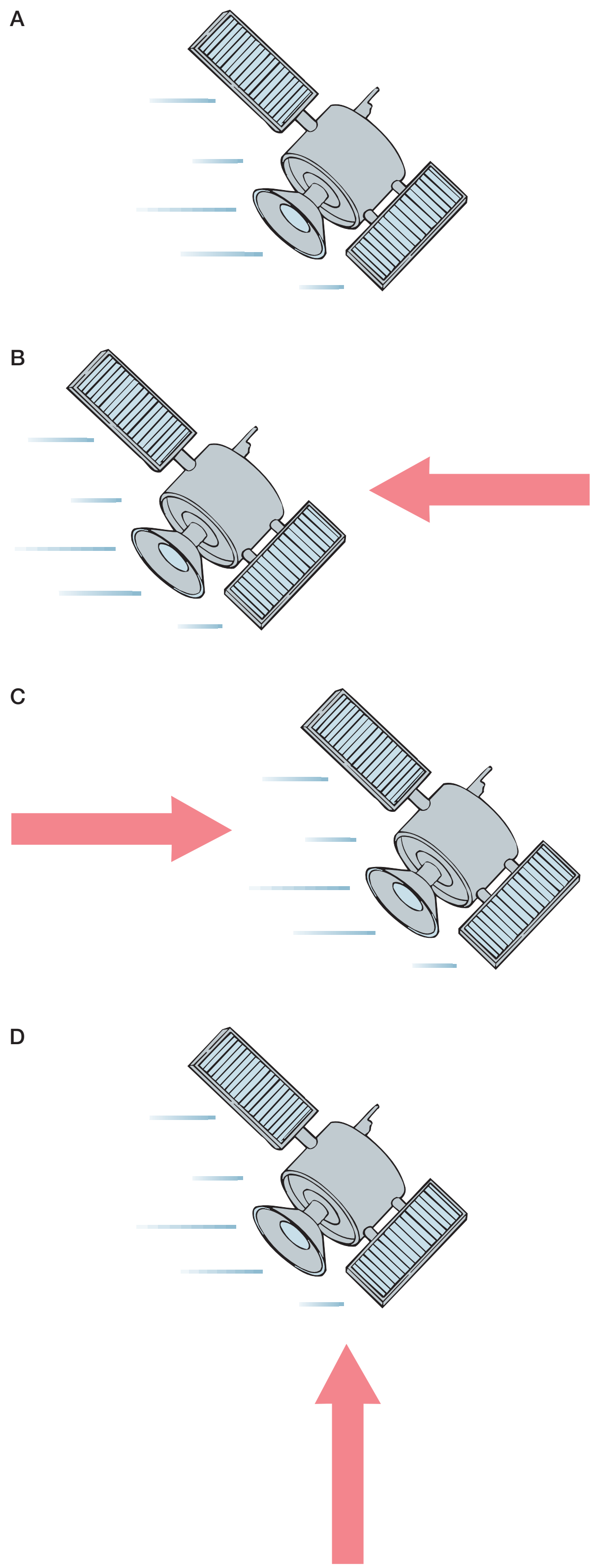

FIGURE 2.10 Examine the four illustrations and explain how together they illustrate inertia.

Myths, Mistakes, & 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 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.

2.4 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 2.11). 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

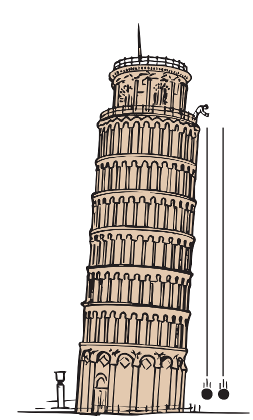

FIGURE 2.11 According to a widespread story, Galileo dropped two objects with different weights from the Leaning Tower of Pisa. They reportedly hit the ground at about the same time, discrediting Aristotle's view that the speed during the fall is proportional to weight.

resistance on the feather has been removed. When objects fall toward Earth without air resistance being considered, they are said to be in **free fall.** Free fall considers only gravity and neglects air resistance.

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.

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 each other? To answer this question, Galileo made calculations involving distance, velocity, and time and, in fact, introduced the concept of acceleration. The relationships between these variables are found in the same three equations that you have already learned. Let's see how the equations can be rearranged to incorporate acceleration, distance, and time for an object in free fall.

Step 1: Equation 2.1 gives a relationship between average velocity ($\bar{v}$), distance (d), and time (t). Solving this equation for distance gives

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

Step 2: An object in free fall should have uniformly accelerated motion, so the average velocity could be calculated from equation 2.3,

$$\bar{v} = \frac{v_f + v_i}{2}$$

Substituting this equation in the rearranged equation 2.1, the distance relationship becomes

$$d = \left(\frac{v_f + v_i}{2}\right)(t)$$

Step 3: The initial velocity of a falling object is always zero just as it is dropped, so the v_i can be eliminated,

$$d = \left(\frac{v_f}{2}\right)(t)$$

Step 4: Now you want to get acceleration into the equation in place of velocity. This can be done by solving equation 2.2 for the final velocity (v_f), then substituting. The initial velocity (v_i) is again eliminated because it equals zero.

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

$$v_f = at$$

$$d = \left(\frac{at}{2}\right)(t)$$

Step 5: Simplifying, the equation becomes

$$d = \frac{1}{2}at^2$$

equation 2.4

Thus, Galileo reasoned that a freely falling object should cover a distance *proportional to the square of the time of the fall* ($d \propto t^2$). 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. Compare this prediction with Figure 2.12.

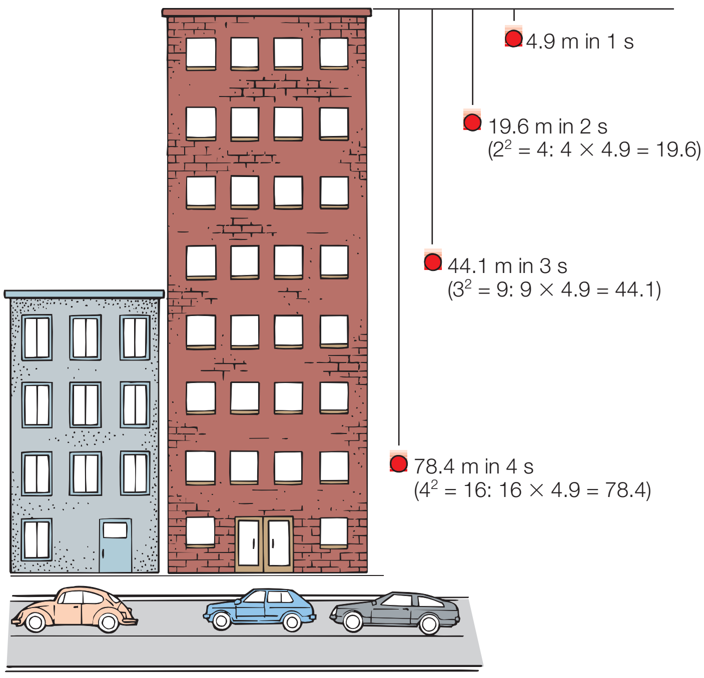

FIGURE 2.12 An object dropped from a tall building covers increasing distances with every successive second of falling. The distance covered is proportional to the square of the time of falling ($d \propto t^2$).

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 2.9, 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. They can move 8 km/h faster than they would expending the same energy 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 32 km/h, a cyclist must move a little less than one-half a ton of air out of the way every minute. Along with the problem of moving air out of the way, 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 teardroplike 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.

BOX FIGURE 2.1 The object of the race is to be in the front, to finish first. If this is true, why are racers forming single-file lines?

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 Lycra 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 and the wearing of Lycra 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.

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*, as shown in Figure 2.13. 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 m/s^2 (32 ft/s^2).

The acceleration of objects falling toward Earth varies slightly from place to place on the 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 m/s^2 (32 ft/s^2) is an approximation that is fairly close to, but

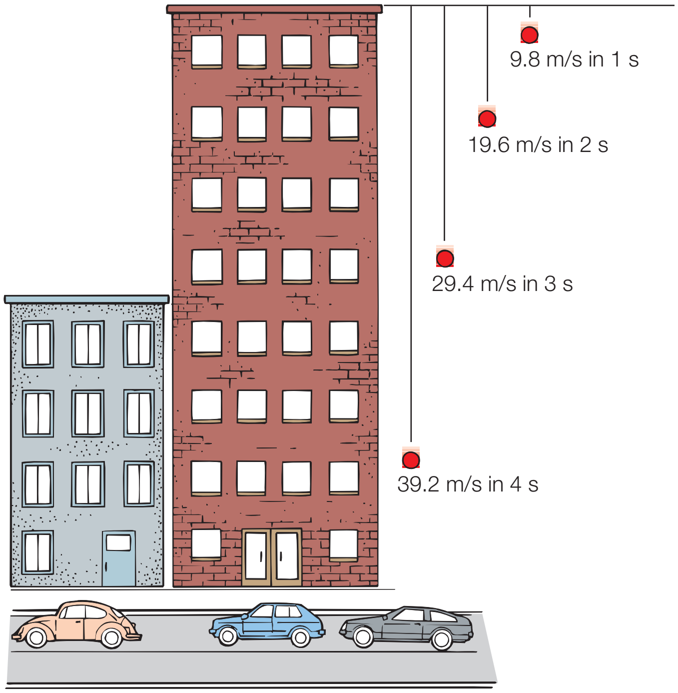

FIGURE 2.13 The velocity of a falling object increases at a constant rate, 9.8 m/s^2.

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, $\boldsymbol{g}$.

EXAMPLE 2.7

A rock that is dropped into a well hits the water in 3.0 s. Ignoring air resistance, how far is it to the water?

SOLUTION 1

The problem concerns a rock in free fall. The time of fall (t) is given, and the problem asks for a distance (d). Since the rock is in free fall, the acceleration due to the force of gravity (g) is implied. The metric value and unit for g is 9.8 m/s^2, and the English value and unit is 32 ft/s^2. You would use the metric g to obtain an answer in meters and the English unit to obtain an answer in feet. Equation 2.4, $d = 1/2\ at^2$, gives a relationship between distance (d), time (t), and average acceleration (a). The acceleration in this case is the acceleration due to gravity (g), so

$t = 3.0$ s

$g = 9.8$ m/s^2

$d = ?$

$$d = \frac{1}{2}gt^2 \quad (a = g = 9.8 \text{ m/s}^2)$$

$$\begin{aligned} d &= \frac{1}{2}(9.8 \text{ m/s}^2)(3.0 \text{ s})^2 \\ &= (4.9 \text{ m/s}^2)(9.0 \text{ s}^2) \\ &= 44 \frac{\text{m}\cdot\cancel{\text{s}^2}}{\cancel{\text{s}^2}} \\ &= \boxed{44 \text{ m}} \end{aligned}$$

SOLUTION 2

You could do each step separately. Check this solution by a three-step procedure:

1. Find the final velocity, v_f, of the rock from $\bar{v}_f = at$.
2. Calculate the average velocity ($\bar{v}$) from the final velocity.

$$\bar{v} = \frac{v_f + v_i}{2}$$

3. Use the average velocity ($\bar{v}$) and the time (t) to find distance $d = \bar{v}t$.

Note that the one-step procedure is preferred over the three-step procedure because fewer steps mean fewer possibilities for mistakes.

2.5 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.

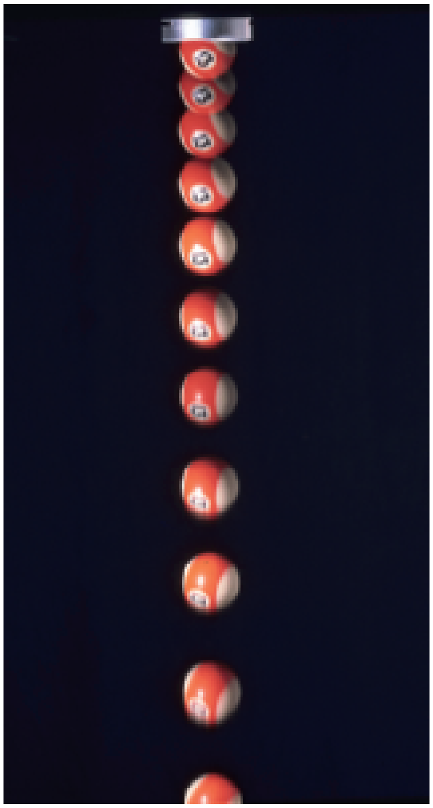

FIGURE 2.14 High-speed, multiflash photograph of a freely falling billiard ball.

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 (Figure 2.14). If it were not for air resistance, the ball would return with the same speed in the opposite direction that it had initially. The velocity arrows for a ball thrown straight up are shown in Figure 2.15.

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

A Closer Look

Free Fall

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 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 to 210 km/h (about 115 to 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.

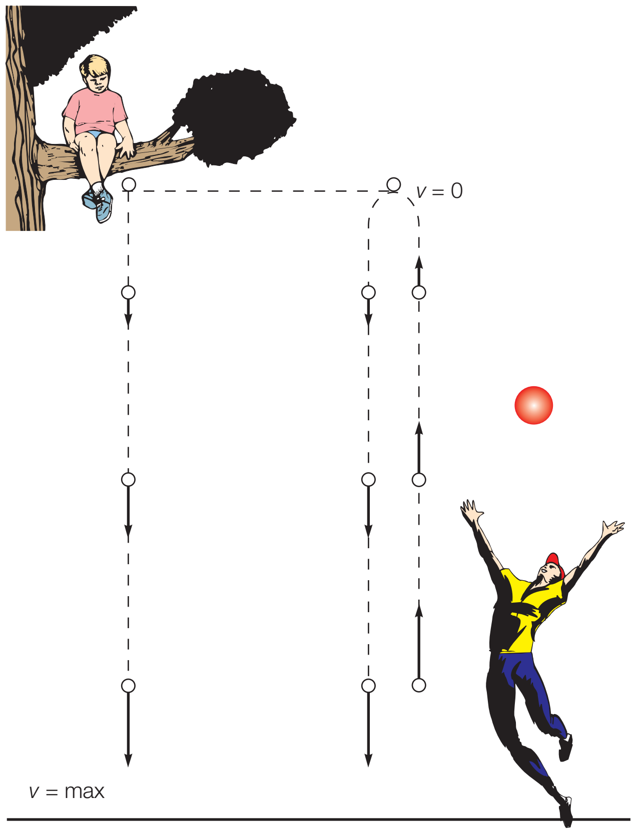

FIGURE 2.15 On its way up, a vertical projectile is slowed by the force of gravity until an instantaneous stop; then it accelerates back to the surface, just as another ball does when dropped from the same height. The straight up and down moving ball has been moved to the side in the sketch so we can see more clearly what is happening. Note that the falling ball has the same speed in the opposite direction that it had on the way up.

downward velocity is shown in Figure 2.16 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 2.16). 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 2.17. The next time you have the opportunity, observe the path of a ball that has been projected at some angle. 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° results in the maximum distance of travel if air resistance is ignored and if the launch point and the landing are at the same elevation.

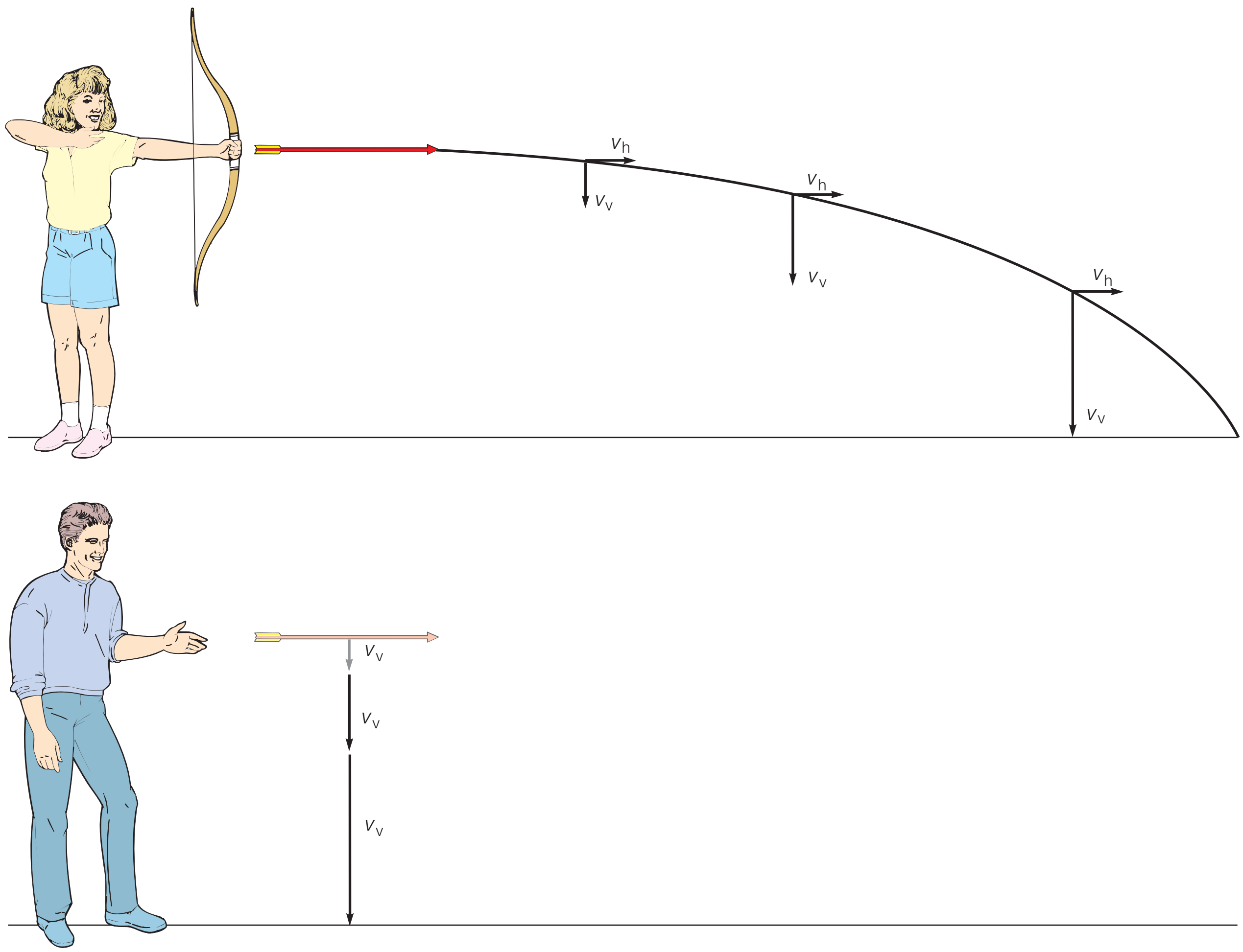

FIGURE 2.16 A horizontal projectile has the same horizontal velocity throughout the fall as it accelerates toward the surface, with the combined effect resulting in a curved path. Neglecting air resistance, an arrow shot horizontally will strike the ground at the same time as one dropped from the same height above the ground, as shown here by the increasing vertical velocity arrows.

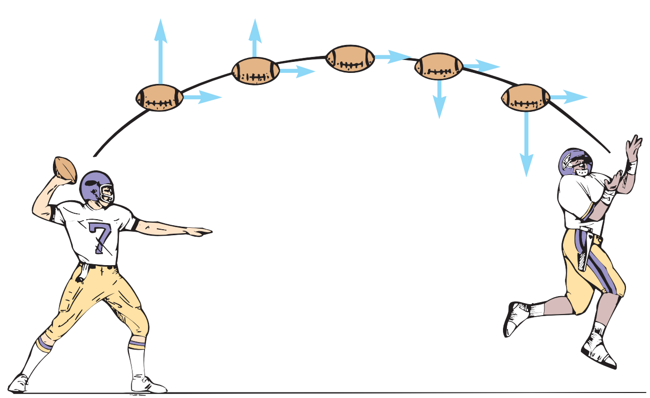

FIGURE 2.17 A football is thrown at some angle to the horizon when it is passed downfield. Neglecting air resistance, the horizontal velocity is a constant, and the vertical velocity decreases, then increases, just as in the case of a vertical projectile. The combined motion produces a parabolic path. 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.

2.6 THREE LAWS OF MOTION

In the previous sections, you learned how to describe motion in terms of distance, time, velocity, and acceleration. In addition, you learned about different kinds of motion, such as straight-line motion, the motion of falling objects, and the compound motion of objects projected up from the surface of Earth. You were also introduced, in general, to two concepts closely associated with motion: (1) that objects have inertia, a tendency to resist a change in motion, and (2) that forces are involved in a change of motion.

The relationship between forces and a change of motion is obvious in many everyday situations (Figure 2.18). When a car, bus, or plane starts moving, you feel a force on your back. Likewise, you feel a force on the bottoms of your feet when an elevator starts moving upward. On the other hand, you seem to be forced toward the dashboard if a car stops quickly, and it feels as if the floor pulls away from your feet when an elevator drops rapidly. These examples all involve patterns between forces and motion, patterns that can be quantified,

FIGURE 2.18 In a moving airplane, you feel forces in many directions when the plane changes its motion. You cannot help but notice the forces involved when there is a change of motion.

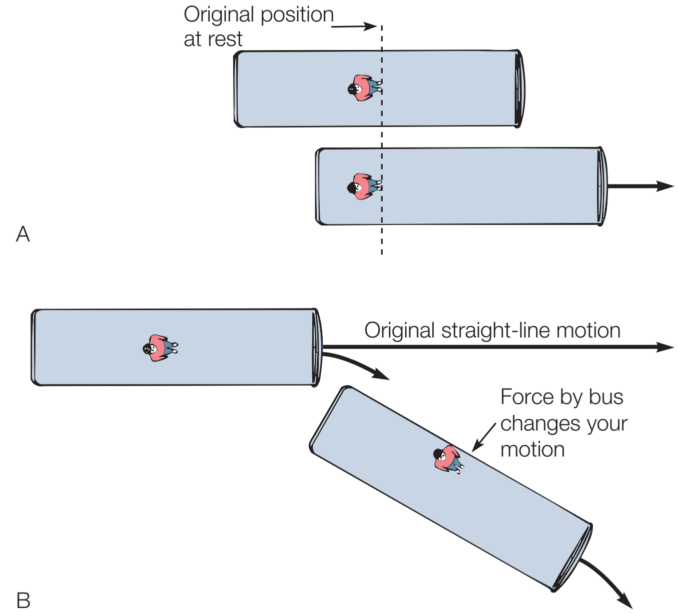

FIGURE 2.19 Top view of a person standing in the aisle of a bus. (*A*) The bus is at rest and then starts to move forward. Inertia causes the person to remain in the original position, appearing to fall backward. (*B*) The bus turns to the right, but inertia causes the person to retain the original straight-line motion until forced in a new direction by the side of the bus.

conceptualized, and used to answer questions about why things move or stand still. These patterns are the subject of Newton's three laws of motion.

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 2.19).

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.

NEWTON'S SECOND LAW OF MOTION

Newton had 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 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 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 2.20).

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. 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 net force applied.

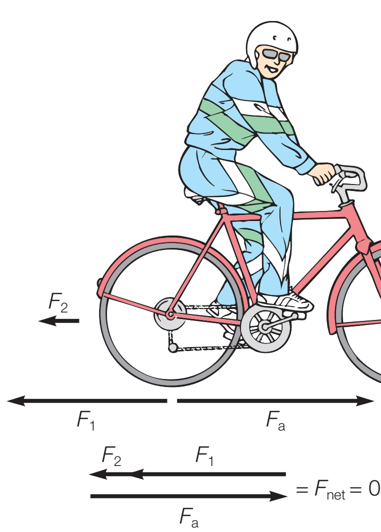

FIGURE 2.20 At a constant velocity, the force of tire friction (F_1) and the force of air resistance (F_2) have a sum that equals the force applied (F_a). The net force is therefore 0.

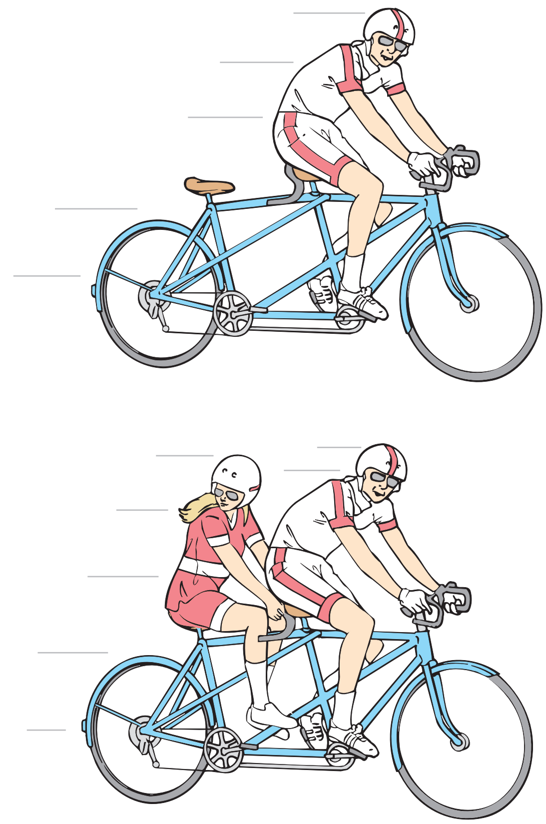

FIGURE 2.21 More mass results in less acceleration when the same force is applied. With the same force applied, the riders and bike with twice the mass will have one-half the acceleration, with all other factors constant. Note that the second rider is not pedaling.

Suppose that your bicycle has two seats, and you have a friend who will ride with you but not pedal. 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 one-half as much (Figure 2.21). An even more massive friend would reduce the acceleration more. 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 is therefore inversely proportional to its mass.

If we express force in appropriate units, we can combine these relationships as an equation,

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

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

$$F = ma$$

equation 2.5

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 m/s^2. The combination of these units, (kg)(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.

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.**

Until now, equations were used to *describe properties* of matter such as density, velocity, and acceleration. This is your first example of an equation that is used to *define a concept,* specifically the concept of what is meant by a force. Since the concept is defined by specifying a measurement procedure, it is also an example of an *operational definition*. You are told not only what a newton of force is, but also how to go about measuring it. Notice that the newton is defined in terms of mass measured in kg and acceleration measured in m/s^2. Any other units must be converted to kg and m/s^2 before a problem can be solved for newtons of force.

EXAMPLE 2.8

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

SOLUTION

The mass (m) of 60 kg and the acceleration (a) of 0.5 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, $F = ma$.

$$m = 60 \text{ kg} \qquad a = 0.5\frac{\text{m}}{\text{s}^2} \qquad F = ?$$

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

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 m/s^2. (Note that the units kg·m/s^2 form the definition of a newton of force, so the symbol N is used.)

EXAMPLE 2.9

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

CONCEPTS *Applied*

Second Law Experiment

Tie one end of a string to a book and the other end to a large elastic band. With your index finger curled in the loop of the elastic band, pull the book across a smooth tabletop. How much the elastic 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?

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.

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 he 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) than 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

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

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

equation 2.6

You learned in the section on falling objects that g is the symbol used to represent acceleration due to gravity. Near Earth's surface, g has an approximate value of 9.8 m/s^2. To understand how g is applied to an object that is 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 acceleration due to gravity. Thus, $F_{net} = w = ma = mg$. 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.

In the metric system, *mass* is measured in kilograms. The acceleration due to gravity, g, is 9.8 m/s^2. According to equation 2.6, weight is mass times acceleration. A kilogram multiplied by an acceleration measured in m/s^2 results in kg·m/s^2, a unit you now recognize as a force called a newton. The *unit of weight* in the metric system is therefore the *newton* (N).

In the English system, the pound is the unit of *force*. The acceleration due to gravity, g, is 32 ft/s^2. The force unit of a pound is defined as the force required to accelerate a unit of mass called the *slug*. Specifically, a force of 1.0 lb will give a 1.0 slug mass an acceleration of 1.0 ft/s^2.

The 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 kg.

TABLE 2.1

Units of Mass and Weight in the Metric and English Systems of Measurement

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

EXAMPLE 2.10

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) of 9.8 m/s^2 is implied. The problem asked for the weight (w). The relationship is found in equation 2.6, $w = mg$, which is a form of $F = ma$.

$m = 60.0$ kg

$g = 9.8 \frac{\text{m}}{\text{s}^2}$

$w = ?$

$$\begin{aligned} w &= mg \\ &= (60.0\ \text{kg})\left(9.8\frac{\text{m}}{\text{s}^2}\right) \\ &= (60.0)(9.8)\ (\text{kg})\left(\frac{\text{m}}{\text{s}^2}\right) \\ &= 588\frac{\text{kg·m}}{\text{s}^2} \\ &= \boxed{590\ \text{N}} \end{aligned}$$

EXAMPLE 2.11

A 60.0 kg person weighs 100.0 N on the Moon. What is the acceleration of gravity on the Moon? (Answer: 1.67 m/s^2)

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 nor 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 spacecraft in space. According to Newton's second law ($F = ma$), a force must be applied to change the state of motion of the spacecraft. What is a possible source of such a force? Perhaps an astronaut pushes on the

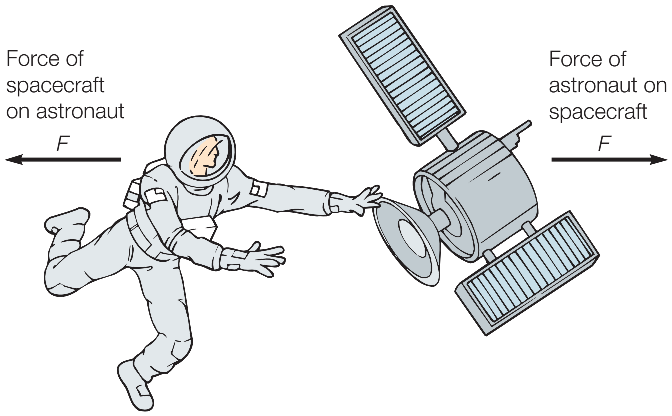

FIGURE 2.22 Forces occur in matched pairs that are equal in magnitude and opposite in direction.

spacecraft for 1 second. The spacecraft 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 2.22). 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 spacecraft, but the spacecraft 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 spacecraft 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 size and opposite in direction to the force exerted on the other object.**

The third law states that forces always occur in matched pairs that act in opposite directions and on two *different* bodies. You could express this law with symbols as

$$F_{\text{A due to B}} = F_{\text{B due to A}}$$

equation 2.7

where the force on the astronaut, for example, would be "A due to B" and the force on the satellite would be "B due to A."

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.

FIGURE 2.23 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.

Consider how the pairs of forces work on Earth's surface. You walk by pushing your feet against the ground (Figure 2.23). 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 forward. You must consider the forces that act on the system of the bike and you 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.

EXAMPLE 2.12

A 60.0 kg astronaut is freely floating in space and pushes on a freely floating 120.0 kg spacecraft with a force of 30.0 N for 1.50 s. (a) Compare the forces exerted on the astronaut and the spacecraft, and (b) compare the acceleration of the astronaut to the acceleration of the spacecraft.

SOLUTION

(a) According to Newton's third law of motion (equation 2.7),

$$F_{\text{A due to B}} = \text{F}_{\text{B due to A}}$$
$$30.0 \text{ N} = 30.0 \text{ N}$$

Both feel a 30.0 N force for 1.50 s but in opposite directions.

(b) Newton's second law describes a relationship between force, mass, and acceleration, $F = ma$.
For the astronaut:

$m = 60.0$ kg
$F = 30.0$ N
$a = ?$

$$F = ma \quad \therefore \quad a = \frac{F}{m}$$

$$a = \frac{30.0 \dfrac{\text{kg}\cdot\text{m}}{\text{s}^2}}{60.0 \text{ kg}}$$

$$= \frac{30.0}{60.0}\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\left(\frac{1}{\text{kg}}\right)$$

$$= 0.500 \frac{\text{kg}\cdot\text{m}}{\text{kg}\cdot\text{s}^2} = \boxed{0.500 \frac{\text{m}}{\text{s}^2}}$$

For the spacecraft:

$m = 120.0$ kg
$F = 30.0$ N
$a = ?$

$$F = ma \quad \therefore \quad a = \frac{F}{m}$$

$$a = \frac{30.0 \dfrac{\text{kg}\cdot\text{m}}{\text{s}^2}}{120.0 \text{ kg}}$$

$$= \frac{30.0}{120.0}\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\left(\frac{1}{\text{kg}}\right)$$

$$= 0.250 \frac{\text{kg}\cdot\text{m}}{\text{kg}\cdot\text{s}^2} = \boxed{0.250 \frac{\text{m}}{\text{s}^2}}$$

EXAMPLE 2.13

After the interaction and acceleration between the astronaut and spacecraft described in example 2.12, they both move away from their original positions. What is the new speed for each? (Answer: astronaut $v_f = 0.750$ m/s; spacecraft $v_f = 0.375$ m/s) (Hint: $v_f = at + v_i$)

2.7 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 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 2.8

The astronaut in example 2.12 had a mass of 60.0 kg and a velocity of 0.750 m/s as a result of the interaction with the spacecraft. The resulting momentum was 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 spacecraft in example 2.12 is *also* 45.0 kg·m/s. The astronaut gained a certain momentum in one direction, and the spacecraft gained the *very same momentum in the opposite direction*. Newton originally defined the second law in terms of a rate of 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 the spacecraft were equal and opposite, you would expect both objects to acquire equal momentum in the opposite direction. This result is observed any time objects in a system interact and the only forces involved are those between the interacting objects (Figure 2.24). 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

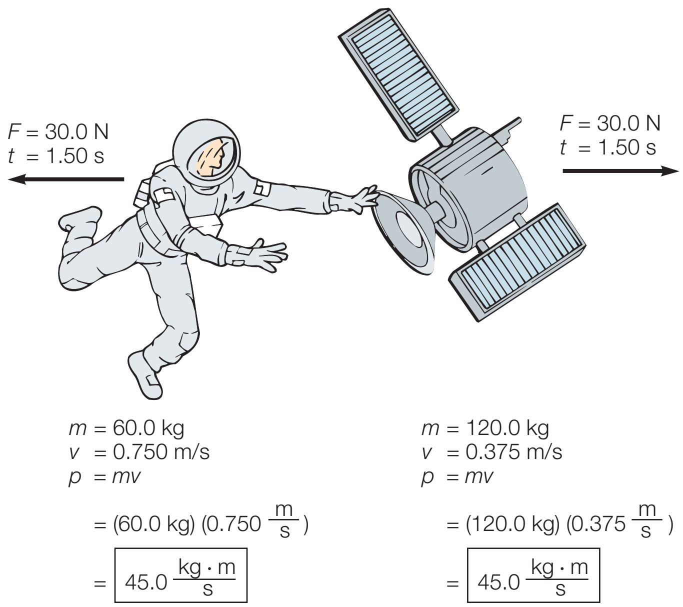

FIGURE 2.24 Both the astronaut and the spacecraft received a force of 30.0 N for 1.50 s when they pushed on each other. Both then have a momentum of 45.0 kg·m/s in the opposite direction. This is an example of the law of conservation of momentum.

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. When this is done, momentum is always found to be conserved.

The firing of a bullet from a rifle and the concurrent "kick" or recoil of the rifle are often used as an example of conservation of momentum where the interaction between objects results in momentum in opposite directions (Figure 2.25). When the rifle is fired, the exploding gunpowder propels the bullet with forward momentum. At the same time, the force from the exploding gunpowder pushes the rifle backward with a momentum opposite that of the bullet. The bullet moves forward with a momentum of $(mv)_b$ and the rifle moves in an opposite direction to the bullet, so its momentum is $-(mv)_r$. According to the law of conservation of momentum, the momentum of

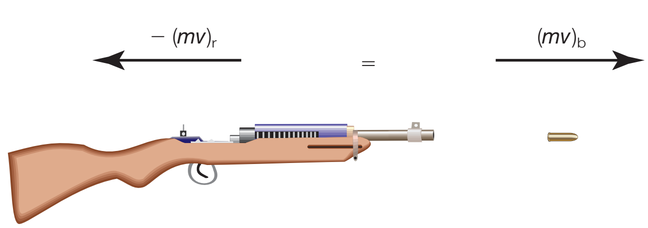

FIGURE 2.25 A rifle and bullet provide an example of conservation of momentum. Before being fired, a rifle and bullet have a total momentum $(p = mv)$ of zero since there is no motion. When fired, the bullet is then propelled in one direction with a forward momentum $(mv)_b$. At the same time, the rifle is pushed backward with a momentum opposite to that of the bullet, so its momentum is shown with a minus sign, or $-(mv)_r$. Since $(mv)_b$ plus $-(mv)_r$ equals zero, the total momentum of the rifle and bullet is zero after as well as before the rifle is fired.

the bullet $(mv)_b$ must equal the momentum of the rifle $-(mv)_r$ in the opposite direction. If the bullet and rifle had the same mass, they would each move with equal velocities when the rifle was fired. The rifle is much more massive than the bullet, however, so the bullet has a much greater velocity than the rifle. The momentum of the rifle is nonetheless equal to the momentum of the bullet, and the recoil can be significant if the rifle is not held firmly against the shoulder. When it is held firmly against the shoulder, the rifle and the person's body are one object. The increased mass results in a proportionally smaller recoil velocity.

EXAMPLE 2.14

A 20,000 kg railroad car is coasting at 3 m/s when it collides and couples with a second, identical car at rest. What is the resulting speed of the combined cars?

SOLUTION

$$\begin{aligned}
&\text{Moving car} \rightarrow m_1 = 20{,}000\text{ kg}, \quad v_1 = 3\text{ m/s}\\
&\text{Second car} \rightarrow m_2 = 20{,}000\text{ kg}, \quad v_2 = 0\\
&\text{Combined cars} \rightarrow v_{1\&2} = ?\text{ m/s}
\end{aligned}$$

Since momentum is conserved, the total momentum of the cars should be the same before and after the collision. Thus,

$$\begin{aligned}
\text{momentum before} &= \text{momentum after}\\
\text{car 1} + \text{car 2} &= \text{coupled cars}\\
m_1v_1 + m_2v_2 &= (m_1 + m_2)v_{1\&2}\\
v_{1\&2} &= \frac{m_1v_2}{m_1 + m_2}\\
v_{1\&2} &= \frac{(20{,}000\text{ kg})\left(3\frac{\text{m}}{\text{s}}\right)}{(20{,}000\text{ kg}) + (20{,}000\text{ kg})}\\
&= \frac{20{,}000\text{ kg}\cdot 3\frac{\text{m}}{\text{s}}}{40{,}000\text{ kg}}\\
&= 0.5 \times 3\frac{\text{kg}\cdot\text{m}}{\text{s}} \times \frac{1}{\text{kg}}\\
&= 1.5\frac{\text{m}}{\text{s}}\\
&= \boxed{2\frac{\text{m}}{\text{s}}}
\end{aligned}$$

(Answer is rounded to one significant figure.) Car 2 had no momentum with a velocity of zero, so m_2v_2 on the left side of the equation equals zero. When the cars couple, the mass is doubled $(m + m)$, and the velocity of the coupled cars will be 2 m/s.

EXAMPLE 2.15

A student and her rowboat have a combined mass of 100.0 kg. Standing in the motionless boat in calm water, she tosses a 5.0 kg rock out the back of the boat with a velocity of 5.0 m/s. What will be the resulting speed of the boat? (Answer: 0.25 m/s)

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 2.9

where Δp 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 greater 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 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 caught it, increasing the contact time. Increasing the contact time has the effect of reducing the force since $\Delta p = Ft$. You change the force applied by increasing the contact time, and, hopefully, you reduce 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 more serious injuries since more time was involved in stopping the car that crumpled. A car that crumples is a safer car in a collision.

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 from ball to ball until the end ball swings out. Make some predictions, then do the experiment for the following. What will happen 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 together on the other side? (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 the use of 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.

2.8 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 magnitude and direction. The 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 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 2.26). When you release the string, the centripetal force ceases, and the ball then follows its natural straight-line

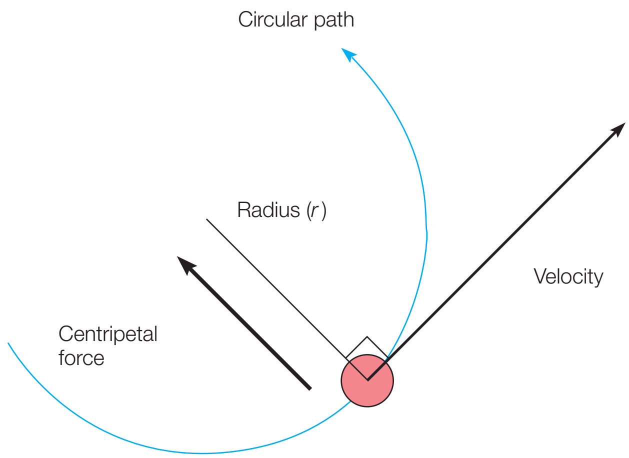

FIGURE 2.26 Centripetal force on the ball causes it to change direction continuously, or accelerate into a circular path. Without the unbalanced force acting on it, the ball would continue in a straight line.

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 in a circle can be shown by geometry or calculus 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

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

equation 2.10

The magnitude of the centripetal force of an object with a mass (m) that is moving with a velocity (v) in a circular orbit of a radius (r) can be found by substituting equation 2.5 in $F = ma$, or

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

equation 2.11

EXAMPLE 2.16

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

$m = 0.25$ kg
$r = 0.5$ m
$v = 2.0$ m/s
$F = ?$

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

EXAMPLE 2.17

Suppose you make the string in example 2.16 one-half as long, 0.25 m. What force is now needed? (Answer: 4.0 N)

2.9 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 at $g = 9.8$ m/s^2 (32 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 24, 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 also 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.**

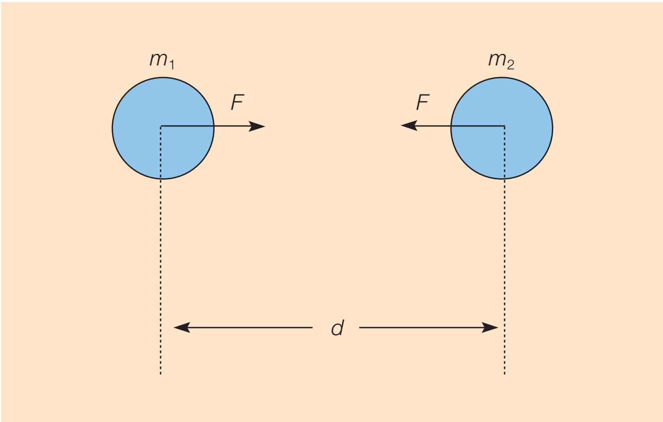

FIGURE 2.27 The variables involved in gravitational attraction. The force of attraction (F) is proportional to the product of the masses (m_1, m_2) and inversely proportional to the square of the distance (d) between the centers of the two masses.

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

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

equation 2.12

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 $G = 6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2$. 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 2.27). 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 don't you notice the forces between you and other objects? The answer is in example 2.18.

EXAMPLE 2.18

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

SOLUTION

$G = 6.67 \times 10^{-11}\text{N·m}^2/\text{kg}^2$

$m_1 = 60.0\ \text{kg}$

$m_2 = 60.0\ \text{kg}$

$d = 1.00\ \text{m}$

$F = ?$

$$\begin{aligned} F &= G\frac{m_1 m_2}{d^2} \\ &= \frac{(6.67 \times 10^{-11}\text{N·m}^2/\text{kg}^2)(60.0\ \text{kg})(60.0\ \text{kg})}{(1.00\ \text{m})^2} \\ &= (6.67 \times 10^{-11})(3.60 \times 10^3)\frac{\frac{\text{N·m}^2\text{·kg}^2}{\text{kg}^2}}{m^2} \\ &= 2.40 \times 10^{-7}(\text{N·m}^2)\left(\frac{1}{\text{m}^2}\right) \\ &= 2.40 \times 10^{-7}\frac{\text{N·}\cancel{\text{m}^2}}{\cancel{\text{m}^2}} \\ &= \boxed{2.40 \times 10^{-7}\ \text{N}} \end{aligned}$$

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

As you can see in example 2.18, 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.

Newton was able to show that the distance used in the equation is the distance from the center of one object to the center of the second object. This means not that the force originates at the center, but that the overall effect is the same as if you considered all the mass to be concentrated at a center point. The weight of an object, for example, can be calculated by using a form of Newton's second law, $F = ma$. This general law shows a relationship between *any* force acting *on* a body, the mass of a body, and the resulting acceleration. When the acceleration is due to gravity, the equation becomes $F = mg$. The law of gravitation deals *specifically with the force of gravity* and how it varies with distance and mass. Since weight is a force, then $F = mg$. You can write the two equations together,

$$mg = G\frac{mm_e}{d^2}$$

where m is the mass of some object on Earth, m_e is the mass of Earth, g is the acceleration due to gravity, and d is the distance between the centers of the masses. Canceling the m's in the equation leaves

$$g = G\frac{m_e}{d^2}$$

which tells you that on the surface of Earth, the acceleration due to gravity, 9.8 m/s^2, is a constant because the other two variables (mass of Earth and the distance to the center of Earth) are constant. Since the m's canceled, you also know that the mass of an object does not affect the rate of free fall; all objects fall at the same rate, with the same acceleration, no matter what their masses are.

Example 2.19 shows that the acceleration due to gravity, g, is about 9.8 m/s^2 and is practically a constant for relatively short distances above the surface. Notice, however, that Newton's law of

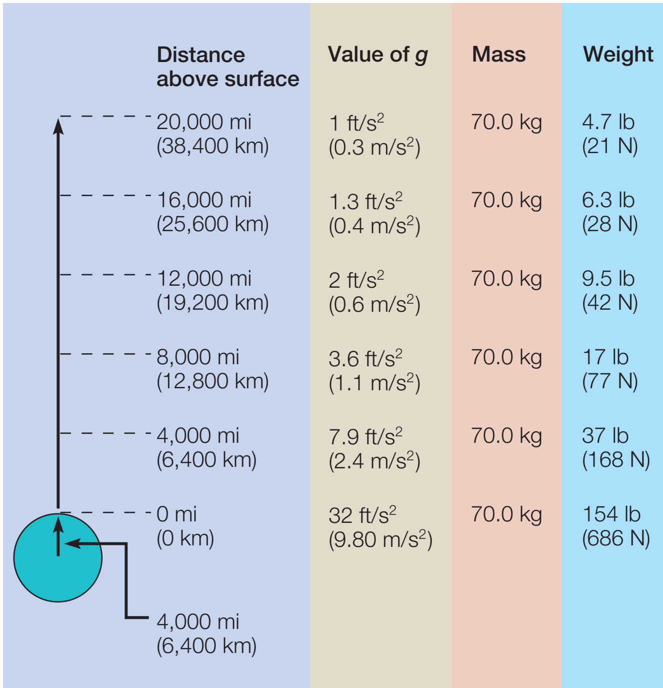

FIGURE 2.28 The force of gravitational attraction decreases inversely with the square of the distance from Earth's center. Note the weight of a 70.0 kg person at various distances above Earth's surface.

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. The weight of an object and the value of *g* are shown for several distances in Figure 2.28. If you have the time, a good calculator, and the inclination, you could check the values given in Figure 2.28 for a 70.0 kg person by doing problems similar to example 2.19. In fact, you could even calculate the mass of Earth, since you already have the value of *g*.

Using reasoning similar to that found in example 2.19, Newton was able to calculate the acceleration of the Moon toward Earth, about 0.0027 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 2.29 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 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

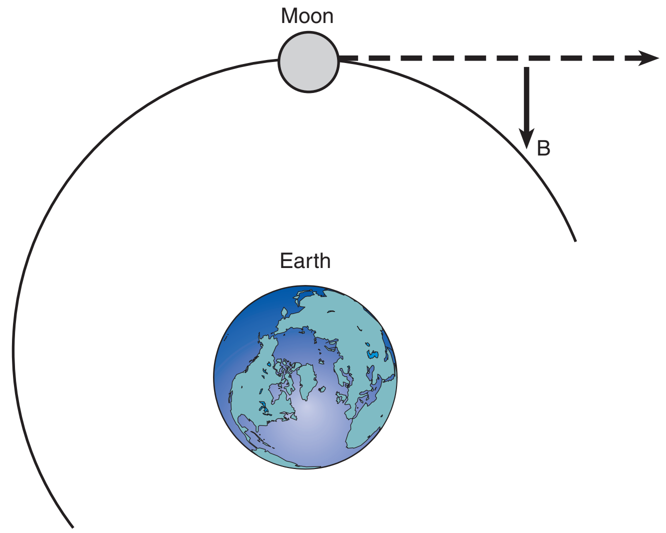

FIGURE 2.29 Gravitational attraction acts as a centripetal force that keeps the Moon from following the straight-line path shown by the dashed line to position A. It was pulled to position B by gravity (0.0027 m/s^2) and thus "fell" toward Earth the distance from the dashed line to B, resulting in a somewhat circular path.

for the next two centuries, as well as accurately describing the world of everyday experience.

EXAMPLE 2.19

The surface of Earth is approximately 6,400 km from its center. If the mass of Earth is 6.0×10^{24} kg, what is the acceleration due to gravity, *g*, near the surface?

$$G = 6.67 \times 10^{-11}\ \mathrm{N{\cdot}m^2/kg^2}$$
$$m_e = 6.0 \times 10^{24}\ \mathrm{kg}$$
$$d = 6{,}400\ \mathrm{km}\ \ (6.4 \times 10^{6}\ \mathrm{m})$$
$$g = ?$$

$$g = \frac{Gm_e}{d^2}$$
$$= \frac{(6.67 \times 10^{-11}\ \mathrm{N{\cdot}m^2/kg^2})(6.0 \times 10^{24}\ \mathrm{kg})}{(6.4 \times 10^{6}\ \mathrm{m})^2}$$
$$= \frac{(6.67 \times 10^{-11})(6.0 \times 10^{24})}{4.1 \times 10^{13}} \frac{\dfrac{\mathrm{N{\cdot}\cancel{m^2}{\cdot}kg}}{\mathrm{kg^2}}}{\cancel{\mathrm{m^2}}}$$
$$= \frac{4.0 \times 10^{14}}{4.1 \times 10^{13}} \frac{\dfrac{\mathrm{kg{\cdot}m}}{\mathrm{s^2}}}{\mathrm{kg}}$$
$$= \boxed{9.8\ \mathrm{m/s^2}}$$

(Note: In the unit calculation, remember that a newton is a kg·m/s^2.)

EXAMPLE 2.20

What would be the value of *g* if Earth were less dense, with the same mass and double the radius? (Answer: $g = 2.4$ m/s^2)

EARTH SATELLITES

As you can see in Figure 2.30, Earth is round and nearly spherical. The curvature is obvious in photographs taken from space but not so obvious back on the surface because Earth is so large. However, you can see evidence of the curvature in places on the surface where you can see with unobstructed vision for long distances. For example, a tall ship appears to "sink" on the horizon as it sails away, following Earth's curvature below your line of sight. The surface of Earth curves away from your line of sight or any other line tangent to the surface, dropping at a rate of about 4.9 m for every 8 km (16 ft in 5 mi). This means that a ship 8 km away will appear to drop about 5 m below the horizon, and anything less than about 5 m tall at this distance will be out of sight, below the horizon.

Recall that a falling object accelerates toward Earth's surface at *g*, which has an average value of 9.8 m/s^2. Ignoring air resistance, a falling object will have a speed of 9.8 m/s at the end of 1 second and will fall a distance of 4.9 m. If you wonder why the object did not fall 9.8 m in 1 second, recall that the object starts with an initial speed of zero and has a speed of 9.8 m/s only during the last instant. The average speed was an average of the initial and final speeds, which is 4.9 m/s. An average speed of 4.9 m/s over a time interval of 1 second will result in a distance covered of 4.9 m.

Did you know that Newton was the first to describe how to put an artificial satellite into orbit around Earth? He did not discuss rockets, however, but described in *Principia* how to put a cannonball into orbit. He described how a cannonball shot with sufficient speed straight out from a mountaintop would go into orbit around Earth. If it had less than the sufficient speed, it would fall back to Earth following the path of projectile motion, as discussed earlier. What speed does it need to go into orbit? Earth curves away from a line tangent to the surface at 4.9 m per 8 km. Any object falling from a resting position will fall a distance of 4.9 m during the first second. Thus, a cannonball shot straight out from a mountaintop with a speed of 8 km/s (nearly 18,000 mi/h, or 5 mi/s) will fall toward the surface, dropping 4.9 m during the first second. But the surface of Earth drops, too, curving away below the falling cannonball. So the cannonball is still moving horizontally, no closer to the surface than it was a second ago. As it falls 4.9 m during the next second, the surface again curves away 4.9 m over the 8 km distance. This repeats again and again, and the cannonball stays the same distance from the surface, and we say it is now an *artificial satellite* in orbit. The satellite requires no engine or propulsion as it continues to fall toward the surface, with Earth curving away from it continuously. This assumes, of course, no loss of speed from air resistance.

Today, an artificial satellite is lofted by a rocket or rockets to an altitude of more than 320 km (about 200 mi), above the air friction of the atmosphere, before being aimed horizontally. The satellite is then "injected" into orbit by giving it the correct tangential speed. This means it has attained an orbital speed of at least 8 km/s (5 mi/s) but less than 11 km/s (7 mi/s). At a speed less than 8 km/s, the satellite would fall back to the surface in a parabolic path. At a speed more than 11 km/s, it will move faster than the surface curves away and will escape from Earth into space. But with the correct tangential speed, and above the atmosphere and air friction, the satellite follows a circular orbit for long periods of time without the need for any more propulsion. An orbit injection speed of more than 8 km/s (5 mi/s) would result in an elliptical rather than a circular orbit.

A satellite could be injected into orbit near the outside of the atmosphere, closer to Earth but outside the air friction that might reduce its speed. The satellite could also be injected far away from Earth, where it takes a longer time to complete one orbit. Near the outer limits of the atmosphere—that is, closer to the surface—a satellite might orbit Earth every 90 minutes or so. A satellite as far away as the Moon, on the other hand, orbits Earth in a little less than 28 days. A satellite at an altitude of 36,000 km (a little more than 22,000 mi) has a period of 1 day. In the right spot over the equator, such a satellite is called a **geosynchronous satellite**, since it turns with Earth and does not appear to move across the sky (Figure 2.31). The photographs of the cloud cover you see in weather reports were taken from one or more geosynchronous weather satellites. Communications networks are also built around geosynchronous satellites. One way to locate one of these geosynchronous satellites is to note the aiming direction of backyard satellite dishes that pick up television signals.

FIGURE 2.30 From space, this photograph of Earth shows that it is nearly spherical.

A Closer Look

Gravity Problems

Gravity does act on astronauts in spacecraft who are in orbit around Earth. 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 the surface. 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 the surface. These changes occur because on Earth, humans are constantly subjected 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 while 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 lived on a planet with a different gravitational force, we would have muscles and bones that were adapted to the gravity on that planet. Many kinds of organisms have been used in experiments in space to try to develop a better understanding of how their systems work without gravity.

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

WEIGHTLESSNESS

News photos sometimes show astronauts "floating" in the Space Shuttle or next to a satellite (Figure 2.32). These astronauts appear to be weightless but technically are no more weightless than a skydiver in free fall or a person in a falling elevator. Recall that weight is a gravitational force, a measure of the gravitational attraction between Earth and an object (mg). The weight of a cup of coffee, for example, can be measured by placing the cup on a scale. The force the cup of coffee exerts against the scale is its weight. You also know that the scale pushes back on the cup of coffee since it is not accelerating, which means the net force is zero.

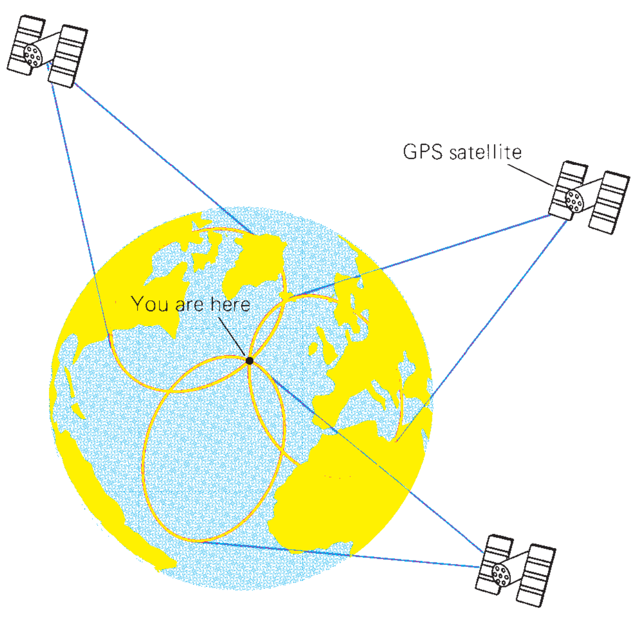

FIGURE 2.31 In the Global Positioning System (GPS), each of a fleet of orbiting satellites sends out coded radio signals that enable a receiver on Earth to determine both the exact position of the satellite in space and its exact distance from the receiver. Given this information, a computer in the receiver then calculates the circle on Earth's surface on which the receiver must lie. Data from three satellites gives three circles, and the receiver must be located at the one point where all three intersect.

FIGURE 2.32 Astronauts in an orbiting space station may appear to be weightless. Technically, however, they are no more weightless than a skydiver in free fall or a person near or on the surface of Earth in a falling elevator.

People Behind the Science

Isaac Newton (1642–1727)

Isaac Newton was a British physicist who is regarded as one of the greatest scientists ever to have lived. He discovered the three laws of motion that bear his name and was the first to explain gravitation, clearly defining the nature of mass, weight, force, inertia, and acceleration. In his honor, the SI unit of force is called the *newton*. Newton also made fundamental discoveries in light, finding that white light is composed of a spectrum of colors and inventing the reflecting telescope.

Newton was born on January 4, 1643 (by the modern calendar). He was a premature, sickly baby born after his father's death, and his survival was not expected. When he was 3, his mother remarried, and the young Newton was left in his grandmother's care. He soon began to take refuge in things mechanical, making water clocks, kites bearing fiery lanterns aloft, and a model mill powered by a mouse, as well as innumerable drawings and diagrams. When Newton was 12, his mother withdrew him from school with the intention of making him into a farmer. Fortunately, his uncle recognized Newton's ability and managed to get him back into school to prepare for college.

Newton was admitted to Trinity College, Cambridge, and graduated in 1665, the same year that the university was closed because of the plague. Newton returned to his boyhood farm to wait out the plague, making only an occasional visit back to Cambridge. During this period, he performed his first prism experiments and thought about motion and gravitation.

Newton returned to study at Cambridge after the plague had run its course, receiving a master's degree in 1668 and becoming a professor at the age of only 26. Newton remained at Cambridge almost thirty years, studying alone for the most part, though in frequent contact with other leading scientists by letter and through the Royal Society in London. These were Newton's most fertile years. He labored day and night, thinking and testing ideas with calculations.

In Cambridge, he completed what may be described as his greatest single work, the *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)*. This was presented to the Royal Society in 1686, which subsequently withdrew from publishing it because of a shortage of funds. The astronomer Edmund Halley (1656–1742), a wealthy man and friend of Newton, paid for the publication of the *Principia* in 1687. In it, Newton revealed his laws of motion and the law of universal gravitation.

Newton's greatest achievement was to demonstrate that scientific principles are of universal application. In the *Principia Mathematica*, he built the evidence of experiment and observation to develop a model of the universe that is still of general validity. "If I have seen further than other men," he once said, "it is because I have stood on the shoulders of giants"; and Newton was certainly able to bring together the knowledge of his forebears in a brilliant synthesis.

No knowledge can ever be total, but Newton's example brought about an explosion of investigation and discovery that has never really abated. He perhaps foresaw this when he remarked, "To myself, I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

With his extraordinary insight into the workings of nature and rare tenacity in wresting its secrets and revealing them in as fundamental and concise a way as possible, Newton stands as a colossus of science. In physics, only Archimedes (287–212 B.C.) and Albert Einstein (1879–1955), who also possessed these qualities, may be compared to him.

Source: Modified from the *Hutchinson Dictionary of Scientific Biography*.

Now consider what happens if a skydiver tries to pour a cup of coffee while in free fall. Even if you ignore air resistance, you can see that the skydiver is going to have a difficult time, at best. The coffee, the cup, and the skydiver will all be falling together. Gravity is acting to pull the coffee downward, but gravity is also acting to pull the cup from under it at the same rate. The coffee, the cup, and the skydiver all fall together, and the skydiver will see the coffee appear to "float" in blobs. If the diver lets go of the cup, it too will appear to float as everything continues to fall together. However, this is only *apparent* weightlessness, since gravity is still acting on everything; the coffee, the cup, and the skydiver only *appear* to be weightless because they are all accelerating at g.

The astronauts in orbit are in free fall, falling toward Earth just as the skydiver, so they too are undergoing apparent weightlessness. To experience true weightlessness, the astronauts would have to travel far from Earth and its gravitational field, and far from the gravitational fields of other planets.

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 in 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, and at the same time drop the cup. 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.

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 the change of velocity during some period 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 m/s^2 (32 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. One *newton* is the force needed to give a 1.0 kg mass an acceleration of 1.0 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

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

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

2.2

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

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

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

2.3

$$\text{average velocity} = \frac{\text{final velocity} + \text{initial velocity}}{2}$$

$$\bar{v} = \frac{v_f + v_i}{2}$$

2.4

$$\text{distance} = \frac{1}{2}(\text{acceleration})(\text{time})^2$$

$$d = \frac{1}{2}at^2$$

2.5

$$\text{force} = \text{mass} \times \text{acceleration}$$

$$F = ma$$

2.6

$$\text{weight} = \text{mass} \times \text{acceleration due to gravity}$$

$$w = mg$$

2.7

$$\text{force on object A} = \text{force on object B}$$

$$F_{\text{A due to B}} = F_{\text{B due to A}}$$

2.8

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

$$p = mv$$

2.9

$$\text{change of momentum} = \text{force} \times \text{time}$$

$$\Delta p = Ft$$

2.10

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

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

2.11

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

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

2.12

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

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

KEY TERMS

acceleration (p. 29)
centrifugal force (p. 49)
centripetal force (p. 48)
first law of motion (p. 41)
force (p. 32)
free fall (p. 36)
fundamental forces (p. 32)
g (p. 38)
geosynchronous satellite (p. 52)
impulse (p. 48)
inertia (p. 34)
law of conservation of momentum (p. 46)
mass (p. 43)
momentum (p. 46)
net force (p. 32)
newton (p. 43)
second law of motion (p. 43)
speed (p. 27)
third law of motion (p. 45)
universal law of gravitation (p. 49)
velocity (p. 29)

APPLYING THE CONCEPTS

1. A straight-line distance covered during a certain amount of time describes an object's
 a. speed.
 b. velocity.
 c. acceleration.
 d. any of the above.

2. How fast an object is moving in a particular direction is described by
 a. speed.
 b. velocity.
 c. acceleration.
 d. none of the above.

3. Acceleration occurs when an object undergoes
 a. a speed increase.
 b. a speed decrease.
 c. a change in the direction of travel.
 d. any of the above.

4. A car moving at 60 km/h comes to a stop in 10 s when the driver slams on the brakes. In this situation, what does 60 km/h represent?
 a. Average speed
 b. Final speed
 c. Initial speed
 d. Constant speed

5. A car moving at 60 km/h comes to a stop in 10 s when the driver slams on the brakes. In this situation, what is the final speed?
 a. 60 km/h
 b. 0 km/h
 c. 0.017 km/s
 d. 0.17 km/s

6. According to Galileo, an object moving without opposing friction or other opposing forces will
 a. still need a constant force to keep it moving at a constant speed.
 b. need an increasing force, or it will naturally slow and then come to a complete stop.
 c. continue moving at a constant speed.
 d. undergo a gradual acceleration.

7. In free fall, an object is seen to have a (an)
 a. constant velocity.
 b. constant acceleration.
 c. increasing acceleration.
 d. decreasing acceleration.

8. A tennis ball is hit, causing it to move upward from the racket at some angle to the horizon before it curves back to the surface in the path of a parabola. While it moves along this path,
 a. the horizontal speed remains the same.
 b. the vertical speed remains the same.
 c. both the horizontal and vertical speeds remain the same.
 d. both the horizontal and vertical speeds change.

9. A quantity of 5 m/s^2 is a measure of
 a. metric area.
 b. acceleration.
 c. speed.
 d. velocity.

10. An automobile has how many different devices that can cause it to undergo acceleration?
 a. None
 b. One
 c. Two
 d. Three or more

11. 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.

12. 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.

13. 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.

14. 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.

15. The basic difference between instantaneous and average speed is that
    a. instantaneous speed is always faster than average speed.
    b. average speed is for a total distance over a total time of trip.
    c. average speed is the sum of two instantaneous speeds, divided by 2.
    d. the final instantaneous speed is always the fastest speed.
16. Does *any change* in the motion of an object result in an acceleration?
    a. Yes.
    b. No.
    c. It depends on the type of change.
17. A measure of how fast your speed is changing as you travel to campus is a measure of
    a. velocity.
    b. average speed.
    c. acceleration.
    d. the difference between initial and final speed.
18. 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.
19. Newton's first law of motion describes
    a. the tendency of a moving or stationary object to resist any change in its state of motion.
    b. a relationship between an applied force, the mass, and the resulting change of motion that occurs from the force.
    c. how forces always occur in matched pairs.
    d. none of the above.
20. You are standing freely on a motionless shuttle bus. When the shuttle bus quickly begins to move forward, you
    a. are moved to the back of the shuttle bus as you move forward over the surface of Earth.
    b. stay in one place over the surface of Earth as the shuttle bus moves from under you.
    c. move along with the shuttle bus.
    d. feel a force toward the side of the shuttle bus.
21. Mass is measured in kilograms, which is a measure of
    a. weight.
    b. force.
    c. inertia.
    d. quantity of matter.
22. Which metric unit is used to express a measure of weight?
    a. kg
    b. J
    c. N
    d. m/s^2
23. Newton's third law of motion states that forces occur in matched pairs that act in opposite directions between two different bodies. This happens
    a. rarely.
    b. sometimes.
    c. often but not always.
    d. every time two bodies interact.
24. 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.
25. 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. one-half as much.
    d. one-fourth as much.
26. 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
27. 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.
28. 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.
29. Suppose the mass of a moving scooter is doubled and its velocity is also doubled. The resulting momentum is
    a. halved.
    b. doubled.
    c. quadrupled.
    d. the same.
30. Two identical moons are moving in identical circular paths, but one moon is moving twice as fast as the other. Compared to the slower moon, the centripetal force required to keep the faster moon on the path is
    a. twice as much.
    b. one-half as much.
    c. four times as much.
    d. one-fourth as much.
31. Which undergoes a greater change of momentum, a golf ball or the head of a golf club, when the ball is hit from a golf tee?
    a. The ball undergoes a greater change.
    b. The head of the club undergoes a greater change.
    c. Both undergo the same change but in opposite directions.
    d. The answer depends on how fast the club is moved.
32. Newton's law of gravitation tells us that
    a. planets are attracted to the Sun's magnetic field.
    b. objects and bodies have weight only on the surface of Earth.
    c. every object in the universe is attracted to every other object in the universe.
    d. only objects in the solar system are attracted to Earth.

33. An astronaut living on a space station that is orbiting Earth will
  a. experience zero gravity.
  b. weigh more than she did on Earth.
  c. be in free fall, experiencing apparent weightlessness.
  d. weigh the same as she would on the Moon.

34. A measure of the force of gravity acting on an object is called
  a. gravitational force.
  b. weight.
  c. mass.
  d. acceleration.

35. You are at rest with a grocery cart at the supermarket when you see a checkout line open. You apply a certain force to the cart for a short time and acquire a certain speed. Neglecting friction, how long would you have to push with *one-half* the force to acquire the same final speed?
  a. One-fourth as long
  b. One-half as long
  c. Twice as long
  d. Four times as long

36. Once again you are at rest with a grocery cart at the supermarket when you apply a certain force to the cart for a short time and acquire a certain speed. Suppose you had bought more groceries, enough to double the mass of the groceries and cart. Neglecting friction, doubling the mass would have what effect on the resulting final speed if you used the same force for the same length of time? The new final speed would be
  a. one-fourth.
  b. one-half.
  c. doubled.
  d. quadrupled.

37. You are moving a grocery cart at a constant speed in a straight line down the aisle of a store. For this situation, the forces on the cart are
  a. unbalanced, in the direction of the movement.
  b. balanced, with a net force of zero.
  c. equal to the force of gravity acting on the cart.
  d. greater than the frictional forces opposing the motion of the cart.

38. You are outside a store, moving a loaded grocery cart down the street on a very steep hill. It is difficult, but you are able to pull back on the handle and keep the cart moving down the street in a straight line and at a constant speed. For this situation, the forces on the cart are
  a. unbalanced, in the direction of the movement.
  b. balanced, with a net force of zero.
  c. equal to the force of gravity acting on the cart.
  d. greater than the frictional forces opposing the motion of the cart.

39. Neglecting air resistance, a ball in free fall near Earth's surface will have
  a. constant speed and constant acceleration.
  b. increasing speed and increasing acceleration.
  c. increasing speed and decreasing acceleration.
  d. increasing speed and constant acceleration.

40. From a bridge, a ball is thrown straight up at the same time a ball is thrown straight down with the same initial speed. Neglecting air resistance, which ball will have a greater speed when it hits the ground?
  a. The one thrown straight up.
  b. The one thrown straight down.
  c. Both balls would have the same speed.

41. After being released, a ball thrown straight up from a bridge will have an acceleration of
  a. 9.8 m/s^2.
  b. zero.
  c. less than 9.8 m/s^2.
  d. more than 9.8 m/s^2.

42. A gun is aimed horizontally at the center of an apple hanging from a tree. The instant the gun is fired, the apple falls and the bullet
  a. hits the apple.
  b. arrives late, missing the apple.
  c. arrives early, missing the apple.
  d. may or may not hit the apple, depending on how fast it is moving.

43. According to the third law of motion, which of the following must be true about a car pulling a trailer?
  a. The car pulls on the trailer and the trailer pulls on the car with an equal and opposite force. Therefore, the net force is zero and the trailer cannot move.
  b. Since they move forward, this means the car is pulling harder on the trailer than the trailer is pulling on the car.
  c. The action force from the car is quicker than the reaction force from the trailer, so they move forward.
  d. The action-reaction forces between the car and trailer are equal, but the force between the ground and car pushes them forward.

44. A small sports car and a large SUV collide head on and stick together without sliding. Which vehicle had the larger momentum change?
  a. The small sports car.
  b. The large SUV.
  c. It would be equal for both.

45. Again consider the small sports car and large SUV that collided head on and stuck together without sliding. Which vehicle must have experienced the larger deceleration during the collision?
  a. The small sports car.
  b. The large SUV.
  c. It would be equal for both.

46. An orbiting satellite is moved from 10,000 to 30,000 km from Earth. This will result in what change in the gravitational attraction between Earth and the satellite?
  a. None—the attraction is the same.
  b. One-half as much.
  c. One-fourth as much.
  d. One-ninth as much.

47. Newton's law of gravitation considers the *product* of two masses because
  a. the larger mass pulls harder on the smaller mass.
  b. both masses contribute equally to the force of attraction.
  c. the large mass is considered before the smaller mass.
  d. the distance relationship is one of an inverse square.

Answers

1. a **2.** b **3.** d **4.** c **5.** b **6.** c **7.** b **8.** a **9.** b **10.** d **11.** b **12.** a **13.** c **14.** a **15.** b **16.** a **17.** c **18.** b **19.** a **20.** b **21.** c **22.** c **23.** d **24.** a **25.** c **26.** b **27.** b **28.** c **29.** c **30.** c **31.** c **32.** c **33.** c **34.** b **35.** c **36.** b **37.** b **38.** b **39.** d **40.** c **41.** a **42.** a **43.** d **44.** c **45.** a **46.** d **47.** b

QUESTIONS FOR THOUGHT

1. An insect inside a bus flies from the back toward the front at 2 m/s. The bus is moving in a straight line at 20 m/s. 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. Without friction, what net force is needed to maintain a 1,000 kg car in uniform motion for 30 minutes?
6. How can there ever be an unbalanced force on an object 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 while 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.

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 her or him 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 ends so they stand face to face in a line. When the domino on the end is tipped over, 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 must determine how to space the dominoes and measure the speed.

PARALLEL EXERCISES

The exercises in groups A and B cover the same concepts. Solutions to group A exercises are located in appendix E.
Note: *Neglect all frictional forces in all exercises.*

Group A

1. What is the average speed in km/h of a car that travels 160 km for 2 h?
2. What is the average speed in km/h for a car that travels 50.0 km in 40.0 min?
3. What is the weight of a 5.2 kg object?
4. What net force is needed to give a 40.0 kg grocery cart an acceleration of 2.4 m/s^2?
5. What is the resulting acceleration when an unbalanced force of 100.0 N is applied to a 5.00 kg object?
6. What is the average speed, in km/h, for a car that travels 22 km in exactly 15 min?
7. Suppose a radio signal travels from Earth and through space at a speed of 3.0×10^8 m/s. How far into space did the signal travel during the first 20.0 minutes?
8. How far away was a lightning strike if thunder is heard 5.00 seconds after the flash is seen? Assume that sound traveled at 350.0 m/s during the storm.

Group B

1. What was the average speed in km/h of a car that travels 400.0 km in 4.5 h?
2. What was the average speed in km/h of a boat that moves 15.0 km across a lake in 45 min?
3. How much would an 80.0 kg person weigh (a) on Mars, where the acceleration of gravity is 3.93 m/s^2, and (b) on Earth's Moon, where the acceleration of gravity is 1.63 m/s^2?
4. What force is needed to give a 6,000 kg truck an acceleration of 2.2 m/s^2 over a level road?
5. What is the resulting acceleration when a 300 N force acts on an object with a mass of 3,000 kg?
6. A boat moves 15.0 km across a lake in 30.0 min. What was the average speed of the boat in kilometers per hour?
7. If the Sun is a distance of 1.5×10^8 km from Earth, how long does it take sunlight to reach Earth if light moves at 3.0×10^8 m/s?
8. How many meters away is a cliff if an echo is heard 0.500 s after the original sound? Assume that sound traveled at 343 m/s on that day.

Group A—Continued

9. A car is driven at an average speed of 100.0 km/h for 2 hours, then at an average speed of 50.0 km/h for the next hour. What was the average speed for the 3-hour trip?
10. What is the acceleration of a car that moves from rest to 15.0 m/s in 10.0 s?
11. How long will be required for a car to go from a speed of 20.0 m/s to a speed of 25.0 m/s if the acceleration is 3.0 m/s^2?
12. A bullet leaves a rifle with a speed of 720 m/s. How much time elapses before it strikes a target 1,609 m away?
13. A pitcher throws a ball at 40.0 m/s, and the ball is electronically timed to arrive at home plate 0.4625 s later. What is the distance from the pitcher to the home plate?
14. The Sun is 1.50×10^8 km from Earth, and the speed of light is 3.00×10^8 m/s. How many minutes elapse as light travels from the Sun to Earth?
15. An archer shoots an arrow straight up with an initial velocity magnitude of 100.0 m/s. After 5.00 s, the velocity is 51.0 m/s. At what rate is the arrow decelerated?
16. A ball thrown straight up climbs for 3.0 s before falling. Neglecting air resistance, with what velocity was the ball thrown?
17. A ball dropped from a building falls for 4 s before it hits the ground. (a) What was its final velocity just as it hit the ground? (b) What was the average velocity during the fall? (c) How high was the building?
18. You drop a rock from a cliff, and 5.00 s later you see it hit the ground. How high is the cliff?
19. What is the resulting acceleration when an unbalanced force of 100 N is applied to a 5 kg object?
20. What is the momentum of a 100 kg football player who is moving at 6 m/s?
21. 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?
22. 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?
23. An astronaut and equipment weigh 2,156 N on Earth. Weightless in space, the astronaut throws away a 5.0 kg wrench with a velocity of 5.0 m/s. What is the resulting velocity of the astronaut in the opposite direction?
24. (a) What is the weight of a 1.25 kg book? (b) What is the acceleration when a net force of 10.0 N is applied to the book?
25. What net force is needed to accelerate a 1.25 kg book 5.00 m/s^2?
26. What net force does the road exert on a 70.0 kg bicycle and rider to give them an acceleration of 2.0 m/s^2?
27. A 1,500 kg car accelerates uniformly from 44.0 km/h to 80.0 km/h in 10.0 s. What was the net force exerted on the car?
28. 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?
29. What is the weight of a 70.0 kg person?
30. 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?
31. 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—Continued

9. A car has an average speed of 80.0 km/h for 1 hour, then an average speed of 90.0 km/h for 2 hours during a 3-hour trip. What was the average speed for the 3-hour trip?
10. 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?
11. How much time is needed for a car to accelerate from 8.0 m/s to a speed of 22 m/s if the acceleration is 3.0 m/s^2?
12. A rocket moves through outer space at 11,000 m/s. At this rate, how much time would be required to travel the distance from Earth to the Moon, which is 380,000 km?
13. Sound travels at 348 m/s in the warm air surrounding a thunderstorm. How far away was the place of discharge if thunder is heard 4.63 s after a lightning flash?
14. How many hours are required for a radio signal from a space probe near the dwarf planet Pluto, 6.00×10^9 km away, to reach Earth? Assume that the radio signal travels at the speed of light, 3.00×10^8 m/s.
15. A rifle is fired straight up, and the bullet leaves the rifle with an initial velocity magnitude of 724 m/s. After 5.00 s, the velocity is 675 m/s. At what rate is the bullet decelerated?
16. A rock thrown straight up climbs for 2.50 s, then falls to the ground. Neglecting air resistance, with what velocity did the rock strike the ground?
17. An object is observed to fall from a bridge, striking the water below 2.50 s later. (a) With what velocity did it strike the water? (b) What was its average velocity during the fall? (c) How high is the bridge?
18. A ball dropped from a window strikes the ground 2.00 s later. How high is the window above the ground?
19. Find the resulting acceleration from a 300 N force that acts on an object with a mass of 3,000 kg.
20. What is the momentum of a 30.0 kg shell fired from a cannon with a velocity of 500 m/s?
21. What is the momentum of a 39.2 N bowling ball with a velocity of 7.00 m/s?
22. A 30.0 kg shell is fired from a 2,000 kg cannon with a velocity of 500 m/s. What is the resulting velocity of the cannon?
23. An 80.0 kg man is standing on a frictionless ice surface when he throws a 2.00 kg book at 10.0 m/s. With what velocity does the man move across the ice?
24. (a) What is the weight of a 5.00 kg backpack? (b) What is the acceleration of the backpack if a net force of 10.0 N is applied?
25. What net force is required to accelerate a 20.0 kg object to 10.0 m/s^2?
26. What forward force must the ground apply to the foot of a 60.0 kg person to result in an acceleration of 1.00 m/s^2?
27. A 1,000.0 kg car accelerates uniformly to double its speed from 36.0 km/h in 5.00 s. What net force acted on this car?
28. 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?
29. How much does a 60.0 kg person weigh?
30. 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?
31. A 200.0 kg astronaut and equipment move with a velocity of 2.00 m/s toward an orbiting spacecraft. How long must the astronaut fire a 100.0 N rocket backpack to stop the motion relative to the spacecraft?