4 LINEAR MOTION

THE BIG IDEA

You can describe the motion of an object by its position, speed, direction, and acceleration.

More than 2000 years ago, the ancient Greek scientists were familiar with some of the ideas of physics that we study today. They had a good understanding of some of the properties of light, but they were confused about motion. Great progress in understanding motion occurred with Galileo and his study of balls rolling on inclined planes, as discussed in the previous chapter. In this chapter, we look at motion in more detail.

discover!

Do Objects Fall Faster the Longer They Fall?

1. Attach washers to a 3.5 m long string at the following distances from one end: 0.0 m, 0.11 m, 0.44 m, 0.99 m, 1.76 m and 2.76 m.
2. Stand on a chair or desk with the string and washers suspended over a piece of metal such as a pie tin. The washer tied to the end of the string should be just touching the metal surface.
3. Release the string and listen to the rate at which the washers hit the metal. You may wish to perform a second trial to confirm your observations.

Analyze and Conclude

1. **Observing** Describe the time intervals between sounds.
2. **Predicting** What would you hear if the washers were evenly spaced on the string?
3. **Making Generalizations** What can you say about the distance traveled by a falling object during each second of fall?

FIGURE 4.1
Although you may be at rest relative to Earth's surface, you're moving about 100,000 km/h relative to the sun.

4.1 Motion Is Relative

Everything moves. Even things that appear to be at rest move. They move with respect to the sun and stars. When we describe the motion of one object with respect to another, we say that the object is moving **relative** to the other object. A book that is at rest, relative to the table it lies on, is moving at about 30 kilometers per second relative to the sun. The book moves even faster relative to the center of our galaxy. When we discuss the motion of something, we describe its motion relative to something else. **An object is moving if its position relative to a fixed point is changing.** When we say that a space shuttle moves at 8 kilometers per second, we mean its movement relative to Earth below. When we say a racing car in the Indy 500 reaches a speed of 300 kilometers per hour, of course we mean relative to the track. Unless stated otherwise, when we discuss the speeds of things in our environment, we mean speed with respect to the surface of Earth even though Earth moves around the sun, as shown in Figure 4.1. Motion is relative.

think!

A hungry mosquito sees you resting in a hammock in a 3-meter per second breeze. How fast and in what direction should the mosquito fly in order to hover above you for lunch?
Answer: 4.1

CONCEPT CHECK How can you tell if an object is moving?

FIGURE 4.2
The racing cars in the Indy 500 move relative to the track.

4.2 Speed

think!

If a cheetah can maintain a constant speed of 25 m/s, it will cover 25 meters every second. At this rate, how far will it travel in 10 seconds? In 1 minute?
Answer: 4.2.1

Before the time of Galileo, people described moving things as simply "slow" or "fast." Such descriptions were vague. Galileo is credited as being the first to measure *speed* by considering the distance covered and the time it takes. **Speed** is how fast an object is moving. **You can calculate the speed of an object by dividing the distance covered by time.**

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

For example, if a cheetah, such as the one shown in Figure 4.3, covers 50 meters in a time of 2 seconds, its speed is 25 m/s.

FIGURE 4.3 ▶
A cheetah is the fastest land animal over distances less than 500 meters and can achieve peak speeds of 100 km/h.

Any combination of units for distance and time that are useful and convenient are legitimate for describing speed. Miles per hour (mi/h), kilometers per hour (km/h), centimeters per day (the speed of a sick snail?), or light-years per century are all legitimate units for speed. The slash symbol (/) is read as "per." Throughout this book, we'll primarily use the units *meters per second* (m/s) for speed. Table 4.1 shows some comparative speeds in different units.

Table 4.1 Approximate Speeds in Different Units

12 mi/h =	20 km/h =	6 m/s	(bowling ball)
25 mi/h =	40 km/h =	11 m/s	(very good sprinter)
37 mi/h =	60 km/h =	17 m/s	(sprinting rabbit)
50 mi/h =	80 km/h =	22 m/s	(tsunami)
62 mi/h =	100 km/h =	28 m/s	(sprinting cheetah)
75 mi/h =	120 km/h =	33 m/s	(batted softball)
100 mi/h =	160 km/h =	44 m/s	(batted baseball)

Instantaneous Speed A car does not always move at the same speed. A car may travel down a street at 50 km/h, slow to 0 km/h at a red light, and speed up to only 30 km/h because of traffic. You can tell the speed of the car at any instant by looking at the car's speedometer, such as the one in Figure 4.4. The speed at any instant is called the **instantaneous speed.** A car traveling at 50 km/h may go at that speed for only one minute. If the car continued at that speed for a full hour, it would cover 50 km. If it continued at that speed for only half an hour, it would cover only half that distance, or 25 km. In one minute, the car would cover less than 1 km.

FIGURE 4.4 ▲
The speedometer for a North American car gives readings of instantaneous speed in both mi/h and km/h. Odometers for the U.S. market give readings in miles; those for the Canadian market give readings in kilometers.

Average Speed In planning a trip by car, the driver often wants to know how long it will take to cover a certain distance. The car will certainly not travel at the same speed all during the trip. The driver cares only about the *average speed* for the trip as a whole. The **average speed** is the total distance covered divided by the time.

$$\text{average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

Average speed can be calculated rather easily. For example, if we drive a distance of 60 kilometers during a time of 1 hour, we say our average speed is 60 kilometers per hour (60 km/h). Or, if we travel 240 kilometers in 4 hours,

$$\text{average speed} = \frac{\text{total distance covered}}{\text{time interval}} = \frac{240\text{ km}}{4\text{ h}} = 60\text{ km/h}$$

Note that when a distance in kilometers (km) is divided by a time in hours (h), the answer is in kilometers per hour (km/h).

Since average speed is the distance covered divided by the time of travel, it does not indicate variations in the speed that may take place during the trip. In practice, we experience a variety of speeds on most trips, so the average speed is often quite different from the instantaneous speed. Whether we talk about average speed or instantaneous speed, we are talking about the rates at which distance is traveled.

If we know average speed and travel time, the distance traveled is easy to find. A simple rearrangement of the definition above gives

$$\text{total distance covered} = \text{average speed} \times \text{travel time}$$

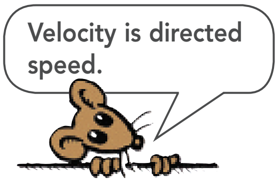
For example, if your average speed is 80 kilometers per hour on a 4-hour trip, then you cover a total distance of 320 kilometers.

CONCEPT CHECK How can you calculate speed?

think!

The speedometer in every car also has an odometer that records the distance traveled. If the odometer reads zero at the beginning of a trip and 35 km a half hour later, what is the average speed?
Answer: 4.2.2

4.3 Velocity



In everyday language, we can use the words *speed* and *velocity* interchangeably. In physics, we make a distinction between the two. Very simply, the difference is that **velocity** is speed in a given direction. When we say a car travels at 60 km/h, we are specifying its speed. But if we say a car moves at 60 km/h to the north, we are specifying its velocity. **Speed is a description of how fast an object moves; velocity is how fast and in what direction it moves.**

A quantity such as velocity that specifies direction as well as magnitude is called a vector quantity. Recall in Chapter 2 that quantities that require only magnitude for a description are scalar quantities. Speed is a scalar quantity. Velocity, like force, is a vector quantity.

Constant Velocity Constant speed means steady speed. Something with constant speed doesn't speed up or slow down. Constant velocity, on the other hand, means both constant speed *and* constant direction. Constant direction is a straight line—the object's path doesn't curve. So constant velocity means motion in a straight line at constant speed. The car in Figure 4.5 may have a constant speed, but its velocity is changing.

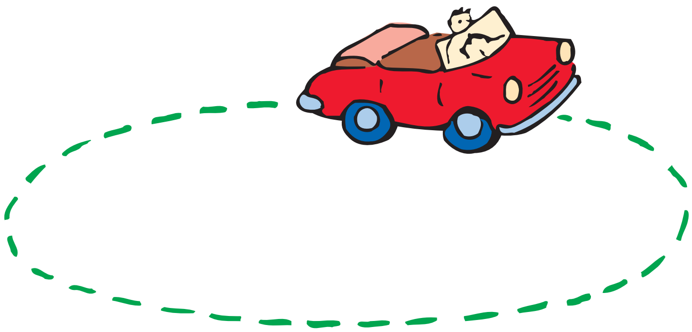


FIGURE 4.5 ▶
The car on the circular track may have a constant speed but not a constant velocity, because its direction of motion is changing every instant.

think!

The speedometer of a car moving northward reads 60 km/h. It passes another car that travels southward at 60 km/h. Do both cars have the same speed? Do they have the same velocity?
Answer: 4.3

Changing Velocity If *either* the speed *or* the direction (or both) is changing, then the velocity is changing. Constant speed and constant velocity are not the same. A body may move at constant speed along a curved path, for example, but it does not move with constant velocity, because its direction is changing every instant.

In a car there are three controls that are used to change the velocity. One is the gas pedal, which is used to maintain or increase the speed. The second is the brake, which is used to decrease the speed. The third is the steering wheel, which is used to change the direction.

CONCEPT CHECK How is velocity different from speed?

4.4 Acceleration

We can change the state of motion of an object by changing its speed, its direction of motion, or both. Any of these changes is a change in velocity. Sometimes we are interested in how fast the velocity is changing. A driver on a two-lane road who wants to pass another car would like to be able to speed up and pass in the shortest possible time. **Acceleration** is the rate at which the velocity is changing.[4.4.1] **You can calculate the acceleration of an object by dividing the change in its velocity by time.**

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

We are familiar with acceleration in an automobile, such as the one shown in Figure 4.6. The driver depresses the gas pedal, which is appropriately called the accelerator. The passengers then experience acceleration, or "pickup" as it is sometimes called, as they are pressed into their seats. The key idea that defines acceleration is *change.* Whenever we change our state of motion, we are accelerating. A car that can accelerate well has the ability to change its velocity rapidly. A car that can go from zero to 60 km/h in 5 seconds has a greater acceleration than another car that can go from zero to 80 km/h in 10 seconds. So having good acceleration means being able to change velocity quickly and does not necessarily refer to how fast something is moving.

In physics, the term *acceleration* applies to decreases as well as increases in speed. The brakes of a car can produce large retarding accelerations, that is, they can produce a large decrease per second in the speed. This is often called *deceleration.* We experience deceleration when the driver of a bus or car slams on the brakes and we tend to hurtle forward.

think!

Suppose a car moving in a straight line steadily increases its speed each second, first from 35 to 40 km/h, then from 40 to 45 km/h, then from 45 to 50 km/h. What is its acceleration?
Answer: 4.4.1

Can you see that the gas pedal (accelerator), brakes, and steering wheel in an automobile are all controls for acceleration?

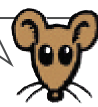
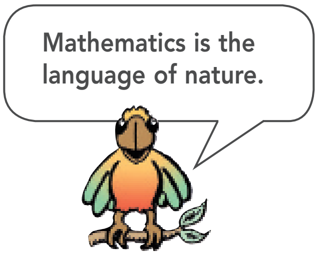


FIGURE 4.6 ▲
A car is accelerating whenever there is a *change* in its state of motion.



Change in Direction Acceleration also applies to changes in *direction*. If you ride around a curve at a constant speed of 50 km/h, you feel the effects of acceleration as your body tends to move toward the outside of the curve. You may round the curve at constant speed, but your velocity is not constant, because your direction is changing every instant. Your state of motion is changing: you are accelerating. It is important to distinguish between speed and velocity. Acceleration is defined as the rate of change in *velocity,* rather than *speed.* Acceleration, like velocity, is a vector quantity because it is directional. The acceleration vector points in the direction the velocity is changing, as shown in Figure 4.7. If we change speed, direction, or both, we change velocity and we accelerate.

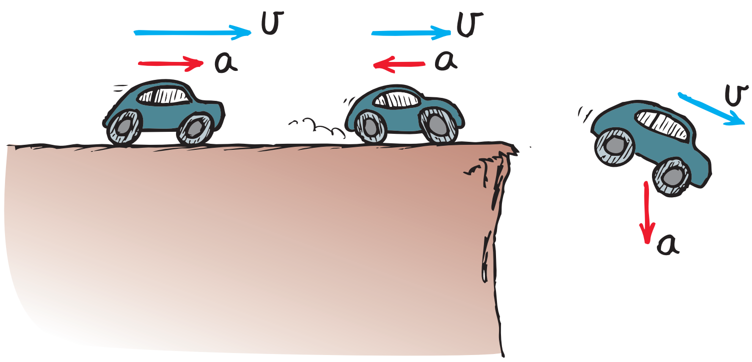


FIGURE 4.7 ▶
When you accelerate in the direction of your velocity, you speed up; against your velocity, you slow down; at an angle to your velocity, your direction changes.

Change in Speed When straight-line motion is considered, it is common to use speed and velocity interchangeably. When the direction is not changing, acceleration may be expressed as the rate at which *speed* changes.

$$\text{acceleration (along a straight line)} = \frac{\text{change in speed}}{\text{time interval}}$$

Speed and velocity are measured in units of distance per time. Since acceleration is the change in velocity or speed per time interval, its units are those of speed per time. If we speed up, without changing direction, from zero to 10 km/h in 1 second, our change in speed is 10 km/h in a time interval of 1 s. Our acceleration along a straight line is

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time interval}} = \frac{10\text{ km/h}}{1\text{ s}} = 10\text{ km/h}\cdot\text{s}$$

The acceleration is 10 km/h·s, which is read as "10 kilometers per hour-second." [4.4.2.] Note that a unit for time appears twice: once for the unit of speed and again for the interval of time in which the speed is changing.

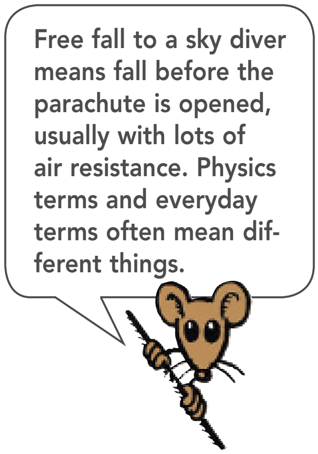
think!

In 5 seconds a car moving in a straight line increases its speed from 50 km/h to 65 km/h, while a truck goes from rest to 15 km/h in a straight line. Which undergoes greater acceleration? What is the acceleration of each vehicle?
Answer: 4.4.2

CONCEPT CHECK How do you calculate acceleration?

4.5 Free Fall: How Fast

An apple falls from a tree. Does it accelerate while falling? We know it starts from a rest position and gains speed as it falls. We know this because it would be safe to catch if it fell a meter or two, but not if it fell from a high-flying balloon. Thus, the apple must gain more speed during the time it drops from a great height than during the shorter time it takes to drop a meter. This gain in speed indicates that the apple does accelerate as it falls.



Falling Objects Gravity causes the apple to accelerate downward once it begins falling. In real life, air resistance affects the acceleration of a falling object. Let's imagine there is no air resistance and that gravity is the only thing affecting a falling object. An object moving under the influence of the gravitational force only is said to be in **free fall.** Freely falling objects are affected only by gravity. Table 4.2 shows the instantaneous speed at the end of each second of fall of a freely falling object dropped from rest. The **elapsed time** is the time that has elapsed, or passed, since the beginning of any motion, in this case the fall.

Note in Table 4.2 the way the speed changes. During each second of fall, the instantaneous speed of the object increases by an additional 10 meters per second. This gain in speed per second is the acceleration.

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time interval}} = \frac{10 \text{ m/s}}{1 \text{ s}} = 10 \text{ m/s}^2$$

Note that when the change in speed is in m/s and the time interval is in s, the acceleration is in m/s^2, which is read as "meters per second squared." The unit of time, the second, occurs twice—once for the unit of speed and again for the time interval during which the speed changes.

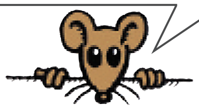
Table 4.2 Free Fall Speeds of Objects

Elapsed Time (seconds)	Instantaneous Speed (meters/second)
0	0
1	10
2	20
3	30
4	40
5	50
t	*10t*

think!

During the span of the second time interval in Table 4.2, the object begins at 10 m/s and ends at 20 m/s. What is the average speed of the object during this 1-second interval? What is its acceleration?
Answer: 4.5.1

Since acceleration is a vector quantity, it's best to say the acceleration due to gravity is 10 m/s² *down.*



The acceleration of an object in free fall is about 10 meters per second squared (10 m/s²). For free fall, it is customary to use the letter g to represent the acceleration because the acceleration is due to gravity. Although g varies slightly in different parts of the world, its average value is nearly 10 m/s². More accurately, g is 9.8 m/s², but it is easier to see the ideas involved when it is rounded off to 10 m/s². Where accuracy is important, the value of 9.8 m/s² should be used for the acceleration during free fall. Note in Table 4.2 that the instantaneous speed of an object falling from rest is equal to the acceleration multiplied by the amount of time it falls, the elapsed time.

$$\text{instantaneous speed} = \text{acceleration} \times \text{elapsed time}$$

The instantaneous speed v of an object falling from rest after an elapsed time t can be expressed in equation form[4.5]

$$v = gt$$

The letter v symbolizes both speed and velocity. Take a moment to check this equation with Table 4.2. You will see that whenever the acceleration $g = 10$ m/s² is multiplied by the elapsed time in seconds, the result is the instantaneous speed in meters per second.

The average speed of any object moving in a straight line with constant acceleration is calculated the way we find the average of any two numbers: add them and divide by 2. For example, the average speed of a freely-falling object in its first second of fall is the sum of its initial and final speed, divided by 2. So, adding the initial speed of zero and the final speed of 10 m/s, and then dividing by 2, we get 5 m/s. Average speed and instantaneous speed are usually very different.

think!

What would the speedometer reading on the falling rock shown in Figure 4.8 be 4.5 seconds after it drops from rest? How about 8 seconds after it is dropped?
Answer: 4.5.2

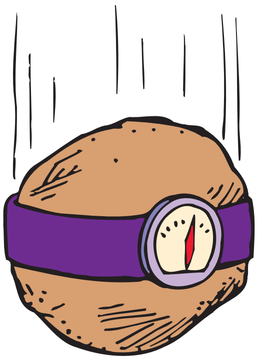


FIGURE 4.8
If a falling rock were somehow equipped with a speedometer, in each succeeding second of fall its reading would increase by the same amount, 10 m/s. Table 4.2 shows the speed we would read at various seconds of fall.

In Figure 4.8 we imagine a freely-falling boulder with a speedometer attached. As the boulder falls, the speedometer shows that the boulder acquires 10 m/s of speed each second. This 10 m/s gain each second is the boulder's acceleration.

discover!

Can You Catch a Falling Bill?

1. Have a friend hold a dollar bill so the midpoint hangs between your fingers.
2. Have your friend release the bill without warning. Try to catch it!
3. **Think** How much reaction time do you have when your friend drops the bill?

Rising Objects So far, we have been looking at objects moving straight downward due to gravity. Now consider an object thrown straight up. It continues to move upward for a while, then it comes back down. At the highest point, when the object is changing its direction of motion from upward to downward, its instantaneous speed is zero. It then starts downward just as if it had been dropped from rest at that height.

During the upward part of this motion, the object slows from its initial upward velocity to zero velocity. We know the object is accelerating because its velocity is changing. How much does its speed decrease each second? It should come as no surprise that the speed decreases at the same rate it increases when moving downward—at 10 meters per second each second. So as Figure 4.9 shows, the *instantaneous speed* at points of equal elevation in the path is the same whether the object is moving upward or downward. The *velocities* are different of course, because they are in opposite directions. During each second, the speed or the velocity changes by 10 m/s. The acceleration is 10 m/s^2 downward the entire time, whether the object is moving upward or downward.

CONCEPT CHECK What is the acceleration of an object in free fall?

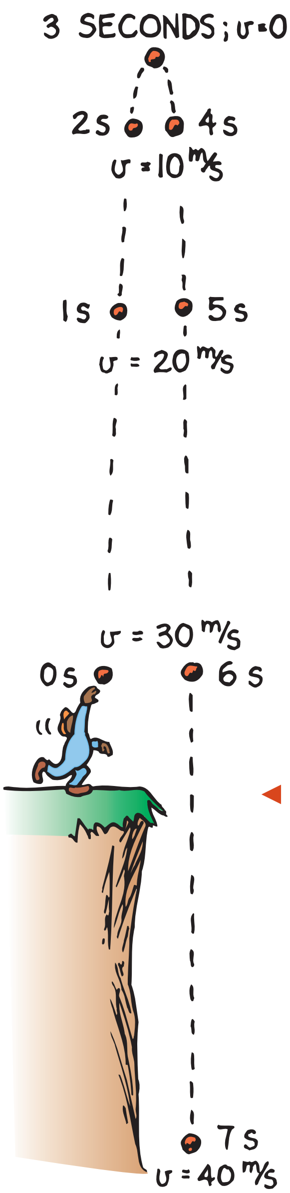


FIGURE 4.9 The change in speed each second is the same whether the ball is going upward or downward.

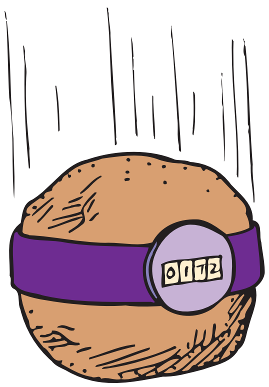


FIGURE 4.10 ▲
Pretend that a falling rock is somehow equipped with an *odometer*. The readings of distance fallen increase with time and are shown in Table 4.3.

4.6 Free Fall: How Far

How *fast* something moves is entirely different from how *far* it moves—speed and distance are not the same thing. To understand the difference, return to Table 4.2. At the end of the first second, the falling object has an instantaneous speed of 10 m/s. Does this mean it falls a distance of 10 meters during this first second? No. Here's where the difference between instantaneous speed and average speed comes in. The initial speed of fall is zero and takes a full second to get to 10 m/s. So the average speed is half way between zero and 10 m/s—that's 5 m/s, as discussed earlier. So during the first second, the object has an average speed of 5 m/s and falls a distance of 5 m.

Table 4.3 shows the total distance moved by a freely falling object dropped from rest. At the end of one second, it has fallen 5 meters. At the end of 2 seconds, it has dropped a total distance of 20 meters. At the end of 3 seconds, it has dropped 45 meters altogether. ✓ **For each second of free fall, an object falls a greater distance than it did in the previous second.** These distances form a mathematical pattern[4.6.1]: at the end of time t, the object has fallen a distance d of $\frac{1}{2}gt^2$.

Table 4.3 Free Fall Distances of an Object

Elapsed Time (seconds)	Distance Fallen (meters)
0	0
1	5
2	20
3	45
4	80
5	125
t	$\frac{1}{2}gt^2$

think!

An apple drops from a tree and hits the ground in one second. What is its speed upon striking the ground? What is its average speed during the one second? How high above ground was the apple when it first dropped?
Answer: 4.6

We used freely falling objects to describe the relationship between distance traveled, acceleration, and velocity acquired. In our examples, we used the acceleration of gravity, $g = 10\ \text{m/s}^2$. But accelerating objects need not be freely falling objects. A car accelerates when we step on the gas or the brake pedal. Whenever an object's initial speed is zero and the acceleration a is constant, that is, steady and "non-jerky," the equations[4.6.2] for the velocity and distance traveled are

$$v = at \text{ and } d = \frac{1}{2}at^2$$

CONCEPT CHECK For a falling object, how does the distance per second change?

4.7 Graphs of Motion

Equations and tables are not the only way to describe relationships such as velocity and acceleration. Another way is to use graphs that visually describe relationships. Since you'll develop basic graphing skills in the laboratory, we won't make a big deal of graphs. Here we'll simply show the graphs for Tables 4.2 and 4.3.

Speed-Versus-Time Figure 4.11 is a graph of the speed-versus-time data in Table 4.2. Note that speed v is plotted on the vertical axis and time t is plotted on the horizontal axis. In this case, the "curve" that best fits the points forms a straight line. The straightness of the curve indicates a "linear" relationship between speed and time. For every increase of 1 s, there is the same 10 m/s increase in speed. Mathematicians call this *linearity,* and the graph shows why—the curve is a straight line. Since the object is dropped from rest, the line starts at the origin, where both v and t are zero. If we double t, we double v; if we triple t, we triple v; and so on. This particular linearity is called a *direct proportion,* and we say that time and speed are directly proportional to each other.

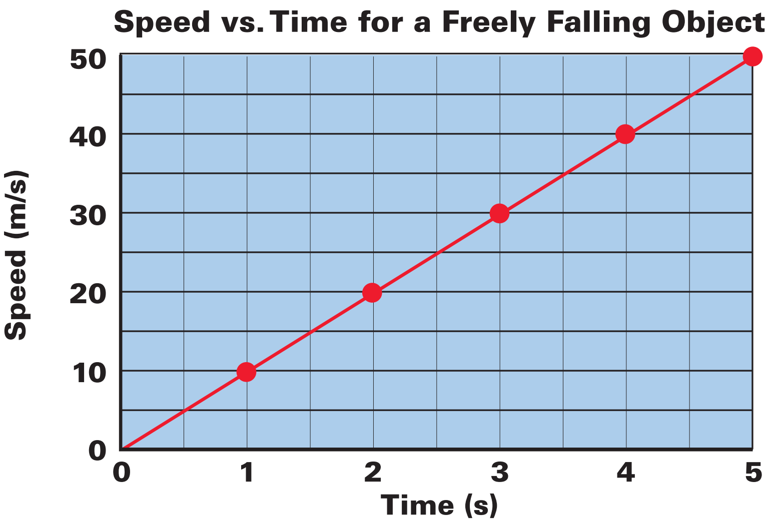
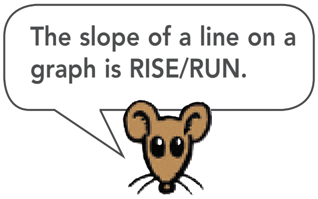


FIGURE 4.11
A speed-versus-time graph of the data from Table 4.2 is linear.

The curve is a straight line, so its slope is constant—like an inclined plane. *Slope* is the vertical change divided by the horizontal change for any part of the line. **On a speed-versus-time graph the slope represents speed per time, or acceleration.** Note that for each 10 m/s of vertical change there is a corresponding horizontal change of 1 s. We see the slope is 10 m/s divided by 1 s, or 10 m/s^2. The straight line shows the acceleration is constant. If the acceleration were greater, the slope of the graph would be steeper. For more information about slope, see Appendix C.



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Distance-Versus-Time Figure 4.12 is a graph of the distance-versus-time data in Table 4.3. Distance d is plotted on the vertical axis, and time t is on the horizontal axis. The result is a curved line. The curve shows that the relationship between distance traveled and time is *nonlinear*. The relationship shown here is *quadratic* and the curve is *parabolic*—when we double t, we do not double d; we quadruple it. Distance depends on time *squared!*

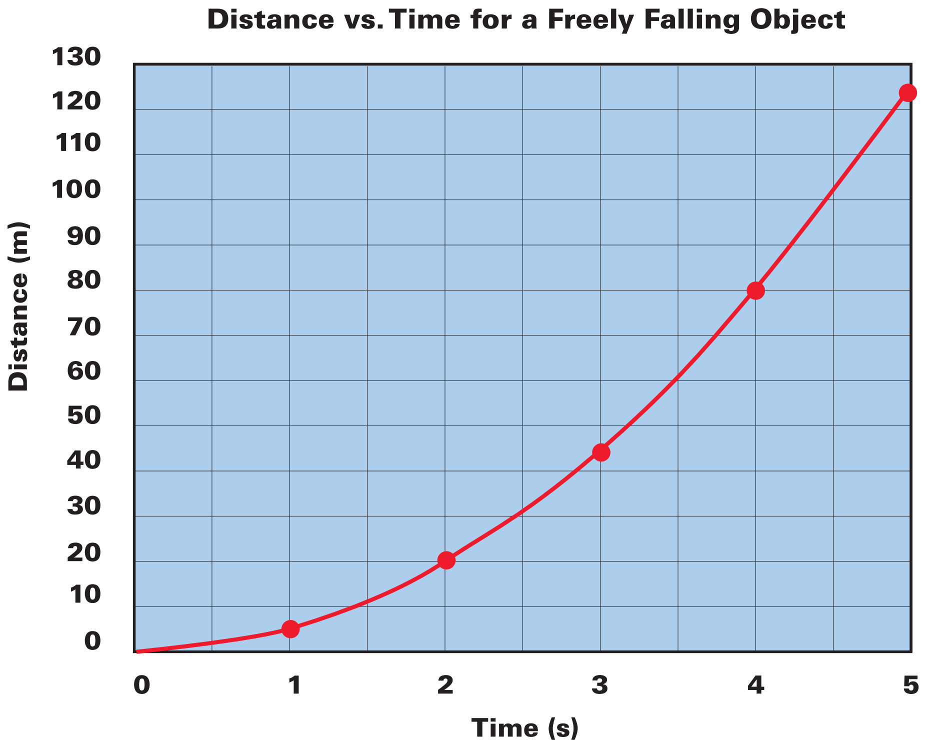
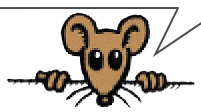


FIGURE 4.12 ▲
A distance-versus-time graph of the data from Table 4.3 is parabolic.

How fast something falls is entirely different than how far it falls. From rest, how fast is given by $v = gt$; how far by $d = \frac{1}{2}gt^2$.



A curved line also has a slope—different at different points. If you look at the graph in Figure 4.12 you can see that the curve has a certain slant or "steepness" at every point. This slope changes from one point to the next. The slope of the curve on a distance-versus-time graph is very significant. It is speed, the *rate* at which distance is covered per unit of time. In this graph the slope steepens (becomes greater) as time passes. This shows that speed increases as time passes. In fact, if the slope could be measured accurately, you would find it increases by 10 meters per second each second.

CONCEPT CHECK What does a slope of a speed-versus-time graph represent?

4.8 Air Resistance and Falling Objects

Drop a feather and a coin and we notice the coin reaches the floor far ahead of the feather. Air resistance is responsible for these different accelerations. This fact can be shown quite nicely with a closed glass tube connected to a vacuum pump. The feather and coin are placed inside. When the tube is inverted with air inside, the coin falls much more rapidly than the feather. The feather flutters through the air. But if the air is removed with a vacuum pump and the tube is quickly inverted, the feather and coin fall side by side with the same acceleration, g, as shown in Figure 4.13.

Air resistance noticeably slows the motion of things with large surface areas like falling feathers or pieces of paper. But air resistance less noticeably affects the motion of more compact objects like stones and baseballs. In many cases the effect of air resistance is small enough to be neglected. With negligible air resistance, falling objects can be considered to be falling freely. Air resistance will be covered in more detail in Chapter 6.

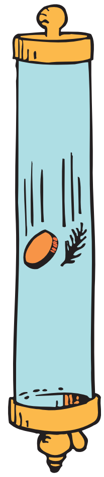


FIGURE 4.13 ▲
A feather and a coin accelerate equally when there is no air around them.

CONCEPT CHECK How does air resistance affect falling objects?

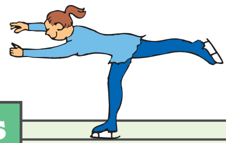
4.9 How Fast, How Far, How Quickly How Fast Changes

Some of the confusion that occurs in analyzing the motion of falling objects comes about from mixing up "how fast" with "how far." When we wish to specify how fast something freely falls from rest after a certain elapsed time, we are talking about speed or velocity. The appropriate equation is $v = gt$. When we wish to specify how far that object has fallen, we are talking about distance. The appropriate equation is $d = \frac{1}{2}gt^2$. Velocity or speed (how fast) and distance (how far) are entirely different from each other.

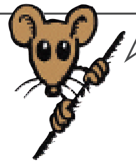
One of the most confusing concepts encountered in this book is acceleration, or "how quickly does speed or velocity change." What makes acceleration so complex is that it is *a rate of a rate*. It is often confused with velocity, which is itself a rate (the rate at which distance is covered). Acceleration is not velocity, nor is it even a change in velocity. **Acceleration is the rate at which velocity itself changes.**

Please be patient with yourself if you find that you require several hours to achieve a clear understanding of motion. It took people nearly 2000 years from the time of Aristotle to Galileo to achieve as much!

CONCEPT CHECK What is the relationship between velocity and acceleration?



Hang time can be several seconds in the sport of sail surfing—quite a bit different when the air plays a major role!



Physics of Sports

Hang Time

Some people are gifted with great jumping ability. Leaping straight up, they seem to hang in the air. Ask your friends to estimate the "hang time" of the great jumpers—the amount of time a jumper is airborne (feet off the ground). One or two seconds? Several? Nope. Surprisingly, the hang time of the greatest jumpers is almost always less than 1 second! Our perception of a longer hang time is one of many illusions we have about nature.

Jumping ability is best measured by a standing vertical jump. Stand facing a wall, and with feet flat on the floor and arms extended upward, make a mark on the wall at the top of your reach. Then make your jump, and at the peak, make another mark. The distance between these two marks measures your vertical leap.

Here's the physics. When you leap upward, jumping force is applied only as long as your feet are still in contact with the ground. The greater the force, the greater your launch speed and the higher the jump is. It is important to note that as soon as your feet leave the ground, whatever upward speed you attain immediately decreases at the steady rate of g, 10 m/s^2. Maximum height is attained when your upward speed decreases to zero. You then begin falling, gaining speed at exactly the same rate, g. If you land as you took off, upright with legs extended, then time rising equals time falling. Hang time is the sum of rising and falling times.

The relationship between rising or falling time and vertical height is given by

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

If we know the vertical height, we can rearrange this expression to read

$$t = \sqrt{\frac{2d}{g}}$$

No basketball player is known to have exceeded a jump of 1.25 meters (4 feet). Setting d equal$^{4.9}$ to 1.25 m, and using the more precise 9.8 m/s^2 for g, we find that t, half the hang time, is

$$t = \sqrt{\frac{2d}{g}} = \sqrt{\frac{2(1.25\text{ m})}{9.8\text{ m/s}^2}} = 0.50\text{ s}$$

Doubling this, we see such a record hang time would be 1 second!

We've only been talking about vertical motion. How about running jumps? We'll learn in Chapter 5 that hang time depends only on the jumper's vertical speed at launch; it does not depend on horizontal speed. While airborne, the jumper's horizontal speed remains constant but the vertical speed undergoes acceleration. Interesting physics!

4 REVIEW

Concept Summary

- An object is moving if its position relative to a fixed point is changing.
- You can calculate the speed of an object by dividing the distance covered by time.
- Speed is a description of how fast an object moves; velocity is how fast and in what direction it moves.
- You can calculate the acceleration of an object by dividing the change in its velocity by time.
- The acceleration of an object in free fall is about 10 meters per second squared (10 m/s^2).
- For each second of free fall, an object falls a greater distance than it did in the previous second.
- On a speed-versus-time graph the slope represents speed per time, or acceleration.
- Air resistance noticeably slows the motion of things with large surface areas like falling feathers or pieces of paper. But air resistance less noticeably affects the motion of more compact objects like stones and baseballs.
- Acceleration is the rate at which velocity itself changes.

Key Terms

relative *(p. 47)*
speed *(p. 48)*
instantaneous speed *(p. 49)*
average speed *(p. 49)*
velocity *(p. 50)*
acceleration *(p. 51)*
free fall *(p. 53)*
elapsed time *(p. 53)*

think! Answers

4.1 The mosquito should fly toward you into the breeze. When above you it should fly at 3 meters per second in order to hover at rest above you. Unless its grip on your skin is strong enough after landing, it must continue flying at 3 meters per second to keep from being blown off. That's why a breeze is an effective deterrent to mosquito bites.

4.2.1 In 10 s the cheetah will cover 250 m, and in 1 minute (or 60 s) it will cover 1500 m.

4.2.2 $$\text{average speed} = \frac{\text{total distance covered}}{\text{time interval}} = \frac{35\text{ km}}{0.5\text{ h}} = 70\text{ km/h}.$$

At some point, the speedometer would have to exceed 70 km/h.

4.3 Both cars have the same speed, but they have opposite velocities because they are moving in opposite directions.

4.4.1 We see that the speed increases by 5 km/h during each 1-s interval. The acceleration is therefore 5 km/h·s during each interval.

4.4.2 The car and truck both increase their speed by 15 km/h during the same time interval, so their acceleration is the same.

4.5.1 The average speed will be 15 m/s. The acceleration will be 10 m/s^2.

4.5.2 The speedometer readings would be 45 m/s and 80 m/s, respectively.

4.6 When it hits the ground, the apple's speed will be 10 m/s. Its average speed is 5 m/s, and it starts 5 m above the ground.

4 ASSESS

Check Concepts

Section 4.1

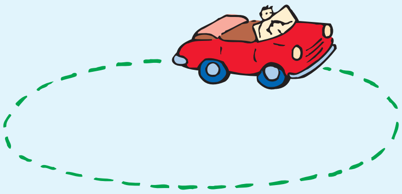
1. How can you be both at rest and also moving about 107,000 km/h at the same time?
2. You cover 10 meters in a time of 1 second. Is your speed the same if you cover 20 meters in 2 seconds?

Section 4.2

3. Does the speedometer of a car read instantaneous speed or average speed?
4. Average speed = distance covered divided by travel time. Do some algebra and multiply both sides of this relation by travel time. What does the result say about distance covered?

Section 4.3

5. Which is a vector quantity, speed or velocity? Defend your answer.



6. What two controls on a car cause a change in speed? What control causes only a change in velocity?

Section 4.4

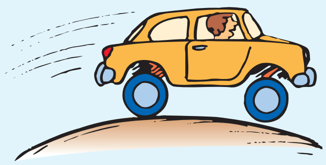
7. What is the acceleration of a car moving along a straight-line path that increases its speed from zero to 100 km/h in 10 s?
8. By how much does the speed of a vehicle moving in a straight line change each second when it is accelerating at 2 km/h·s? At 4 km/h·s? At 10 km/h·s?
9. Why does the unit of time enter twice in the unit of acceleration?

Section 4.5

10. What is the meaning of *free fall?*
11. For a freely falling object dropped from rest, what is the instantaneous speed at the end of the fifth second of fall? The sixth second?
12. For a freely falling object dropped from rest, what is the *acceleration* at the end of the fifth second of fall? The sixth second? At the end of any elapsed time t?

Section 4.6

13. How far will a freely falling object fall from rest in five seconds? Six seconds?
14. How far will an object move in one second if its average speed is 5 m/s?



15. How far will a freely falling object have fallen from a position of rest when its instantaneous speed is 10 m/s?

Section 4.7

16. What does the slope of the curve on a distance-versus-time graph represent?

17. What does the slope of the curve on a velocity-versus-time graph represent?

Section 4.8

18. Does air resistance increase or decrease the acceleration of a falling object?

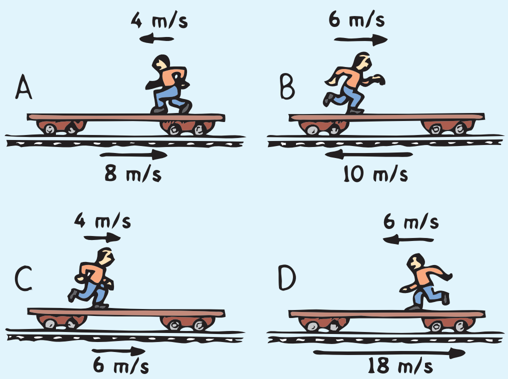
Section 4.9

19. What is the appropriate equation for how fast an object freely falls from a position of rest? For how far that object falls?

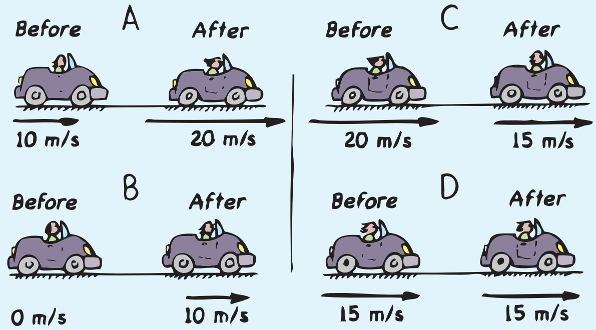
Think and Rank

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

20. Jogging Jake runs along a train flatcar that moves at the velocities shown. From greatest to least, rank the relative velocities of Jake as seen by an observer on the ground. (Call the direction to the right positive.)



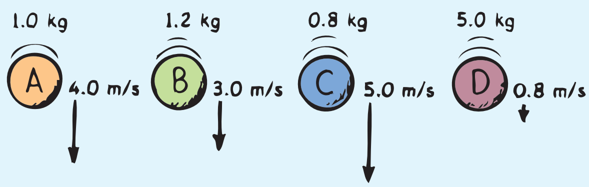
21. Below we see before and after snapshots of a car's velocity. The time interval between before and after for each is the same.



a. Rank the cars in terms of the change in velocity, from most positive to most negative. (Negative numbers rank lower than positive ones, and remember, tie scores can be part of your ranking.)

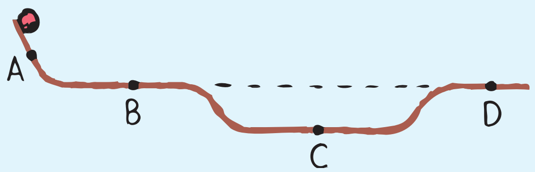
b. Rank them in terms of acceleration, from greatest to least.

22. These are drawings of same-size balls of different masses thrown straight downward. The speeds shown occur immediately after leaving the thrower's hand. Ignore air resistance. Rank their *accelerations* from greatest to least. Or are the accelerations the same for each?

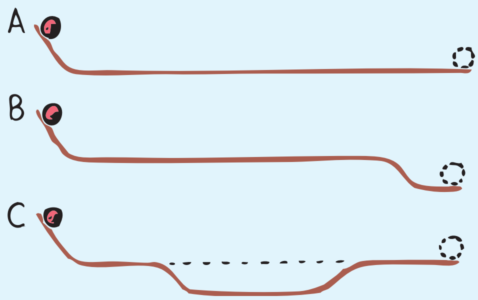


4 ASSESS *(continued)*

23. A track is made of a piece of channel metal bent as shown. A ball is released from rest at the left end of the track and continues past the various points. Rank the ball at points A, B, C, and D, from fastest to slowest. (Again, watch for tie scores.)



24. A ball is released from rest at the left end of three different tracks. The tracks are bent from pieces of metal of the same length.

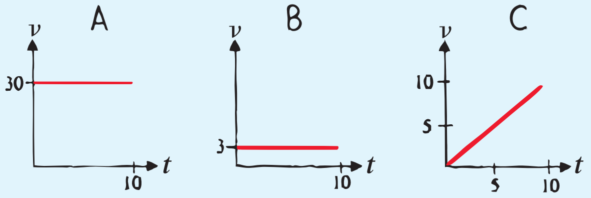


a. From fastest to slowest, rank the tracks in terms of the *speed* of the ball at the end. Or, do all balls have the same speed there?

b. From longest to shortest, rank the tracks in terms of the *time* for the ball to reach the end. Or do all balls reach the end in the same time?

c. From greatest to least, rank the tracks in terms of the *average speed* of the ball. Or do the balls all have the same average speed on all three tracks?

25. In the speed versus time graphs, all times t are in s and all speeds v are in m/s.



a. From greatest to least, rank the graphs in terms of the greatest *speed* at 10 seconds.

b. From greatest to least, rank the graphs in terms of the greatest *acceleration.*

c. From greatest to least, rank the graphs in terms of the greatest *distance* covered in 10 seconds.

Plug and Chug

These are to familiarize you with the central equations of the chapter.

$$\textbf{Average speed} = \frac{\textbf{total distance covered}}{\textbf{time interval}}$$

26. Calculate your average walking speed when you step 1 meter in 0.5 second.

27. Calculate the speed of a bowling ball that moves 8 meters in 4 seconds.

28. Calculate your average speed if you run 50 meters in 10 seconds.

$$\textbf{Distance} = \textbf{average speed} \times \textbf{time}$$

29. Calculate the distance (in km) that Charlie runs if he maintains an average speed of 8 km/h for 1 hour.

30. Calculate the distance you will travel if you maintain an average speed of 10 m/s for 40 seconds.

31. Calculate the distance (in km) you will travel if you maintain an average speed of 10 km/h for 1/2 hour.

$$\textbf{Acceleration} = \frac{\textbf{change of velocity}}{\textbf{time interval}}$$

32. Calculate the acceleration of a car (in km/h/s) that can go from rest to 100 km/h in 10 s.

33. Calculate the acceleration of a bus that goes from 10 km/h to a speed of 50 km/h in 10 seconds.

34. Calculate the acceleration of a ball that starts from rest and rolls down a ramp and gains a speed of 25 m/s in 5 seconds.

From a rest position:

$$\textbf{Instantaneous speed} = \textbf{acceleration} \times \textbf{time}$$

$$v = at$$

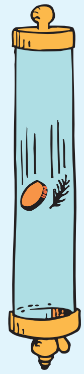
35. Calculate the instantaneous speed (in m/s) at the 10-second mark for a car that accelerates at 2 m/s^2 from a position of rest.

36. Calculate the speed (in m/s) of a skateboarder who accelerates from rest for 3 seconds down a ramp at an acceleration of 5 m/s^2.

Velocity acquired in free fall, from rest:

$$v = gt$$

37. Calculate the instantaneous speed of an apple 8 seconds after being dropped from rest.

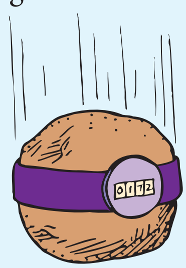


38. On a distant planet a freely-falling object has an acceleration of 20 m/s^2. Calculate the speed an object dropped from rest on this distant planet acquires in 1.5 seconds.

Distance fallen in free fall, from rest:

$$d = \tfrac{1}{2}gt^2$$

39. A sky diver steps from a high-flying helicopter. If there were no air resistance, how fast would she be falling at the end of a 12-second jump?



40. Calculate the vertical distance an object dropped from rest would cover in 12 seconds if it fell freely without air resistance.

41. An apple drops from a tree and hits the ground in 1.5 seconds. Calculate how far it falls.

Think and Explain

42. Light travels in a straight line at a constant speed of 300,000 km/s. What is the light's acceleration?

43. **a.** If a freely falling rock were equipped with a speedometer, by how much would its speed readings increase with each second of fall?
b. Suppose the freely falling rock were dropped near the surface of a planet where $g = 20\ m/s^2$. By how much would its speed readings change each second?

44. Which has more acceleration when moving in a straight line—a car increasing its speed from 50 to 60 km/h, or a bicycle that goes from zero to 10 km/h in the same time? Defend your answer.

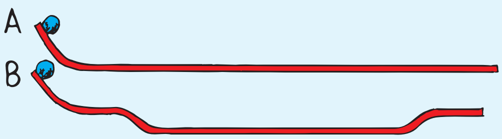
45. Correct your friend who says, "The dragster rounded the curve at a constant velocity of 100 km/h."

46. What is the acceleration of a car that moves at a steady velocity of 100 km/h due north for 100 seconds? Explain your answer and state why this question is an exercise in careful reading as well as physics.

47. Tiffany stands at the edge of a cliff and throws a ball straight up at a certain speed and another ball straight down with the same initial speed. Neglect air resistance.
   a. Which ball is in the air for the longest time?
   b. Which ball has the greater speed when it strikes the ground below?

48. A ball is thrown straight up. What will be the instantaneous velocity at the top of its path? What will be its acceleration at the top? Why are your answers different?

49. Two balls are released simultaneously from rest at the left ends of the equal-length tracks A and B as shown. Which ball reaches the end of its track first?



50. Refer to the tracks in the previous problem.
   a. Does the ball on B roll faster in the dip than the ball rolling along track A?
   b. On track B, is the speed gained going down into the dip equal to the speed lost going up the dip? If so, do the balls then have the same speed at the ends of both tracks?
   c. Is the average speed of the ball on the lower part of track B greater than the average speed of the ball on A during the same time?
   d. So overall, which ball has the greater *average* speed? (Do you wish to change your answer to the previous exercise?)

Think and Solve

51. A dragster going at 15 m/s north increases its velocity to 25 m/s north in 4 seconds. What is its acceleration during this time interval?

52. An apple drops from a tree and hits the ground in 1.5 s. What is its speed just before it hits the ground?

53. On a distant planet a freely falling object has an acceleration of 20 m/s^2. What vertical distance will an object dropped from rest on this planet cover in 1.8 s?

54. If you throw a ball straight upward at a speed of 10 m/s, how long will it take to reach zero speed? How long will it take to return to its starting point? How fast will it be going when it returns to its starting point?

55. Hanna tosses a ball straight up with enough speed to remain in the air for several seconds.
   a. What is the velocity of the ball when it reaches its highest point?
   b. What is its velocity 1 s before it reaches its highest point?
   c. What is the change in its velocity during this 1-s interval?
   d. What is its velocity 1 s after it reaches its highest point?
   e. What is the change in velocity during this 1-s interval?
   f. What is the change in velocity during the 2-s interval? (Caution: velocity, not speed!)
   g. What is the acceleration of the ball during any of these time intervals and at the moment the ball has zero velocity?

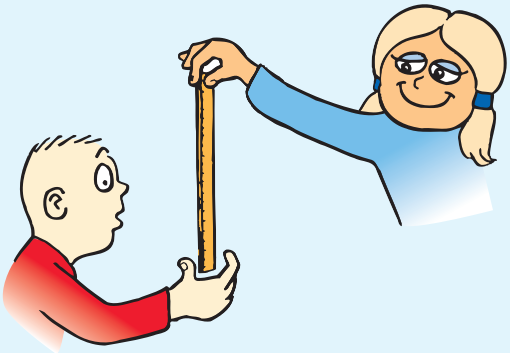
56. Kenny Klutz drops his physics book off his aunt's high-rise balcony. It hits the ground below 1.5 s later.
   a. With what speed does it hit?
   b. How high is the balcony?
   Ignore air drag.

57. Calculate the hang time of an athlete who jumps a vertical distance of 0.75 meter.

Activities

58. By any method you choose, determine your average speed of walking. How do your results compare with those of your classmates?

59. You can compare your reaction time with that of a friend by catching a ruler that is dropped between your fingers. Let your friend hold the ruler as shown in the figure.



Snap your fingers together as soon as you see the ruler released. On what does the number of centimeters that pass through your fingers depend? You can calculate your reaction time in seconds by solving $d = \frac{1}{2}gt^2$ for time: $t = \sqrt{2d/g}$. If you express d in meters (likely a fraction of a meter), then $t = 0.45\sqrt{d}$; if you express d in centimeters, then $t = 0.045\sqrt{d}$. Compare your reaction time with those of your classmates.

60. Calculate your personal "hang time," the time your feet are off the ground during a vertical jump.

More Problem-Solving Practice
Appendix F