Craig Breedlove, five times world land speed record holder, accelerates across the Black Rock Desert in Gerlach, Nevada, in his jet-powered car, Spirit of America, on its first test run on September 6, 1997. Subsequent jet-powered cars have broken the sound barrier on land.

### 2.1 Displacement

### 2.2 Velocity

### 2.3 Acceleration

### 2.4 Motion Diagrams

### 2.5 One-Dimensional Motion with Constant Acceleration

### 2.6 Freely Falling Objects

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**MOTION IN ONE DIMENSION**

Life is motion. Our muscles coordinate motion microscopically to enable us to walk and jog. Our hearts pump tirelessly for decades, moving blood through our bodies. Cell wall mechanisms move select atoms and molecules in and out of cells. From the prehistoric chase of antelopes across the savanna to the pursuit of satellites in space, mastery of motion has been critical to our survival and success as a species.

The study of motion and of physical concepts such as force and mass is called **dynamics**. The part of dynamics that describes motion without regard to its causes is called **kinematics**. In this chapter the focus is on kinematics in one dimension: motion along a straight line. This kind of motion—and, indeed, any motion—involves the concepts of displacement, velocity, and acceleration. Here, we use these concepts to study the motion of objects undergoing constant acceleration. In Chapter 3 we will repeat this discussion for objects moving in two dimensions.

The first recorded evidence of the study of mechanics can be traced to the people of ancient Sumeria and Egypt, who were interested primarily in understanding the motions of heavenly bodies. The most systematic and detailed early studies of the heavens were conducted by the Greeks from about 300 B.C. to A.D. 300. Ancient scientists and laypeople regarded the Earth as the center of the Universe. This **geocentric model** was accepted by such notables as Aristotle (384–322 B.C.) and Claudius Ptolemy (about A.D. 140). Largely because of the authority of Aristotle, the geocentric model became the accepted theory of the Universe until the 17th century.

About 250 B.C., the Greek philosopher Aristarchus worked out the details of a model of the Solar System based on a spherical Earth that rotated on its axis and revolved around the Sun. He proposed that the sky appeared to turn westward because the Earth was turning eastward. This model wasn’t given much consideration because it was believed that a turning Earth would generate powerful winds as it moved through the air. We now know that the Earth carries the air and everything else with it as it rotates.

The Polish astronomer Nicolaus Copernicus (1473–1543) is credited with initiating the revolution that finally replaced the geocentric model. In his system, called the **heliocentric model**, Earth and the other planets revolve in circular orbits around the Sun.
This early knowledge formed the foundation for the work of Galileo Galilei (1564–1642), who stands out as the dominant facilitator of the entrance of physics into the modern era. In 1609 he became one of the first to make astronomical observations with a telescope. He observed mountains on the Moon, the larger satellites of Jupiter, spots on the Sun, and the phases of Venus. Galileo’s observations convinced him of the correctness of the Copernican theory. His quantitative study of motion formed the foundation of Newton’s revolutionary work in the next century.

2.1 DISPLACEMENT

Motion involves the displacement of an object from one place in space and time to another. Describing motion requires some convenient coordinate system and a specified origin. A frame of reference is a choice of coordinate axes that defines the starting point for measuring any quantity, an essential first step in solving virtually any problem in mechanics (Fig. 2.1). In Active Figure 2.2a, for example, a car moves along the x-axis. The coordinates of the car at any time describe its position in space and, more importantly, its displacement at some given time of interest.

The displacement \( \Delta x \) of an object is defined as its change in position, and is given by

\[
\Delta x = x_f - x_i \tag{2.1}
\]

where the initial position of the car is labeled \( x_i \) and the final position is \( x_f \). (The indices \( i \) and \( f \) stand for initial and final, respectively.)

SI unit: meter (m)

We will use the Greek letter delta, \( \Delta \), to denote a change in any physical quantity. From the definition of displacement, we see that \( \Delta x \) (read “delta ex”) is positive if \( x_f \) is greater than \( x_i \) and negative if \( x_f \) is less than \( x_i \). For example, if the car moves from point \( \bullet \) to point \( \circ \) so that the initial position is \( x_i = 30 \text{ m} \) and the final position is \( x_f = 52 \text{ m} \), the displacement is \( \Delta x = x_f - x_i = 52 \text{ m} - 30 \text{ m} = +22 \text{ m} \). However, if the car moves from point \( \circ \) to point \( \triangle \), then the initial position is \( x_i = 38 \text{ m} \) and the final position is \( x_f = -53 \text{ m} \), and the displacement is \( \Delta x = x_f - x_i = -53 \text{ m} - 38 \text{ m} = -91 \text{ m} \). A positive answer indicates a displacement in the positive \( x \)-direction, whereas a negative answer indicates a displacement in the negative \( x \)-direction. Active Figure 2.2b displays the graph of the car’s position as a function of time.

Because displacement has both a magnitude (size) and a direction, it’s a vector quantity, as are velocity and acceleration. In general, a vector quantity is characterized by having both a magnitude and a direction. By contrast, a scalar quantity

**Tip 2.1 A Displacement Isn’t a Distance!**

The displacement of an object is not the same as the distance it travels. Toss a tennis ball up and catch it. The ball travels a distance equal to twice the maximum height reached, but its displacement is zero.

**ACTIVE FIGURE 2.2**

(a) A car moves back and forth along a straight line taken to be the \( x \)-axis. Because we are interested only in the car’s translational motion, we can model it as a particle.
(b) Graph of position vs. time for the motion of the “particle.”
Chapter 2  Motion in One Dimension

Tip 2.2  Vectors Have Both a Magnitude and a Direction.
Scalars have size. Vectors, too, have size, but they also indicate a direction.

has magnitude, but no direction. Scalar quantities such as mass and temperature are completely specified by a numeric value with appropriate units; no direction is involved.

Vector quantities will be usually denoted in boldface type with an arrow over the top of the letter. For example, \( \vec{v} \) represents velocity and \( \vec{a} \) denotes an acceleration, both vector quantities. In this chapter, however, it won’t be necessary to use that notation because in one-dimensional motion an object can only move in one of two directions, and these directions are easily specified by plus and minus signs.

2.2  VELOCITY

In everyday usage the terms speed and velocity are interchangeable. In physics, however, there’s a clear distinction between them: Speed is a scalar quantity, having only magnitude, whereas velocity is a vector, having both magnitude and direction.

Why must velocity be a vector? If you want to get to a town 70 km away in an hour’s time, it’s not enough to drive at a speed of 70 km/h; you must travel in the correct direction as well. This is obvious, but shows that velocity gives considerably more information than speed, as will be made more precise in the formal definitions.

Definition of average speed

The average speed of an object over a given time interval is the total distance traveled divided by the total time elapsed:

\[
\text{Average speed} = \frac{\text{total distance}}{\text{total time}}
\]

SI unit: meter per second (m/s)

In symbols, this equation might be written \( v = \frac{d}{t} \), with the letter \( v \) understood in context to be the average speed, not a velocity. Because total distance and total time are always positive, the average speed will be positive, also. The definition of average speed completely ignores what may happen between the beginning and the end of the motion. For example, you might drive from Atlanta, Georgia, to St. Petersburg, Florida, a distance of about 500 miles, in 10 hours. Your average speed is 500 mi/10 h = 50 mi/h. It doesn’t matter if you spent two hours in a traffic jam traveling only 5 mi/h and another hour at a rest stop. For average speed, only the total distance traveled and total elapsed time are important.

Example 2.1  The Tortoise and the Hare

Goal  Apply the concept of average speed.

Problem  A turtle and a rabbit engage in a footrace over a distance of 4.00 km. The rabbit runs 0.500 km and then stops for a 90.0-min nap. Upon awakening, he remembers the race and runs twice as fast. Finishing the course in a total time of 1.75 h, the rabbit wins the race. (a) Calculate the average speed of the rabbit. (b) What was his average speed before he stopped for a nap?

Strategy  Finding the overall average speed in part (a) is just a matter of dividing the total distance by the total time. Part (b) requires two equations and two unknowns, the latter turning out to be the two different average speeds: \( v_1 \) before the nap and \( v_2 \) after the nap. One equation is given in the statement of the problem \( (v_2 = 2v_1) \), whereas the other comes from the fact the rabbit ran for only 15 minutes because he napped for 90 minutes.

Solution

(a) Find the rabbit’s overall average speed.

Apply the equation for average speed:

\[
\text{Average speed} = \frac{\text{total distance}}{\text{total time}} = \frac{4.00 \text{ km}}{1.75 \text{ h}}
\]

\[= 2.29 \text{ km/h} \]
Unlike average speed, average velocity is a vector quantity, having both a magnitude and a direction. Consider again the car of Figure 2.2, moving along the road (the x-axis). Let the car’s position be \( x_i \) at some time \( t_i \) and \( x_f \) at a later time \( t_f \).

In the time interval \( t_f - t_i \), the displacement of the car is \( x_f - x_i \).

The average velocity \( \bar{v} \) during a time interval \( \Delta t \) is the displacement \( \Delta x \) divided by \( \Delta t \):

\[
\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i} \tag{2.2}
\]

**SI unit:** meter per second (m/s)

Unlike the average speed, which is always positive, the average velocity of an object in one dimension can be either positive or negative, depending on the sign of the displacement. (The time interval \( \Delta t \) is always positive.) In Figure 2.2a, for example, the average velocity of the car is positive in the upper illustration, a positive sign indicating motion to the right along the x-axis. Similarly, a negative average velocity for the car in the lower illustration of the figure indicates that it moves to the left along the x-axis.

As an example, we can use the data in Table 2.1 to find the average velocity in the time interval from point \( \text{A} \) to point \( \text{B} \) (assume two digits are significant):

\[
\bar{v} = \frac{\Delta x}{\Delta t} = \frac{52 \text{ m} - 30 \text{ m}}{10 \text{ s} - 0 \text{ s}} = 2.2 \text{ m/s}
\]

Aside from meters per second, other common units for average velocity are feet per second (ft/s) in the U.S. customary system and centimeters per second (cm/s) in the cgs system.

To further illustrate the distinction between speed and velocity, suppose we’re watching a drag race from the Goodyear blimp. In one run we see a car follow the straight-line path from \( \text{P} \) to \( \text{Q} \) shown in Figure 2.3 during the time interval \( \Delta t \),

(b) Find the rabbit’s average speed before his nap.

Sum the running times, and set the sum equal to 0.25 h: \( t_1 + t_2 = 0.25 \text{ h} \)

Substitute \( t_1 = d_1/v_1 \) and \( t_2 = d_2/v_2 \):

\[
(1) \quad \frac{d_1}{v_1} + \frac{d_2}{v_2} = 0.25 \text{ h}
\]

Substitute \( v_2 = 2v_1 \) and the values of \( d_1 \) and \( d_2 \) into Equation (1):

\[
(2) \quad \frac{0.500 \text{ km}}{v_1} + \frac{3.50 \text{ km}}{2v_1} = 0.25 \text{ h}
\]

Solve Equation (2) for \( v_1 \):

\[
v_1 = 9.00 \text{ km/h}
\]

**Remark** As seen in this example, average speed can be calculated regardless of any variation in speed over the given time interval.

**QUESTION 2.1**

Does a doubling of an object’s average speed always double the magnitude of its displacement in a given amount of time? Explain.

**EXERCISE 2.1**

Estimate the average speed of the Apollo spacecraft in meters per second, given that the craft took five days to reach the Moon from Earth. (The Moon is \( 3.8 \times 10^8 \text{ m} \) from Earth.)

**Answer** \( \sim 900 \text{ m/s} \)
and in a second run a car follows the curved path during the same interval. From
the definition in Equation 2.2, the two cars had the same average velocity because
they had the same displacement $\Delta x = x_f - x_i$ during the same time interval $\Delta t$.
The car taking the curved route, however, traveled a greater distance and had the
higher average speed.

Quick Quiz 2.1 Figure 2.4 shows the unusual path of a confused football player. After
receiving a kickoff at his own goal, he runs downfield to within inches of a touchdown,
then reverses direction and races back until he’s tackled at the exact location where he first
catched the ball. During this run, which took 25 s, what is (a) the total distance he travels, (b) his
displacement, and (c) his average velocity in the $x$-direction? (d) What is his average speed?

Graphical Interpretation of Velocity

If a car moves along the $x$-axis from $A$ to $B$ to $C$, and so forth, we can plot the
positions of these points as a function of the time elapsed since the start of the
motion. The result is a **position vs. time graph** like those of Figure 2.5. In Figure
2.5a, the graph is a straight line because the car is moving at constant velocity.
The same displacement $\Delta x$ occurs in each time interval $\Delta t$. In this case, the average
velocity is always the same and is equal to $\Delta x/\Delta t$. Figure 2.5b is a graph of the
data in Table 2.1. Here, the position vs. time graph is not a straight line because the
velocity of the car is changing. Between any two points, however, we can draw a
straight line just as in Figure 2.5a, and the slope of that line is the average velocity
$\Delta x/\Delta t$ in that time interval. In general, the **average velocity of an object during
the time interval $\Delta t$ is equal to the slope of the straight line joining the initial and
final points on a graph of the object’s position versus time**.

From the data in Table 2.1 and the graph in Figure 2.5b, we see that the car
first moves in the positive $x$-direction as it travels from $A$ to $B$, reaches a position
of 52 m at time $t = 10$ s, then reverses direction and heads backwards. In the first
10 s of its motion, as the car travels from $A$ to $B$, its average velocity is 2.2 m/s,
as previously calculated. In the first 40 seconds, as the car goes from $A$ to $C$,
its displacement is $\Delta x = -37 m - (30 m) = -67 m$. So the average velocity in this
interval, which equals the slope of the blue line in Figure 2.5b from $A$ to $C$, is
\[
\vec{v} = \Delta x/\Delta t = (-67 m)/(40 s) = -1.7 m/s.
\]
In general, there will be a different average velocity between any distinct pair of points.

Instantaneous Velocity

Average velocity doesn’t take into account the details of what happens during an
interval of time. On a car trip, for example, you may speed up or slow down a number
of times in response to the traffic and the condition of the road, and on rare occasions
even pull over to chat with a police officer about your speed. What is most important
to the police (and to your own safety) is the speed of your car and the direction it was going at a particular instant in time, which together determine the car’s **instantaneous velocity**.
So in driving a car between two points, the average velocity must be computed over an interval of time, but the magnitude of instantaneous velocity can be read on the car’s speedometer.

The instantaneous velocity $v$ is the limit of the average velocity as the time interval $\Delta t$ becomes infinitesimally small:

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} \quad [2.3]$$

SI unit: meter per second (m/s)

The notation $\lim_{\Delta t \to 0}$ means that the ratio $\Delta x/\Delta t$ is repeatedly evaluated for smaller and smaller time intervals $\Delta t$. As $\Delta t$ gets extremely close to zero, the ratio $\Delta x/\Delta t$ gets closer and closer to a fixed number, which is defined as the instantaneous velocity.

To better understand the formal definition, consider data obtained on our vehicle via radar (Table 2.2). At $t = 1.00$ s, the car is at $x = 5.00$ m, and at $t = 3.00$ s, it’s at $x = 52.5$ m. The average velocity computed for this interval $\Delta x/\Delta t = (52.5 \text{ m} - 5.00 \text{ m})/(3.00 \text{ s} - 1.00 \text{ s}) = 23.8 \text{ m/s}$. This result could be used as an estimate for the velocity at $t = 1.00$ s, but it wouldn’t be very accurate because the speed changes considerably in the two-second time interval. Using the rest of the data, we can construct Table 2.3. As the time interval gets smaller, the average velocity more closely approaches the instantaneous velocity. Using the final interval of only $0.010 \text{ s}$, we find that the average velocity is $\bar{v} = \Delta x/\Delta t = 0.470 \text{ m/s}$. Because $0.010 \text{ s}$ is a very short time interval, the actual instantaneous velocity is probably very close to this latter average velocity, given the limits on the car’s ability to accelerate. Finally using the conversion factor on the inside front cover of the book, we see that this is $105 \text{ mi/h}$, a likely violation of the speed limit.

**TABLE 2.2**

<table>
<thead>
<tr>
<th>$t$ (s)</th>
<th>$x$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>5.00</td>
</tr>
<tr>
<td>1.01</td>
<td>5.47</td>
</tr>
<tr>
<td>1.10</td>
<td>9.67</td>
</tr>
<tr>
<td>1.20</td>
<td>14.3</td>
</tr>
<tr>
<td>1.50</td>
<td>26.3</td>
</tr>
<tr>
<td>2.00</td>
<td>34.7</td>
</tr>
<tr>
<td>3.00</td>
<td>52.5</td>
</tr>
</tbody>
</table>

**TABLE 2.3**

<table>
<thead>
<tr>
<th>Time Interval (s)</th>
<th>$\Delta t$ (s)</th>
<th>$\Delta x$ (m)</th>
<th>$\bar{v}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 to 3.00</td>
<td>2.00</td>
<td>47.5</td>
<td>23.8</td>
</tr>
<tr>
<td>1.00 to 2.00</td>
<td>1.00</td>
<td>29.7</td>
<td>29.7</td>
</tr>
<tr>
<td>1.00 to 1.50</td>
<td>0.50</td>
<td>21.3</td>
<td>42.6</td>
</tr>
<tr>
<td>1.00 to 1.20</td>
<td>0.20</td>
<td>9.30</td>
<td>46.5</td>
</tr>
<tr>
<td>1.00 to 1.10</td>
<td>0.10</td>
<td>4.67</td>
<td>46.7</td>
</tr>
<tr>
<td>1.00 to 1.01</td>
<td>0.01</td>
<td>0.470</td>
<td>47.0</td>
</tr>
</tbody>
</table>
As can be seen in Figure 2.6, the chords formed by the blue lines gradually approach a tangent line as the time interval becomes smaller. The slope of the line tangent to the position vs. time curve at “a given time” is defined to be the instantaneous velocity at that time.

The instantaneous speed of an object, which is a scalar quantity, is defined as the magnitude of the instantaneous velocity. Like average speed, instantaneous speed (which we will usually call, simply, “speed”) has no direction associated with it and hence carries no algebraic sign. For example, if one object has an instantaneous velocity of $\frac{15}{10.0} \text{ m/s}$ along a given line and another object has an instantaneous velocity of $-15 \text{ m/s}$ along the same line, both have an instantaneous speed of $15 \text{ m/s}$.

**EXAMPLE 2.2 Slowly Moving Train**

**Goal** Obtain average and instantaneous velocities from a graph.

**Problem** A train moves slowly along a straight portion of track according to the graph of position versus time in Figure 2.7a. Find (a) the average velocity for the total trip, (b) the average velocity during the first 4.00 s of motion, (c) the average velocity during the next 4.00 s of motion, (d) the instantaneous velocity at $t = 2.00 \text{ s}$, and (e) the instantaneous velocity at $t = 9.00 \text{ s}$.

**Strategy** The average velocities can be obtained by substituting the data into the definition. The instantaneous velocity at $t = 2.00 \text{ s}$ is the same as the average velocity at that point because the position vs. time graph is a straight line, indicating constant velocity. Finding the instantaneous velocity when $t = 9.00 \text{ s}$ requires sketching a line tangent to the curve at that point and finding its slope.

**Solution**

(a) Find the average velocity from $A$ to $C$.

Calculate the slope of the dashed blue line:

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{10.0 \text{ m}}{12.0 \text{ s}} = +0.833 \text{ m/s}$$

(b) Find the average velocity during the first 4 seconds of the train’s motion.

Again, find the slope:

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{4.00 \text{ m}}{4.00 \text{ s}} = +1.00 \text{ m/s}$$

(c) Find the average velocity during the next 4 seconds.

Here, there is no change in position, so the displacement $\Delta x$ is zero:

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{0 \text{ m}}{4.00 \text{ s}} = 0 \text{ m/s}$$
2.3 ACCELERATION

Going from place to place in your car, you rarely travel long distances at constant velocity. The velocity of the car increases when you step harder on the gas pedal and decreases when you apply the brakes. The velocity also changes when you round a curve, altering your direction of motion. The changing of an object’s velocity with time is called **acceleration**.

### Average Acceleration

A car moves along a straight highway as in Figure 2.8. At time \( t_i \) it has a velocity of \( v_i \), and at time \( t_f \) its velocity is \( v_f \), with \( \Delta v = v_f - v_i \) and \( \Delta t = t_f - t_i \).

The average acceleration \( \bar{a} \) during the time interval \( \Delta t \) is the change in velocity \( \Delta v \) divided by \( \Delta t \):

\[
\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}
\]

**SI unit:** meter per second per second (m/s\(^2\))

For example, suppose the car shown in Figure 2.8 accelerates from an initial velocity of \( v_i = +10 \text{ m/s} \) to a final velocity of \( v_f = +20 \text{ m/s} \) in a time interval of 2 s. (Both velocities are toward the right, selected as the positive direction.) These values can be inserted into Equation 2.4 to find the average acceleration:

\[
\bar{a} = \frac{\Delta v}{\Delta t} = \frac{20 \text{ m/s} - 10 \text{ m/s}}{2 \text{ s}} = +5 \text{ m/s}^2
\]

Acceleration is a vector quantity having dimensions of length divided by the time squared. Common units of acceleration are meters per second per second ((m/s)/s, which is usually written m/s\(^2\)) and feet per second per second (ft/s\(^2\)).

**Remarks** From the origin to \( \oplus \), the train moves at constant speed in the positive x-direction for the first 4.00 s, because the position vs. time curve is rising steadily toward positive values. From \( \oplus \) to \( \odot \), the train stops at \( x = 4.00 \text{ m} \) for 4.00 s. From \( \odot \) to \( \ominus \), the train travels at increasing speed in the positive x-direction.

**QUESTION 2.2**

Would a vertical line in a graph of position versus time make sense? Explain.

**EXERCISE 2.2**

Figure 2.7b graphs another run of the train. Find (a) the average velocity from \( \ominus \) to \( \ominus \); (b) the average and instantaneous velocities from \( \odot \) to \( \oplus \); (c) the approximate instantaneous velocity at \( t = 6.0 \text{ s} \); and (d) the average and instantaneous velocity at \( t = 9.0 \text{ s} \).

**Answers**
(a) 0 m/s
(b) both are +0.5 m/s
(c) 2 m/s
(d) both are −2.5 m/s
average acceleration of +5 m/s² means that, on average, the car increases its velocity by 5 m/s every second in the positive x-direction.

For the case of motion in a straight line, the direction of the velocity of an object and the direction of its acceleration are related as follows. When the object’s velocity and acceleration are in the same direction, the speed of the object increases with time. When the object’s velocity and acceleration are in opposite directions, the speed of the object decreases with time.

To clarify this point, suppose the velocity of a car changes from −10 m/s to −20 m/s in a time interval of 2 s. The minus signs indicate that the velocities of the car are in the negative x-direction; they do not mean that the car is slowing down! The average acceleration of the car in this time interval is

\[ \bar{a} = \frac{\Delta v}{\Delta t} = \frac{-20 \text{ m/s} - (-10 \text{ m/s})}{2 \text{ s}} = -5 \text{ m/s}^2 \]

The minus sign indicates that the acceleration vector is also in the negative x-direction. Because the velocity and acceleration vectors are in the same direction, the speed of the car must increase as the car moves to the left. Positive and negative accelerations specify directions relative to chosen axes, not “speeding up” or “slowing down.” The terms “speeding up” or “slowing down” refer to an increase and a decrease in speed, respectively.

**QUICK QUIZ 2.2** True or False? (a) A car must always have an acceleration in the same direction as its velocity. (b) It’s possible for a slowing car to have a positive acceleration. (c) An object with constant nonzero acceleration can never stop and remain at rest.

**Instantaneous Acceleration**

The value of the average acceleration often differs in different time intervals, so it’s useful to define the instantaneous acceleration, which is analogous to the instantaneous velocity discussed in Section 2.2.

The instantaneous acceleration \( a \) is the limit of the average acceleration as the time interval \( \Delta t \) goes to zero:

\[ a = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t} \quad [2.5] \]

SI unit: meter per second per second (m/s²)

Here again, the notation \( \lim \) means that the ratio \( \Delta v/\Delta t \) is evaluated for smaller and smaller values of \( \Delta t \). The closer \( \Delta t \) gets to zero, the closer the ratio gets to a fixed number, which is the instantaneous acceleration.

Figure 2.9, a velocity vs. time graph, plots the velocity of an object against time. The graph could represent, for example, the motion of a car along a busy street. The average acceleration of the car between times \( t_i \) and \( t_f \) can be found by determining the slope of the line joining points \( \circ \) and \( \odot \). If we imagine that point \( \odot \) is brought closer and closer to point \( \circ \), the line comes closer and closer to becoming tangent at \( \circ \). The instantaneous acceleration of an object at a given time equals the slope of the tangent to the velocity vs. time graph at that time. From now on, we will use the term acceleration to mean “instantaneous acceleration.”

In the special case where the velocity vs. time graph of an object’s motion is a straight line, the instantaneous acceleration of the object at any point is equal to its average acceleration. This also means that the tangent line to the graph overlaps the graph itself. In that case, the object’s acceleration is said to be uniform, which means that it has a constant value. Constant acceleration problems are important in kinematics and will be studied extensively in this and the next chapter.
QUICK QUIZ 2.3 Parts (a), (b), and (c) of Figure 2.10 represent three graphs of the velocities of different objects moving in straight-line paths as functions of time. The possible accelerations of each object as functions of time are shown in parts (d), (e), and (f). Match each velocity vs. time graph with the acceleration vs. time graph that best describes the motion.

EXAMPLE 2.3 Catching a Fly Ball

Goal Apply the definition of instantaneous acceleration.

Problem A baseball player moves in a straight-line path in order to catch a fly ball hit to the outfield. His velocity as a function of time is shown in Figure 2.11a. Find his instantaneous acceleration at points A, B, and C.

Strategy At each point, the velocity vs. time graph is a straight line segment, so the instantaneous acceleration will be the slope of that segment. Select two points on each segment and use them to calculate the slope.

Solution

Acceleration at A.
The acceleration at A equals the slope of the line connecting the points (0 s, 0 m/s) and (2.0 s, 4.0 m/s):

\[
a = \frac{\Delta v}{\Delta t} = \frac{4.0 \text{ m/s} - 0}{2.0 \text{ s} - 0} = +2.0 \text{ m/s}^2
\]

Acceleration at B.
\[
\Delta v = 0, \text{ because the segment is horizontal:}
\]
\[
a = \frac{\Delta v}{\Delta t} = \frac{4.0 \text{ m/s} - 4.0 \text{ m/s}}{3.0 \text{ s} - 2.0 \text{ s}} = 0 \text{ m/s}^2
\]

Acceleration at C.
The acceleration at C equals the slope of the line connecting the points (3.0 s, 4.0 m/s) and (4.0 s, 2.0 m/s):

\[
a = \frac{\Delta v}{\Delta t} = \frac{2.0 \text{ m/s} - 4.0 \text{ m/s}}{4.0 \text{ s} - 3.0 \text{ s}} = -2.0 \text{ m/s}^2
\]

Remarks Assume the player is initially moving in the positive x-direction. For the first 2.0 s, the ballplayer moves in the positive x-direction (the velocity is positive) and steadily accelerates (the curve is steadily rising) to a maximum speed of 4.0 m/s. He moves for 1.0 s at a steady speed of 4.0 m/s and then slows down in the last second (the v vs. t curve is falling), still moving in the positive x-direction (v is always positive).

QUESTION 2.3 Can the tangent line to a velocity vs. time graph ever be vertical? Explain.

EXERCISE 2.3 Repeat the problem, using Figure 2.11b.

Answer The accelerations at A, B, and C are -3.0 m/s², 1.0 m/s², and 0 m/s², respectively.
2.4 MOTION DIAGRAMS

Velocity and acceleration are sometimes confused with each other, but they’re very different concepts, as can be illustrated with the help of motion diagrams. A **motion diagram** is a representation of a moving object at successive time intervals, with velocity and acceleration vectors sketched at each position, red for velocity vectors and violet for acceleration vectors, as in Active Figure 2.12. The time intervals between adjacent positions in the motion diagram are assumed equal.

A motion diagram is analogous to images resulting from a stroboscopic photograph of a moving object. Each image is made as the strobe light flashes. Active Figure 2.12 represents three sets of strobe photographs of cars moving along a straight roadway from left to right. The time intervals between flashes of the stroboscope are equal in each diagram.

In Active Figure 2.12a, the images of the car are equally spaced: The car moves the same distance in each time interval. This means that the car moves with **constant positive velocity** and has **zero acceleration**. The red arrows are all the same length (constant velocity) and there are no violet arrows (zero acceleration).

In Active Figure 2.12b, the images of the car become farther apart as time progresses and the velocity vector increases with time, because the car’s displacement between adjacent positions increases as time progresses. The car is moving with a **positive velocity** and a **constant positive acceleration**. The red arrows are successively longer in each image, and the violet arrows point to the right.

In Active Figure 2.12c, the car slows as it moves to the right because its displacement between adjacent positions decreases with time. In this case, the car moves initially to the right with a constant negative acceleration. The velocity vector decreases in time (the red arrows get shorter) and eventually reaches zero, as would happen when the brakes are applied. Note that the acceleration and velocity vectors are **not** in the same direction. The car is moving with a **positive velocity**, but with a **negative acceleration**.

Try constructing your own diagrams for various problems involving kinematics.

**QUICK QUIZ 2.4** The three graphs in Active Figure 2.13 represent the position vs. time for objects moving along the x-axis. Which, if any, of these graphs is not physically possible?

![Active Figure 2.12](image)

![Active Figure 2.13](image)
Consequently, at \( t = 0 \) \((\text{for constant}\) acceleration\), Equation 2.2, to obtain an expression for the displacement of an object as a function of time, we can express the average acceleration as:

\[
\bar{a} = a = \frac{v_f - v_i}{t_f - t_i}
\]

The observer timing the motion is always at liberty to choose the initial time, so for convenience, let \( t_i = 0 \) and \( t_f \) be any arbitrary time \( t \). Also, let \( v_i = v_0 \) \((\text{the initial velocity at } t = 0)\) and \( v_f = v \) \((\text{the velocity at any arbitrary time } t)\). With this notation, we can express the acceleration as:

\[
a = \frac{v - v_0}{t}
\]

or

\[
v = v_0 + at\] \tag{2.6}

Equation 2.6 states that the acceleration \( a \) steadily changes the initial velocity \( v_0 \) by an amount \( at \). For example, if a car starts with a velocity of +2.0 m/s to the right and accelerates to the right with \( a = +6.0 \text{ m/s}^2 \), it will have a velocity of +14 m/s after 2.0 s have elapsed:

\[
v = v_0 + at = +2.0 \text{ m/s} + (6.0 \text{ m/s}^2)(2.0 \text{ s}) = +14 \text{ m/s}
\]

The graphical interpretation of \( v \) is shown in Active Figure 2.15b. The velocity varies linearly with time according to Equation 2.6, as it should for constant acceleration.

Because the velocity is increasing or decreasing \( \text{uniformly with time} \), we can express the average velocity in any time interval as the arithmetic average of the initial velocity \( v_i \) and the final velocity \( v_f \):

\[
\bar{v} = \frac{v_i + v_f}{2} \quad \text{(for constant } a) \tag{2.7}
\]

Remember that this expression is valid only when the acceleration is constant, in which case the velocity increases uniformly.

We can now use this result along with the defining equation for average velocity, Equation 2.2, to obtain an expression for the displacement of an object as a function of time:

\[
x = x_0 + \bar{v}t = x_0 + \frac{v_i + v_f}{2}t \quad \text{(for constant } a) \tag{2.8}
\]

2.5 \text{ ONE-DIMENSIONAL MOTION WITH CONSTANT ACCELERATION}

Many applications of mechanics involve objects moving with \( \text{constant acceleration} \). This type of motion is important because it applies to numerous objects in nature, such as an object in free fall near Earth’s surface (assuming air resistance can be neglected). A graph of acceleration versus time for motion with constant acceleration is shown in Active Figure 2.15a. \( \text{When an object moves with constant acceleration, the instantaneous acceleration at any point in a time interval is equal to the value of the average acceleration over the entire time interval} \). Consequently, the velocity increases or decreases at the same rate throughout the motion, and a plot of \( v \) versus \( t \) gives a straight line with either positive, zero, or negative slope.

Because the average acceleration equals the instantaneous acceleration when \( a \) is constant, we can eliminate the bar used to denote average values from our defining equation for acceleration, writing \( \bar{a} = a \), so that Equation 2.4 becomes:

\[
a = \frac{v_f - v_i}{t_f - t_i}
\]

Choose the correct graphs.

\[
\begin{align*}
\text{FIGURE 2.14} & \quad (\text{Quick Quiz 2.5}) \\
& \text{Choose the correct graphs.}
\end{align*}
\]

\[
\begin{align*}
\text{(a)} & \quad \text{The acceleration vs. time graph,} \\
\text{(b)} & \quad \text{the velocity vs. time graph, and} \\
\text{(c)} & \quad \text{the position vs. time graph.}
\end{align*}
\]

\[
\text{ACTIVE FIGURE 2.15} \\
\text{A particle moving along the x-axis with constant acceleration } a. \\
(\text{a}) \quad \text{the acceleration vs. time graph,} \\
(\text{b}) \quad \text{the velocity vs. time graph, and} \\
(\text{c}) \quad \text{the position vs. time graph.}
\]
function of time. Again, we choose $t_i = 0$ and $t_f = t$, and for convenience, we write $\Delta x = x_f - x_i = x - x_0$. This results in

$$\Delta x = \frac{1}{2}(v_0 + v)t$$  \[2.8\]

We can obtain another useful expression for displacement by substituting the equation for $v$ (Eq. 2.6) into Equation 2.8:

$$\Delta x = \frac{1}{2}(v_0 + v + at)t$$  \[2.9\]

This equation can also be written in terms of the position $x$, since $\Delta x = x - x_0$. Active Figure 2.15c shows a plot of $x$ versus $t$ for Equation 2.9, which is related to the graph of velocity vs. time: The area under the curve in Active Figure 2.15b is equal to $v_0 t + \frac{1}{2}at^2$, which is equal to the displacement $\Delta x$. In fact, the area under the graph of $v$ versus $t$ for any object is equal to the displacement $\Delta x$ of the object.

Finally, we can obtain an expression that doesn’t contain time by solving Equation 2.6 for $t$ and substituting into Equation 2.8, resulting in

$$\Delta x = \frac{1}{2}(v + v_0)\left(\frac{v - v_0}{a}\right) = \frac{v^2 - v_0^2}{2a}$$

$$v^2 = v_0^2 + 2a\Delta x$$  \[2.10\]

Equations 2.6 and 2.9 together can solve any problem in one-dimensional motion with constant acceleration, but Equations 2.7, 2.8, and, especially, 2.10 are sometimes convenient. The three most useful equations—Equations 2.6, 2.9, and 2.10—are listed in Table 2.4.

The best way to gain confidence in the use of these equations is to work a number of problems. There is usually more than one way to solve a given problem, depending on which equations are selected and what quantities are given. The difference lies mainly in the algebra.

### PROBLEM-SOLVING STRATEGY

#### ACCELERATED MOTION

The following procedure is recommended for solving problems involving accelerated motion.

1. **Read** the problem.
2. **Draw** a diagram, choosing a coordinate system, labeling initial and final points, and indicating directions of velocities and accelerations with arrows.
3. **Label** all quantities, circling the unknowns. Convert units as needed.

---

**TABLE 2.4**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Information Given by Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v = v_0 + at$</td>
<td>Velocity as a function of time</td>
</tr>
<tr>
<td>$\Delta x = \frac{1}{2}v_0^2 + 2a\Delta x$</td>
<td>Displacement as a function of time</td>
</tr>
<tr>
<td>$v^2 = v_0^2 + 2a\Delta x$</td>
<td>Velocity as a function of displacement</td>
</tr>
</tbody>
</table>

Note: Motion is along the $x$-axis. At $t = 0$, the velocity of the particle is $v_0$. The best way to gain confidence in the use of these equations is to work a number of problems.
4. **Equations** from Table 2.4 should be selected next. All kinematics problems in this chapter can be solved with the first two equations, and the third is often convenient.

5. **Solve** for the unknowns. Doing so often involves solving two equations for two unknowns. It’s usually more convenient to substitute all known values before solving.

6. **Check** your answer, using common sense and estimates.

Most of these problems reduce to writing the kinematic equations from Table 2.4 and then substituting the correct values into the constants $a$, $v_0$, and $x_0$ from the given information. Doing this produces two equations—one linear and one quadratic—for two unknown quantities.

### EXAMPLE 2.4  The Daytona 500

**Goal**  Apply the basic kinematic equations.

**Problem**  (a) A race car starting from rest accelerates at a constant rate of 5.00 m/s$^2$. What is the velocity of the car after it has traveled 1.00 × $10^2$ ft? (b) How much time has elapsed?

**Strategy**  (a) We’ve read the problem, drawn the diagram in Figure 2.16, and chosen a coordinate system (steps 1 and 2). We’d like to find the velocity $v$ after a certain known displacement $\Delta x$. The acceleration $a$ is also known, as is the initial velocity $v_0$ (step 3, labeling, is complete), so the third equation in Table 2.4 looks most useful for solving part (a). Given the velocity, the first equation in Table 2.4 can then be used to find the time in part (b).

**Solution**  (a) Convert units of $\Delta x$ to SI, using the information in the inside front cover.

Write the kinematics equation for $v^2$ (step 4):

$$v^2 = v_0^2 + 2a \Delta x$$

Solve for $v$, taking the positive square root because the car moves to the right (step 5):

$$v = \sqrt{v_0^2 + 2a \Delta x}$$

Substitute $v_0 = 0$, $a = 5.00$ m/s$^2$, and $\Delta x = 30.5$ m:

$$v = \sqrt{0^2 + 2(5.00 \text{ m/s}^2)(30.5 \text{ m})} = 17.5 \text{ m/s}$$

(b) How much time has elapsed?

Apply the first equation of Table 2.4:

$$v = at + v_0$$

Substitute values and solve for time $t$:

$$17.5 \text{ m/s} = (5.00 \text{ m/s}^2)t$$

$$t = \frac{17.5 \text{ m/s}}{5.0 \text{ m/s}^2} = 3.50 \text{ s}$$

**Remarks**  The answers are easy to check. An alternate technique is to use $\Delta x = v_0t + \frac{1}{2}at^2$ to find $t$ and then use the equation $v = v_0 + at$ to find $v$.

**QUESTION 2.4**

What is the final speed if the displacement is increased by a factor of 4?
Chapter 2  Motion in One Dimension

EXERCISE 2.4
Suppose the driver in this example now slams on the brakes, stopping the car in 4.00 s. Find (a) the acceleration and (b) the distance the car travels while braking, assuming the acceleration is constant.

Answers  (a) $a = -4.38 \text{ m/s}^2$  (b) $d = 35.0 \text{ m}$

EXAMPLE 2.5  Car Chase

Goal  Solve a problem involving two objects, one moving at constant acceleration and the other at constant velocity.

Problem  A car traveling at a constant speed of 24.0 m/s passes a trooper hidden behind a billboard, as in Figure 2.17. One second after the speeding car passes the billboard, the trooper sets off in chase with a constant acceleration of 3.00 m/s$^2$. (a) How long does it take the trooper to overtake the speeding car? (b) How fast is the trooper going at that time?

Strategy  Solving this problem involves two simultaneous kinematics equations of position, one for the trooper and the other for the car. Choose $t = 0$ to correspond to the time the trooper takes up the chase, when the car is at $x_{\text{car}} = 24.0 \text{ m}$ because of its head start (24.0 m/s × 1.00 s). The trooper catches up with the car when their positions are the same, which suggests setting $x_{\text{trooper}} = x_{\text{car}}$ and solving for time, which can then be used to find the trooper’s speed in part (b).

Solution

(a) How long does it take the trooper to overtake the car?

Write the equation for the car’s displacement:

$$\Delta x_{\text{car}} = x_{\text{car}} - x_0 = v_0 t + \frac{1}{2} a_{\text{car}} t^2$$

Take $x_0 = 24.0 \text{ m}$, $v_0 = 24.0 \text{ m/s}$ and $a_{\text{car}} = 0$. Solve for $x_{\text{car}}$:

$$x_{\text{car}} = x_0 + vt = 24.0 \text{ m} + (24.0 \text{ m/s}) t$$

Write the equation for the trooper’s position, taking $x_0 = 0$, $v_0 = 0$, and $a_{\text{trooper}} = 3.00 \text{ m/s}^2$:

$$x_{\text{trooper}} = \frac{1}{2} a_{\text{trooper}} t^2 = \frac{1}{2} (3.00 \text{ m/s}^2) t^2 = (1.50 \text{ m/s}^2) t^2$$

Set $x_{\text{trooper}} = x_{\text{car}}$ and solve the quadratic equation. (The quadratic formula appears in Appendix A, Equation A.8.) Only the positive root is meaningful.

$$(1.50 \text{ m/s}^2) t^2 = 24.0 \text{ m} + (24.0 \text{ m/s}) t - 24.0 \text{ m} = 0$$

$$t = 16.9 \text{ s}$$

(b) Find the trooper’s speed at this time.

Substitute the time into the trooper’s velocity equation:

$$v_{\text{trooper}} = v_0 + a_{\text{trooper}} t = 0 + (3.00 \text{ m/s}^2)(16.9 \text{ s}) = 50.7 \text{ m/s}$$

Remarks  The trooper, traveling about twice as fast as the car, must swerve or apply his brakes strongly to avoid a collision! This problem can also be solved graphically by plotting position versus time for each vehicle on the same graph. The intersection of the two graphs corresponds to the time and position at which the trooper overtakes the car.
QUESTION 2.5
The graphical solution corresponds to finding the intersection of what two types of curves in the $xt$-plane?

EXERCISE 2.5
A motorist with an expired license tag is traveling at 10.0 m/s down a street, and a policeman on a motorcycle, taking another 5.00 s to finish his donut, gives chase at an acceleration of 2.00 m/s$^2$. Find (a) the time required to catch the car and (b) the distance the trooper travels while overtaking the motorist.

Answers  (a) 13.7 s (b) 188 m

EXAMPLE 2.6 Runway Length

Goal Apply kinematics to horizontal motion with two phases.

Problem A typical jetliner lands at a speed of 160 mi/h and decelerates at the rate of (10 mi/h)/s. If the plane travels at a constant speed of 160 mi/h for 1.0 s after landing before applying the brakes, what is the total displacement of the aircraft between touchdown on the runway and coming to rest?

Strategy See Figure 2.18. First, convert all quantities to SI units. The problem must be solved in two parts, or phases, corresponding to the initial coast after touchdown, followed by braking. Using the kinematic equations, find the displacement during each part and add the two displacements.

Solution Convert units of speed and acceleration to SI:

\[ v_0 = \left(160 \text{ mi/h}\right) \left(\frac{0.447 \text{ m/s}}{1 \text{ mi/h}}\right) = 71.5 \text{ m/s} \]
\[ a = \left(-10.0 \text{ (mi/h)/s}\right) \left(\frac{0.447 \text{ m/s}}{1 \text{ mi/h}}\right) = -4.47 \text{ m/s}^2 \]

Taking \( a = 0 \), \( v_0 = 71.5 \text{ m/s} \), and \( t = 1.0 \text{ s} \), find the displacement while the plane is coasting:

\[ \Delta x_{\text{coasting}} = v_0 t + \frac{1}{2}at^2 = (71.5 \text{ m/s})(1.00 \text{ s}) + 0 = 71.5 \text{ m} \]

Use the time-independent kinematic equation to find the displacement while the plane is braking.

\[ v^2 = v_0^2 + 2a\Delta x_{\text{braking}} \]

Take \( a = -4.47 \text{ m/s}^2 \) and \( v_0 = 71.5 \text{ m/s} \). The negative sign on \( a \) means that the plane is slowing down.

\[ \Delta x_{\text{braking}} = \frac{v^2 - v_0^2}{2a} = \frac{0 - (71.5 \text{ m/s})^2}{2.00(-4.47 \text{ m/s}^2)} = 572 \text{ m} \]

Sum the two results to find the total displacement:

\[ \Delta x_{\text{coasting}} + \Delta x_{\text{braking}} = 72 \text{ m} + 572 \text{ m} = 644 \text{ m} \]

Remarks To find the displacement while braking, we could have used the two kinematics equations involving time, namely, \( \Delta x = v_0 t + \frac{1}{2}at^2 \) and \( v = v_0 + at \), but because we weren’t interested in time, the time-independent equation was easier to use.

QUESTION 2.6
How would the answer change if the plane coasted for 2.0 s before the pilot applied the brakes?

EXERCISE 2.6
A jet lands at 80.0 m/s, the pilot applying the brakes 2.00 s after landing. Find the acceleration needed to stop the jet within $5.00 \times 10^2 \text{ m}$.

Answer \( a = -9.41 \text{ m/s}^2 \)
EXAMPLE 2.7  The Acela: The Porsche of American Trains

Goal  Find accelerations and displacements from a velocity vs. time graph.

Problem  The sleek high-speed electric train known as the Acela (pronounced ahh-sell-ah) is currently in service on the Washington-New York-Boston run. The Acela consists of two power cars and six coaches and can carry 304 passengers at speeds up to 170 mi/h. In order to negotiate curves comfortably at high speeds, the train carriages tilt as much as 6° from the vertical, preventing passengers from being pushed to the side. A velocity vs. time graph for the Acela is shown in Figure 2.19a. (a) Describe the motion of the Acela. (b) Find the peak acceleration of the Acela in miles per hour per second ((mi/h)/s) as the train speeds up from 45 mi/h to 170 mi/h. (c) Find the train’s displacement in miles between \( t = 0 \) and \( t = 200 \) s. (d) Find the average acceleration of the Acela and its displacement in the interval from 200 s to 300 s. (The train has regenerative braking, which means that it feeds energy back into the utility lines each time it stops!) (e) Find the total displacement in the interval from 0 to 400 s.

Strategy  For part (a), remember that the slope of the tangent line at any point of the velocity vs. time graph gives the acceleration at that time. To find the peak acceleration in part (b), study the graph and locate the point at which the slope is steepest. In parts (c) through (e), estimating the area under the curve gives the displacement during a given period, with areas below the time axis, as in part (e), subtracted from the total. The average acceleration in part (d) can be obtained by substituting numbers taken from the graph into the definition of average acceleration, \( \bar{a} = \frac{\Delta v}{\Delta t} \).

Solution

(a) Describe the motion.

From about \(-50 \) s to \(50 \) s, the Acela cruises at a constant velocity in the +x-direction. Then the train accelerates in the +x-direction from \(50 \) s to \(200 \) s, reaching a top speed of about 170 mi/h, whereupon it brakes to rest at \(350 \) s and reverses, steadily gaining speed in the \(-x\)-direction.

(b) Find the peak acceleration.

Calculate the slope of the steepest tangent line, which connects the points \((50 \text{ s}, 50 \text{ mi/h})\) and \((100 \text{ s}, 150 \text{ mi/h})\) (the light blue line in Figure 2.19b):

\[
a = \text{slope} = \frac{\Delta v}{\Delta t} = \frac{(1.5 \times 10^2 - 5.0 \times 10^1) \text{ mi/h}}{(1.0 \times 10^2 - 5.0 \times 10^1) \text{ s}} = 2.0 \text{ (mi/h)/s}
\]

(c) Find the displacement between \(0 \) s and \(200 \) s.

Using triangles and rectangles, approximate the area in Figure 2.19c:

\[
\Delta x_{0 \rightarrow 200} = \text{area}_1 + \text{area}_2 + \text{area}_3 + \text{area}_4 + \text{area}_5 \\
\approx (5.0 \times 10^1 \text{ mi/h})(5.0 \times 10^1 \text{ s}) \\
+ (5.0 \times 10^1 \text{ mi/h})(5.0 \times 10^1 \text{ s}) \\
+ (1.6 \times 10^2 \text{ mi/h})(1.0 \times 10^2 \text{ s}) \\
+ \frac{1}{2}(5.0 \times 10^1 \text{ s})(5.0 \times 10^1 \text{ mi/h}) \\
+ \frac{1}{2}(1.0 \times 10^2 \text{ s})(1.7 \times 10^2 \text{ mi/h} - 1.6 \times 10^2 \text{ mi/h}) \\
= 2.4 \times 10^4 \text{ (mi/h)s}
\]

Convert units to miles by converting hours to seconds:

\[
\Delta x_{0 \rightarrow 200} \approx 2.4 \times 10^4 \frac{\text{mi} \cdot \text{s}}{\text{h}} \left( \frac{1 \text{ h}}{3600 \text{ s}} \right) = 6.7 \text{ mi}
\]

(d) Find the average acceleration from \(200 \) s to \(300 \) s, and find the displacement.

The slope of the green line is the average acceleration from \(200 \) s to \(300 \) s (Fig. 2.19b):  

\[
\bar{a} = \text{slope} = \frac{\Delta v}{\Delta t} = \frac{(1.0 \times 10^1 - 1.7 \times 10^2) \text{ mi/h}}{1.0 \times 10^2 \text{ s}} = -1.6 \text{ (mi/h)/s}
\]

(e) Find the total displacement in the interval from \(0 \) to \(400 \) s.

The train has regenerative braking, which means that it feeds energy back into the utility lines each time it stops!
The displacement from 200 s to 300 s is equal to area $a_9$, which is the area of a triangle plus the area of a very narrow rectangle beneath the triangle:

\[
\Delta x_{200 \to 300} \approx \frac{1}{2} (1.0 \times 10^2 s)(1.7 \times 10^2 - 1.0 \times 10^3) \text{ mi/h} + (1.0 \times 10^3 \text{ mi/h})(1.0 \times 10^2 s) = 9.0 \times 10^3 (\text{mi/h})(s) = 2.5 \text{ mi}
\]

(e) Find the total displacement from 0 s to 400 s.

The total displacement is the sum of all the individual displacements. We still need to calculate the displacements for the time intervals from 300 s to 350 s and from 350 s to 400 s. The latter is negative because it's below the time axis.

Find the total displacement by summing the parts:

\[
\Delta x_{0 \to 400} \approx \frac{1}{2} (5.0 \times 10^1 s)(1.0 \times 10^3 \text{ mi/h}) = 2.5 \times 10^2 (\text{mi/h})(s) \]

\[
\Delta x_{350 \to 400} \approx \frac{1}{2} (5.0 \times 10^1 s)(-5.0 \times 10^3 \text{ mi/h}) = -1.3 \times 10^3 (\text{mi/h})(s)
\]

\[
\Delta x_{0 \to 400} = (2.4 \times 10^4 + 9.0 \times 10^3 + 2.5 \times 10^2 - 1.3 \times 10^3)(\text{mi/h})(s) = 8.9 \text{ mi}
\]

Remarks There are a number of ways to find the approximate area under a graph. Choice of technique is a personal preference.

QUESTION 2.7

According to the graph in Figure 2.19a, at what different times is the acceleration zero?

EXERCISE 2.7

Suppose the velocity vs. time graph of another train is given in Figure 2.19d. Find (a) the maximum instantaneous acceleration and (b) the total displacement in the interval from 0 s to 4.00 $\times 10^2$ s.

Answers (a) 1.0 (mi/h)/s (b) 4.7 mi
2.6 FREELY FALLING OBJECTS

When air resistance is negligible, all objects dropped under the influence of gravity near Earth’s surface fall toward Earth with the same constant acceleration. This idea may seem obvious today, but it wasn’t until about 1600 that it was accepted. Prior to that time, the teachings of the great philosopher Aristotle (384–322 B.C.) had held that heavier objects fell faster than lighter ones.

According to legend, Galileo discovered the law of falling objects by observing that two different weights dropped simultaneously from the Leaning Tower of Pisa hit the ground at approximately the same time. Although it’s unlikely that this particular experiment was carried out, we know that Galileo performed many systematic experiments with objects moving on inclined planes. In his experiments he rolled balls down a slight incline and measured the distances they covered in successive time intervals. The purpose of the incline was to reduce the acceleration and enable Galileo to make accurate measurements of the intervals. (Some people refer to this experiment as ‘diluting gravity.’) By gradually increasing the slope of the incline he was finally able to draw mathematical conclusions about freely falling objects, because a falling ball is equivalent to a ball going down a vertical incline. Galileo’s achievements in the science of mechanics paved the way for Newton in his development of the laws of motion, which we will study in Chapter 4.

Try the following experiment: Drop a hammer and a feather simultaneously from the same height. The hammer hits the floor first because air drag has a greater effect on the much lighter feather. On August 2, 1971, this same experiment was conducted on the Moon by astronaut David Scott, and the hammer and feather fell with exactly the same acceleration, as expected, hitting the lunar surface at the same time. In the idealized case where air resistance is negligible, such motion is called free fall.

The expression freely falling object doesn’t necessarily refer to an object dropped from rest. A freely falling object is any object moving freely under the influence of gravity alone, regardless of its initial motion. Objects thrown upward or downward and those released from rest are all considered freely falling.

We denote the magnitude of the free-fall acceleration by the symbol \( g \). The value of \( g \) decreases with increasing altitude, and varies slightly with latitude as well. At Earth’s surface, the value of \( g \) is approximately 9.80 m/s\(^2\). Unless stated otherwise, we will use this value for \( g \) in doing calculations. For quick estimates, use \( g \approx 10 \) m/s\(^2\).

If we neglect air resistance and assume that the free-fall acceleration doesn’t vary with altitude over short vertical distances, then the motion of a freely falling object is the same as motion in one dimension under constant acceleration. This means that the kinematics equations developed in Section 2.6 can be applied. It’s conventional to define “up” as the \(+y\)-direction and to use \( y \) as the position variable. In that case the acceleration is \( a = -g = -9.80 \) m/s\(^2\). In Chapter 7, we study the variation in \( g \) with altitude.

---

**QUICK QUIZ 2.6** A tennis player on serve tosses a ball straight up. While the ball is in free fall, does its acceleration (a) increase, (b) decrease, (c) increase and then decrease, (d) decrease and then increase, or (e) remain constant?

**QUICK QUIZ 2.7** As the tennis ball of Quick Quiz 2.6 travels through the air, does its speed (a) increase, (b) decrease, (c) decrease and then increase, (d) increase and then decrease, or (e) remain the same?

**QUICK QUIZ 2.8** A skydiver jumps out of a hovering helicopter. A few seconds later, another skydiver jumps out, so they both fall along the same vertical line relative to the helicopter. Both skydivers fall with the same acceleration. Does the vertical distance between them (a) increase, (b) decrease, or (c) stay the same? Does the difference in their velocities (d) increase, (e) decrease, or (f) stay the same? (Assume \( g \) is constant.)
EXAMPLE 2.8  Not a Bad Throw for a Rookie!

Goal  Apply the kinematic equations to a freely falling object with a nonzero initial velocity.

Problem  A stone is thrown from the top of a building with an initial velocity of 20.0 m/s straight upward, at an initial height of 50.0 m above the ground. The stone just misses the edge of the roof on its way down, as shown in Figure 2.20. Determine (a) the time needed for the stone to reach its maximum height, (b) the maximum height, (c) the time needed for the stone to return to the height from which it was thrown and the velocity of the stone at that instant, (d) the time needed for the stone to reach the ground, and (e) the velocity and position of the stone at \( t = 5.00 \) s.

Strategy  The diagram in Figure 2.20 establishes a coordinate system with \( y_0 = 0 \) at the level at which the stone is released from the thrower’s hand, with \( y \) positive upward. Write the velocity and position kinematic equations for the stone, and substitute the given information. All the answers come from these two equations by using simple algebra or by just substituting the time. In part (a), for example, the stone comes to rest for an instant at its maximum height, so set \( v = 0 \) at this point and solve for time. Then substitute the time into the displacement equation, obtaining the maximum height.

Solution  
(a) Find the time when the stone reaches its maximum height.

Write the velocity and position kinematic equations:

\[
\begin{align*}
v &= at + v_0 \\
\Delta y &= y - y_0 = v_0 t + \frac{1}{2}at^2
\end{align*}
\]

Substitute \( a = -9.80 \text{ m/s}^2 \), \( v_0 = 20.0 \text{ m/s} \), and \( y_0 = 0 \) into the preceding two equations:

\[
\begin{align*}
(1) \quad v &= (-9.80 \text{ m/s}^2)t + 20.0 \text{ m/s} \\
(2) \quad y &= (20.0 \text{ m/s})t - \frac{1}{2}(9.80 \text{ m/s}^2)t^2
\end{align*}
\]

Substitute \( v = 0 \), the velocity at maximum height, into Equation (1) and solve for time:

\[
t = \frac{-20.0 \text{ m/s}}{-9.80 \text{ m/s}^2} = 2.04 \text{ s}
\]

(b) Determine the stone’s maximum height.

Substitute the time \( t = 2.04 \) s into Equation (2):

\[
y_{\text{max}} = (20.0 \text{ m/s})(2.04 \text{ s}) - \frac{1}{2}(9.80 \text{ m/s}^2)(2.04 \text{ s})^2 = 20.4 \text{ m}
\]
(c) Find the time the stone takes to return to its initial position, and find the velocity of the stone at that time.

Set \( y = 0 \) in Equation (2) and solve for \( t \):

\[
0 = (20.0 \, \text{m/s})t - (4.90 \, \text{m/s}^2)t^2
\]

\[
t = 4.08 \, \text{s}
\]

Substitute the time into Equation (1) to get the velocity:

\[
v = 20.0 \, \text{m/s} + (-9.80 \, \text{m/s}^2)(4.08 \, \text{s}) = -20.0 \, \text{m/s}
\]

(d) Find the time required for the stone to reach the ground.

In Equation (2), set \( y = -50.0 \, \text{m} \):

\[-50.0 \, \text{m} = (20.0 \, \text{m/s})t - (4.90 \, \text{m/s}^2)t^2
\]

Apply the quadratic formula and take the positive root:

\[
t = 5.83 \, \text{s}
\]

(e) Find the velocity and position of the stone at \( t = 5.00 \, \text{s} \).

Substitute values into Equations (1) and (2):

\[
v = (-9.80 \, \text{m/s}^2)(5.00 \, \text{s}) + 20.0 \, \text{m/s} = -29.0 \, \text{m/s}
\]

\[
y = (20.0 \, \text{m/s})(5.00 \, \text{s}) - (4.90 \, \text{m/s}^2)(5.00 \, \text{s})^2 = -22.5 \, \text{m}
\]

**Remarks** Notice how everything follows from the two kinematic equations. Once they are written down and the constants correctly identified as in Equations (1) and (2), the rest is relatively easy. If the stone were thrown downward, the initial velocity would have been negative.

**QUESTION 2.8**
How would the answer to part (b), the maximum height, change if the person throwing the ball jumped upward at the instant he released the ball?

**EXERCISE 2.8**
A projectile is launched straight up at 60.0 m/s from a height of 80.0 m, at the edge of a sheer cliff. The projectile falls, just missing the cliff and hitting the ground below. Find (a) the maximum height of the projectile above the point of firing, (b) the time it takes to hit the ground at the base of the cliff, and (c) its velocity at impact.

**Answers**
(a) 184 m  (b) 13.5 s  (c) −72.3 m/s

**EXAMPLE 2.9** **Maximum Height Derived**

**Goal** Find the maximum height of a thrown projectile using symbols.

**Problem** Refer to Example 2.8. Use symbolic manipulation to find (a) the time \( t_{\text{max}} \) it takes the ball to reach its maximum height and (b) an expression for the maximum height that doesn’t depend on time. Answers should be expressed in terms of the quantities \( v_0, g, \) and \( y_0 \) only.

**Strategy** When the ball reaches its maximum height, its velocity is zero, so for part (a) solve the kinematics velocity equation for time \( t \) and set \( v = 0 \). For part (b), substitute the expression for time found in part (a) into the displacement equation, solving it for the maximum height.

**Solution**
(a) Find the time it takes the ball to reach its maximum height.

Write the velocity kinematics equation:

\[
v = at + v_0
\]

Move \( v_0 \) to the left side of the equation:

\[
v - v_0 = at
\]

Divide both sides by \( a \):

\[
\frac{v - v_0}{a} = \frac{at}{a} = t
\]
Turn the equation around so that \( t \) is on the left and substitute \( v = 0 \), corresponding to the velocity at maximum height:

\[
\begin{align*}
\text{Replace } t \text{ by } t_{\text{max}} \text{ and substitute } a = -g: \\
\end{align*}
\]

\( t_{\text{max}} = \frac{v_0}{g} \) \hspace{1cm} (2)

(b) Find the maximum height.

Write the equation for the position \( y \) at any time:

\[
\begin{align*}
\text{Substitute } t = -\frac{v_0}{a}, \text{ which corresponds to the time it takes to reach } y_{\text{max}}, \text{ the maximum height:} \\
\end{align*}
\]

\( y_{\text{max}} = y_0 + \frac{v_0^2}{a} + \frac{1}{2}a \left( \frac{-v_0}{a} \right)^2 \)

Combine the last two terms and substitute \( a = -g \):

\[
\begin{align*}
\text{(3) } y_{\text{max}} &= y_0 + \frac{v_0^2}{2g} \\
\end{align*}
\]

Remarks Notice that \( g = +9.8 \text{ m/s}^2 \), so the second term is positive overall. Equations (1)–(3) are much more useful than a numerical answer because the effect of changing one value can be seen immediately. For example, doubling the initial velocity \( v_0 \) quadruples the displacement above the point of release. Notice also that \( y_{\text{max}} \) could be obtained more readily from the time-independent equation, \( v^2 - v_0^2 = 2a \Delta y \).

QUESTION 2.9

By what factor would the maximum displacement above the rooftop be increased if the building were transported to the Moon, where \( a = -\frac{1}{6}g \)?

EXERCISE 2.9

(a) Using symbols, find the time \( t_E \) it takes for a ball to reach the ground on Earth if released from rest at height \( y_0 \).

(b) In terms of \( t_E \), how much time \( t_M \) would be required if the building were on Mars, where \( a = -0.385g \)?

Answers

(a) \( t_E = \sqrt{\frac{2y_0}{g}} \) 

(b) \( t_M = 1.61t_E \)

EXAMPLE 2.10 \hspace{1em} A Rocket Goes Ballistic

Goal Solve a problem involving a powered ascent followed by free-fall motion.

Problem A rocket moves straight upward, starting from rest with an acceleration of \(+29.4 \text{ m/s}^2\). It runs out of fuel at the end of 4.00 s and continues to coast upward, reaching a maximum height before falling back to Earth. (a) Find the rocket’s velocity and position at the end of 4.00 s. (b) Find the maximum height the rocket reaches. (c) Find the velocity the instant before the rocket crashes on the ground.

Strategy Take \( y = 0 \) at the launch point and \( y \) positive upward, as in Figure 2.21. The problem consists of two phases. In phase 1 the rocket has a net upward acceleration of \( 29.4 \text{ m/s}^2 \), and we can use the kinematic equations with constant acceleration \( a \) to find the height and velocity of the rocket at the end of phase 1, when the fuel is burned up. In phase 2 the rocket is in free fall and has an acceleration of \(-9.80 \text{ m/s}^2 \), with initial velocity and position given by the results of phase 1. Apply the kinematic equations for free fall.

\[ \text{FIGURE 2.21 (Example 2.10) Two linked phases of motion for a rocket that is launched, uses up its fuel, and crashes.} \]
Solution

(a) Phase 1: Find the rocket’s velocity and position after 4.00 s.

Write the velocity and position kinematic equations:

1. \( v = v_0 + at \)
2. \( \Delta y = y - y_0 = v_0 t + \frac{1}{2} at^2 \)

Adapt these equations to phase 1, substituting \( a = 29.4 \text{ m/s}^2 \), \( v_0 = 0 \), and \( y_0 = 0 \):

3. \( v = (29.4 \text{ m/s}^2) t \)
4. \( y = \frac{1}{2} (29.4 \text{ m/s}^2) t^2 = (14.7 \text{ m/s}^2) t^2 \)

Substitute \( t = 4.00 \) s into Equations (3) and (4) to find the rocket’s velocity \( v_b \) and position \( y_b \) at the time of burnout. These will be called \( v_b \) and \( y_b \) respectively.

\[ v_b = 118 \text{ m/s} \] and \( y_b = 235 \text{ m} \)

(b) Phase 2: Find the maximum height the rocket attains.

Adapt Equations (1) and (2) to phase 2, substituting \( a = -9.8 \text{ m/s}^2 \), \( v_0 = v_b = 118 \text{ m/s} \), and \( y_0 = y_b = 235 \text{ m} \):

5. \( v = (-9.8 \text{ m/s}^2) t + 118 \text{ m/s} \)
6. \( y = 235 \text{ m} + (118 \text{ m/s}) t - (4.90 \text{ m/s}^2) t^2 \)

Substitute \( v = 0 \) (the rocket’s velocity at maximum height) in Equation (5) to get the time it takes the rocket to reach its maximum height:

\[ 0 = (-9.8 \text{ m/s}^2) t + 118 \text{ m/s} \quad \rightarrow \quad t = \frac{118 \text{ m/s}}{9.80 \text{ m/s}^2} = 12.0 \text{ s} \]

Substitute \( t = 12.0 \) s into Equation (6) to find the rocket’s maximum height:

\[ y_{\text{max}} = 235 \text{ m} + (118 \text{ m/s})(12.0 \text{ s}) - (4.90 \text{ m/s}^2)(12.0 \text{ s})^2 \]
\[ = 945 \text{ m} \]

(c) Phase 2: Find the velocity of the rocket just prior to impact.

Find the time to impact by setting \( y = 0 \) in Equation (6) and using the quadratic formula:

\[ t = 25.9 \text{ s} \]

Substitute this value of \( t \) into Equation (5):

\[ v = (-9.8 \text{ m/s}^2)(25.9 \text{ s}) + 118 \text{ m/s} = -136 \text{ m/s} \]

Remarks You may think that it is more natural to break this problem into three phases, with the second phase ending at the maximum height and the third phase a free fall from maximum height to the ground. Although this approach gives the correct answer, it’s an unnecessary complication. Two phases are sufficient, one for each different acceleration.

QUESTION 2.10

If, instead, some fuel remains, at what height should the engines be fired again to brake the rocket’s fall and allow a perfectly soft landing? (Assume the same acceleration as during the initial ascent.)

EXERCISE 2.10

An experimental rocket designed to land upright falls freely from a height of \( 2.00 \times 10^2 \text{ m} \), starting at rest. At a height of 80.0 m, the rocket’s engines start and provide constant upward acceleration until the rocket lands. What acceleration is required if the speed on touchdown is to be zero? (Neglect air resistance.)

Answer 14.7 \text{ m/s}^2
SUMMARY

2.1 Displacement
The displacement of an object moving along the x-axis is defined as the change in position of the object,
\[ \Delta x = x_f - x_i \]  
where \( x_i \) is the initial position of the object and \( x_f \) is its final position.
A vector quantity is characterized by both a magnitude and a direction. A scalar quantity has a magnitude only.

2.2 Velocity
The average speed of an object is given by
\[ \text{Average speed} = \frac{\text{total distance}}{\text{total time}} \]
The average velocity \( \bar{v} \) during a time interval \( \Delta t \) is the displacement \( \Delta x \) divided by \( \Delta t \).
\[ \bar{v} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i} \]  

The average velocity is equal to the slope of the straight line joining the initial and final points on a graph of the position of the object versus time.
The slope of the line tangent to the position vs. time curve at some point is equal to the instantaneous velocity at that time. The instantaneous speed of an object is defined as the magnitude of the instantaneous velocity.

2.3 Acceleration
The average acceleration \( \bar{a} \) of an object undergoing a change in velocity \( \Delta v \) during a time interval \( \Delta t \) is
\[ \bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i} \]  

The instantaneous acceleration of an object at a certain time equals the slope of a velocity vs. time graph at that instant.

2.5 One-Dimensional Motion with Constant Acceleration
The most useful equations that describe the motion of an object moving with constant acceleration along the x-axis are as follows:
\[ v = v_0 + at \]  
\[ \Delta x = v_0 t + \frac{1}{2}at^2 \]  
\[ v^2 = v_0^2 + 2a\Delta x \]

All problems can be solved with the first two equations alone, the last being convenient when time doesn’t explicitly enter the problem. After the constants are properly identified, most problems reduce to one or two equations in as many unknowns.

2.6 Freely Falling Objects
An object falling in the presence of Earth’s gravity exhibits a free-fall acceleration directed toward Earth’s center. If air friction is neglected and if the altitude of the falling object is small compared with Earth’s radius, then we can assume that the free-fall acceleration \( g = 9.8 \text{ m/s}^2 \) is constant over the range of motion. Equations 2.6, 2.9, and 2.10 apply, with \( a = -g \).

FOR ADDITIONAL STUDENT RESOURCES, GO TO WWW.SERWAYPHYSICS.COM

MULTIPLE-CHOICE QUESTIONS

1. An arrow is shot straight up in the air at an initial speed of 15.0 m/s. After how much time is the arrow heading downward at a speed of 8.00 m/s? (a) 0.714 s (b) 1.24 s (c) 1.87 s (d) 2.55 s (e) 3.22 s

2. A cannon shell is fired straight up in the air at an initial speed of 225 m/s. After how much time is the shell at a height of 6.20 \( \times 10^2 \) m and heading down? (a) 2.96 s (b) 17.3 s (c) 25.4 s (d) 33.6 s (e) 43.0 s

3. When applying the equations of kinematics for an object moving in one dimension, which of the following statements must be true? (a) The velocity of the object must remain constant. (b) The acceleration of the object must remain constant. (c) The velocity of the object must increase with time. (d) The position of the object must increase with time. (e) The velocity of the object must always be in the same direction as its acceleration.

4. A juggler throws a bowling pin straight up in the air. After the pin leaves his hand and while it is in the air, which statement is true? (a) The velocity of the pin is always in the same direction as its acceleration. (b) The velocity of the pin is never in the same direction as its acceleration. (c) The acceleration of the pin is zero. (d) The velocity of the pin is opposite its acceleration on the way up. (e) The velocity of the pin is in the same direction as its acceleration on the way up.

5. A racing car starts from rest and reaches a final speed in a time \( t \). If the acceleration of the car is constant during this time, which of the following statements must be true? (a) The car travels a distance \( vt \). (b) The average speed of the car is \( v/2 \). (c) The acceleration of the car is \( v/t \). (d) The velocity of the car remains constant. (e) None of these

6. A pebble is dropped from rest from the top of a tall cliff and falls 4.9 m after 1.0 s has elapsed. How much farther does it drop in the next 2.0 seconds? (a) 9.8 m (b) 19.6 m (c) 39 m (d) 44 m (e) 27 m

7. An object moves along the x-axis, its position measured at each instant of time. The data are organized into an accurate graph of x vs. t. Which of the following quantities cannot be obtained from this graph? (a) the velocity at any instant (b) the acceleration at any instant (c) the displacement during some time interval (d) the average...
velocity during some time interval (e) the speed of the particle at any instant

8. People become uncomfortable in an elevator if it accelerates from rest at a rate such that it attains a speed of about 6 m/s after descending ten stories (about 30 m). What is the approximate magnitude of its acceleration? (Choose the closest answer.) (a) 10 m/s² (b) 0.3 m/s² (c) 0.6 m/s² (d) 1 m/s² (e) 0.8 m/s²

9. Races are timed to an accuracy of 1/1000 of a second. What distance could a person rollerblading at a speed of 8.5 m/s travel in that period of time? (a) 85 mm (b) 85 cm (c) 8.5 m (d) 8.5 mm (e) 8.5 km

10. A student at the top of a building throws a red ball upward with speed \( v_0 \) and then throws a blue ball downward with the same initial speed \( v_0 \). Immediately before the two balls reach the ground, which of the following statements are true? (Choose all correct statements; neglect air friction.) (a) The speed of the red ball is less than that of the blue ball. (b) The speed of the red ball is greater than that of the blue ball. (c) Their velocities are equal. (d) The speed of each ball is greater than \( v_0 \). (e) The acceleration of the blue ball is greater than that of the red ball.

11. A rock is thrown downward from the top of a 40.0 m tower with an initial speed of 12 m/s. Assuming negligible air resistance, what is the speed of the rock just before hitting the ground? (a) 28 m/s (b) 30 m/s (c) 56 m/s (d) 784 m/s (e) More information is needed.

12. A ball is thrown straight up in the air. For which situation are both the instantaneous velocity and the acceleration zero? (a) on the way up (b) at the top of the flight path (c) on the way down (d) halfway up and halfway down (e) none of these

CONCEPTUAL QUESTIONS

1. If the velocity of a particle is nonzero, can the particle’s acceleration be zero? Explain.

2. If the velocity of a particle is zero, can the particle’s acceleration be zero? Explain.

3. If a car is traveling eastward, can its acceleration be westward? Explain.

4. Can the equations of kinematics be used in a situation where the acceleration varies with time? Can they be used when the acceleration is zero?

5. If the average velocity of an object is zero in some time interval, what can you say about the displacement of the object during that interval?

6. Figure CQ2.6 shows strobe photographs taken of a disk moving from left to right under different conditions. The time interval between images is constant. Taking the direction to the right to be positive, describe the motion of the disk in each case. For which case is

(a) the acceleration positive? (b) the acceleration negative? (c) the velocity constant?

7. Can the instantaneous velocity of an object at an instant of time ever be greater in magnitude than the average velocity over a time interval containing that instant? Can it ever be less?

8. A ball is thrown vertically upward. (a) What are its velocity and acceleration when it reaches its maximum altitude? (b) What is the acceleration of the ball just before it hits the ground?

9. Consider the following combinations of signs and values for the velocity and acceleration of a particle with respect to a one-dimensional x-axis:

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Positive Positive</td>
<td></td>
</tr>
<tr>
<td>b. Positive Negative</td>
<td></td>
</tr>
<tr>
<td>c. Positive Zero</td>
<td></td>
</tr>
<tr>
<td>d. Negative Positive</td>
<td></td>
</tr>
<tr>
<td>e. Negative Negative</td>
<td></td>
</tr>
<tr>
<td>f. Negative Zero</td>
<td></td>
</tr>
<tr>
<td>g. Zero Positive</td>
<td></td>
</tr>
<tr>
<td>h. Zero Negative</td>
<td></td>
</tr>
</tbody>
</table>

Describe what the particle is doing in each case and give a real-life example for an automobile on an east–west one-dimensional axis, with east considered the positive direction.

10. A ball rolls in a straight line along the horizontal direction. Using motion diagrams (or multiflash photographs), describe the velocity and acceleration of the ball for each of the following situations: (a) The ball moves to the right at a constant speed. (b) The ball moves from right to left and continually slows down. (c) The ball moves from right to left and continually speeds up. (d) The ball moves to the right, first speeding up at a constant rate and then slowing down at a constant rate.
The Problems for this chapter may be assigned online at WebAssign.

1, 2, 3 = straightforward, intermediate, challenging

GP = denotes guided problem
ecp = denotes enhanced content problem
= denotes full solution available in Student Solutions Manual/Study Guide

SECTION 2.1 DISPLACEMENT

SECTION 2.2 VELOCITY

1. The speed of a nerve impulse in the human body is about 100 m/s. If you accidentally stub your toe in the dark, estimate the time it takes the nerve impulse to travel to your brain.

2. Light travels at a speed of about $3 \times 10^8$ m/s. How many miles does a pulse of light travel in a time interval of 0.1 s, which is about the blink of an eye? Compare this distance to the diameter of Earth.

3. A person travels by car from one city to another with different constant speeds between pairs of cities. She drives for 30.0 min at 80.0 km/h, 12.0 min at 100 km/h, and 45.0 min at 40.0 km/h and spends 15.0 min eating lunch and buying gas. (a) Determine the average speed for the trip. (b) Determine the distance between the initial and final cities along the route.

4. (a) Sand dunes on a desert island move as sand is swept up the windward side to settle in the leeward side. Such “walking” dunes have been known to travel 20 feet in a year and can travel as much as 100 feet per year in particularly windy times. Calculate the average speed in each case in meters per second. (b) Fingernails grow at the rate of drifting continents, about 10 mm/yr. Approximately how long did it take for North America to separate from Europe, a distance of about 3,000 mi?

5. Two boats start together and race across a 60-km-wide lake and back. Boat A goes across at 60 km/h and returns at 60 km/h. Boat B goes across at 30 km/h, and its crew, realizing how far behind it is getting, returns at 90 km/h. Turnaround times are negligible, and the boat that completes the round trip first wins. (a) Which boat wins and by how much? (Or is it a tie?) (b) What is the average velocity of the winning boat?

6. A graph of position versus time for a certain particle moving along the x-axis is shown in Figure P2.6. Find the average velocity in the time intervals from (a) 0 to 2.00 s, (b) 0 to 4.00 s, (c) 2.00 s to 4.00 s, (d) 4.00 s to 7.00 s, and (e) 0 to 8.00 s.

7. A motorist drives north for 35.0 minutes at 85.0 km/h and then stops for 15.0 minutes. He then continues north, traveling 130 km in 2.00 h. (a) What is his total displacement? (b) What is his average velocity?

8. A tennis player moves in a straight-line path as shown in Figure P2.8. Find her average velocity in the time intervals from (a) 0 to 1.0 s, (b) 0 to 4.0 s, (c) 1.0 s to 5.0 s, and (d) 0 to 5.0 s.

9. Find the instantaneous velocities of the tennis player of Figure P2.8 at (a) 0.50 s, (b) 2.0 s, (c) 3.0 s, and (d) 4.5 s.

10. Two cars travel in the same direction along a straight highway, one at a constant speed of 55 mi/h and the other at 70 mi/h. (a) Assuming they start at the same point, how much sooner does the faster car arrive at a destination 10 mi away? (b) How far must the faster car travel before it has a 15-min lead on the slower car?

11. If the average speed of an orbiting space shuttle is 19,800 mi/h, determine the time required for it to circle Earth. Make sure you consider that the shuttle is orbiting about 2.00 $\times 10^2$ mi above Earth’s surface and assume that Earth’s radius is 3,963 miles.

12. An athlete swims the length L of a pool in a time $t_1$ and makes the return trip to the starting position in a time $t_2$. If she is swimming initially in the positive x-direction, determine her average velocities symbolically in (a) the first half of the swim, (b) the second half of the swim, and (c) the round trip. (d) What is her average speed for the round trip?

13. A person takes a trip, driving with a constant speed of 89.5 km/h, except for a 22.0-min rest stop. If the person’s average speed is 77.8 km/h, how much time is spent on the trip and how far does the person travel?

14. A tortoise can run with a speed of 0.10 m/s, and a hare can run 20 times as fast. In a race, they both start at the same time, but the hare stops to rest for 2.0 minutes. The tortoise wins by a shell (20 cm). (a) How long does the race take? (b) What is the length of the race?

15. To qualify for the finals in a racing event, a race car must achieve an average speed of 250 km/h on a track with a total length of 1,600 m. If a particular car covers the first half of the track at an average speed of 230 km/h, what minimum average speed must it have in the second half of the event in order to qualify?
16. **SECTION 2.3 ACCELERATION**

   One athlete in a race running on a long, straight track with a constant speed \( v_1 \) is a distance \( d \) behind a second athlete running with a constant speed \( v_2 \). (a) Under what circumstances is the first athlete able to overtake the second athlete? (b) Find the time \( t \) it takes the first athlete to overtake the second athlete, in terms of \( d, v_1 \), and \( v_2 \). (c) At what minimum distance \( d \) from the leading athlete must the finish line be located so that the trailing athlete can at least tie for first place? Express \( d \) in terms of \( d, v_1 \), and \( v_2 \) by using the result of part (b).

17. A graph of position versus time for a certain particle moving along the x-axis is shown in Figure P2.6. Find the instantaneous velocity at the instants (a) \( t = 1.00 \ s \), (b) \( t = 3.00 \ s \), (c) \( t = 4.50 \ s \), and (d) \( t = 7.50 \ s \).

18. A race car moves such that its position fits the relationship

\[
x(t) = (5.0 \text{ m/s})t + (0.75 \text{ m/s}^2)t^2
\]

where \( x \) is measured in meters and \( t \) in seconds. (a) Plot a graph of the car’s position versus time. (b) Determine the instantaneous velocity of the car at \( t = 4.0 \) s, using time intervals of 0.40 s, 0.20 s, and 0.10 s. (c) Compare the average velocity during the first 4.0 s with the results of part (b).

19. **SECTION 2.3 ACCELERATION**

   Runner A is initially 4.0 mi west of a flagpole and is running with a constant velocity of 6.9 mi/h due east. Runner B is initially 3.0 mi east of the flagpole and is running with a constant velocity of 5.0 mi/h due west. How far are the runners from the flagpole when they meet?

20. **SECTION 2.3 ACCELERATION**

   Assume a canister in a straight tube moves with a constant acceleration of \(-4.00 \text{ m/s}^2\) and has a velocity of 13.0 m/s at \( t = 0 \). (a) What is its velocity at \( t = 1.00 \) s? (b) At \( t = 2.00 \) s? (c) At \( t = 2.50 \) s? (d) At \( t = 4.00 \) s? (e) Describe the shape of the canister’s velocity versus time graph. (f) What two things must be known at a given time to predict the canister’s velocity at any later time?

21. Secretariat ran the Kentucky Derby with times of 25.2 s, 24.0 s, 23.8 s, 23.2 s, and 23.0 s for the quarter mile. (a) Find his average speed during each quarter-mile segment in ft/s. (b) Assuming that Secretariat’s instantaneous speed at the finish line was the same as his average speed during the final quarter mile, find his average acceleration for the entire race in ft/s\(^2\). (Hint: Recall that horses in the Derby start from rest.)

22. The average person passes out at an acceleration of 7 g (that is, seven times the gravitational acceleration on Earth). Suppose a car is designed to accelerate at this rate. How much time would be required for the car to accelerate from rest to 60.0 miles per hour? (The car would need rocket boosters!)

23. A certain car is capable of accelerating at a rate of 10.60 m/s\(^2\). How long does it take for this car to go from a speed of 55 mi/h to a speed of 60 mi/h?

24. The velocity vs. time graph for an object moving along a straight path is shown in Figure P2.24. (a) Find the average acceleration of the object during the time intervals 0 to 5.0 s, 5.0 s to 15 s, and 0 to 20 s. (b) Find the instantaneous acceleration at 2.0 s, 10 s, and 18 s.

**SECTION 2.5 ONE-DIMENSIONAL MOTION WITH CONSTANT ACCELERATION**

25. A steam catapult launches a jet aircraft from the aircraft carrier John C. Stennis, giving it a speed of 175 mi/h in 2.50 s. (a) Find the average acceleration of the plane. (b) Assuming the acceleration is constant, find the distance the plane moves.

26. A car is traveling due east at 25.0 m/s at some instant. (a) If its constant acceleration is 0.750 m/s\(^2\) due east, find its velocity after 8.50 s have elapsed. (b) If its constant acceleration is 0.750 m/s\(^2\) due west, find its velocity after 8.50 s have elapsed.

27. A car traveling east at 40.0 m/s passes a trooper hiding at the roadside. The driver uniformly reduces his speed to 20.0 m/s in a distance of 2.00 km. (a) What is the magnitude and direction of the car’s acceleration as it slows down? (b) How far does the car travel in the 3.5-s time period?

28. In 1865 Jules Verne proposed sending men to the Moon by firing a space capsule from a 220-m-long cannon with final speed of 10.97 km/s. What would have been the unrealistically large acceleration experienced by the space travelers during their launch? (A human can stand an acceleration of 15g for a short time.) Compare your answer with the free-fall acceleration, 9.80 m/s\(^2\).

29. A truck covers 40.0 m in 8.50 s while smoothly slowing down to a final velocity of 2.80 m/s. (a) Find the truck’s original speed. (b) Find its acceleration.

30. **SECTION 2.3 ACCELERATION**

   A speedboat increases its speed uniformly from \( v_1 = 20.0 \text{ m/s} \) to \( v_f = 30.0 \text{ m/s} \) in a distance of \( 2.00 \times 10^2 \text{ m} \). (a) Draw a coordinate system for this situation and label the relevant quantities, including vectors. (b) For the given information, what single equation is most appropriate for finding the acceleration? (c) Solve the equation selected in part (b) symbolically for the boat’s acceleration in terms of \( v_f, v_1, \) and \( \Delta x \). (d) Substitute given values, obtaining that acceleration. (e) Find the time it takes the boat to travel the given distance.

31. A Cessna aircraft has a liftoff speed of 120 km/h. (a) What minimum constant acceleration does the aircraft require if it is to be airborne after a takeoff run of 240 m? (b) How long does it take the aircraft to become airborne?

32. A truck on a straight road starts from rest and accelerates at 2.0 m/s\(^2\) until it reaches a speed of 20 m/s. Then the
truck travels for 20 s at constant speed until the brakes are applied, stopping the truck in a uniform manner in an additional 5.0 s. (a) How long is the truck in motion? (b) What is the average velocity of the truck during the motion described?

33. In a test run, a certain car accelerates uniformly from zero to 24.0 m/s in 2.95 s. (a) What is the magnitude of the car’s acceleration? (b) How long does it take the car to change its speed from 10.0 m/s to 20.0 m/s? (c) Will doubling the time always double the change in speed? Why?

34. A jet plane lands with a speed of 100 m/s and can accelerate only at 5.00 m/s^2 as it comes to rest. (a) From the instant the plane touches the runway, what is the minimum time needed before it can come to rest? (b) Can this plane land on a small tropical island airport where the runway is 0.800 km long?

35. Speedy Sue, driving at 30.0 m/s, enters a one-lane tunnel. She then observes a slow-moving van 155 m ahead traveling at 5.00 m/s. Sue applies her brakes but can accelerate only at −2.00 m/s^2 because the road is wet. Will there be a collision? State how you decide. If yes, determine how far into the tunnel and at what time the collision occurs. If no, determine the distance of closest approach between Sue’s car and the van.

36. A record of travel along a straight path is as follows:

1. Start from rest with a constant acceleration of 2.77 m/s^2 for 15.0 s.
2. Maintain a constant velocity for the next 2.05 min.
3. Apply a constant negative acceleration of −9.47 m/s^2 for 4.39 s.

(a) What was the total displacement for the trip? (b) What were the average speeds for legs 1, 2, and 3 of the trip, as well as for the complete trip?

37. A train is traveling down a straight track at 20 m/s when the engineer applies the brakes, resulting in an acceleration of −1.0 m/s^2 as long as the train is in motion. How far does the train move during a 40-s time interval starting at the instant the brakes are applied?

38. A car accelerates uniformly from rest to a speed of 40.0 mi/h in 12.0 s. Find (a) the distance the car travels during this time and (b) the constant acceleration of the car.

39. A car starts from rest and travels for 5.0 s with a uniform acceleration of +1.5 m/s^2. The driver then applies the brakes, causing a uniform acceleration of −2.0 m/s^2. If the brakes are applied for 3.0 s, (a) how fast is the car going at the end of the braking period, and (b) how far has the car gone?

40. A car starts from rest and travels for t_1 seconds with a uniform acceleration a_1. The driver then applies the brakes, causing a uniform acceleration a_2. If the brakes are applied for t_2 seconds, (a) how fast is the car going just before the beginning of the braking period? (b) How far does the car go before the driver begins to brake? (c) Using the answers to parts (a) and (b) as the initial velocity and position for the motion of the car during braking, what total distance does the car travel? Answers are in terms of the variables a_1, a_2, t_1, and t_2.

41. In the Daytona 500 auto race, a Ford Thunderbird and a Mercedes Benz are moving side by side down a straightaway at 71.5 m/s. The driver of the Thunderbird realizes that she must make a pit stop, and she smoothly slows to a stop over a distance of 250 m. She spends 5.00 s in the pit and then accelerates out, reaching her previous speed of 71.5 m/s after a distance of 350 m. At this point, how far has the Thunderbird fallen behind the Mercedes Benz, which has continued at a constant speed?

42. A certain cable car in San Francisco can stop in 10 s when traveling at maximum speed. On one occasion, the driver sees a dog a distance d m in front of the car and slams on the brakes instantly. The car reaches the dog 8.0 s later, and the dog jumps off the track just in time. If the car travels 4.0 m beyond the position of the dog before coming to a stop, how far was the car from the dog? (Hint: You will need three equations.)

43. A hockey player is standing on his skates on a frozen pond when an opposing player, moving with a uniform speed of 12 m/s, skates by with the puck. After 3.0 s, the first player makes up his mind to chase his opponent. If he accelerates uniformly at 4.0 m/s^2, (a) how long does it take him to catch his opponent, and (b) how far has he traveled in that time? (Assume the player with the puck remains in motion at constant speed.)

44. A train 400 m long is moving on a straight track with a speed of 82.4 km/h. The engineer applies the brakes at a crossing, and later the last car passes the crossing with a speed of 16.4 km/h. Assuming constant acceleration, determine how long the train blocked the crossing. Disregard the width of the crossing.

SECTION 2.6 FREELY FALLING OBJECTS

45. A ball is thrown vertically upward with a speed of 25.0 m/s. (a) How high does it rise? (b) How long does it take to reach its highest point? (c) How long does the ball take to hit the ground after it reaches its highest point? (d) What is its velocity when it returns to the level from which it started?

46. It is possible to shoot an arrow at a speed as high as 100 m/s. (a) If friction is neglected, how high would an arrow launched at this speed rise if shot straight up? (b) How long would the arrow be in the air?

47. A certain freely falling object requires 1.50 s to travel the last 30.0 m before it hits the ground. From what height above the ground did it fall?

48. An attacker at the base of a castle wall 3.65 m high throws a rock straight up with speed 7.40 m/s at a height of 1.55 m above the ground. (a) Will the rock reach the top of the wall? (b) If so, what is the rock’s speed at the top? If not, what initial speed must the rock have to reach the top? (c) Find the change in the speed of a rock thrown straight down from the top of the wall at an initial speed of 7.40 m/s and moving between the same two points. (d) Does the change in speed of the downward-moving rock agree with the magnitude of the speed change of the rock moving upward between the same elevations? Explain physically why or why not.
49. Traumatic brain injury such as concussion results when the head undergoes a very large acceleration. Generally, an acceleration less than 800 m/s² lasting for any length of time will not cause injury, whereas an acceleration greater than 1 000 m/s² lasting for at least 1 ms will cause injury. Suppose a small child rolls off a bed that is 0.40 m above the floor. If the floor is hardwood, the child’s head is brought to rest in approximately 2.0 mm. If the floor is carpeted, this stopping distance is increased to about 1.0 cm. Calculate the magnitude and duration of the deceleration in both cases, to determine the risk of injury. Assume the child remains horizontal during the fall to the floor. Note that a more complicated fall could result in a head velocity greater or less than the speed you calculate.

50. A small mailbag is released from a helicopter that is descending steadily at 1.50 m/s. After 2.00 s, (a) what is the speed of the mailbag, and (b) how far is it below the helicopter? (c) What are your answers to parts (a) and (b) if the helicopter is rising steadily at 1.50 m/s?

51. A tennis player tosses a tennis ball straight up and then catches it after 2.00 s at the same height as the point of release. (a) What is the acceleration of the ball while it is in flight? (b) What is the velocity of the ball when it reaches its maximum height? Find (c) the initial velocity of the ball and (d) the maximum height it reaches.

52. A package is dropped from a helicopter that is descending steadily at 1.50 m/s. After t seconds have elapsed, (a) what is the speed of the package in terms of v, g, and t? (b) What distance d is it from the helicopter in terms of g and t? (c) What are the answers to parts (a) and (b) if the helicopter is rising steadily at the same speed?

53. A model rocket is launched straight upward with an initial speed of 50.0 m/s. It accelerates with a constant upward acceleration of 2.00 m/s² until its engines stop at an altitude of 150 m. (a) What can you say about the motion of the rocket after its engines stop? (b) What is the maximum height reached by the rocket? (c) How long after liftoff does the rocket reach its maximum height? (d) How long is the rocket in the air?

54. A parachutist with a camera descends in free fall at a speed of 10 m/s. The parachutist releases the camera at an altitude of 50 m. (a) How long does it take the camera to reach the ground? (b) What is the velocity of the camera just before it hits the ground?

ADDITIONAL PROBLEMS

55. A truck tractor pulls two trailers, one behind the other, at a constant speed of 100 km/h. It takes 0.600 s for the big rig to completely pass onto a bridge 400 m long. For what duration of time is all or part of the truck-trailer combination on the bridge?

56. A speedboat moving at 30.0 m/s approaches a no-wake buoy marker 100 m ahead. The pilot slows the boat with a constant acceleration of −3.50 m/s² by reducing the throttle. (a) How long does it take the boat to reach the buoy? (b) What is the velocity of the boat when it reaches the buoy?

57. A bullet is fired through a board 10.0 cm thick in such a way that the bullet’s line of motion is perpendicular to the face of the board. If the initial speed of the bullet is 400 m/s and it emerges from the other side of the board with a speed of 300 m/s, find (a) the acceleration of the bullet as it passes through the board and (b) the total time the bullet is in contact with the board.

58. An indestructible bullet 2.00 cm long is fired straight through a board that is 10.0 cm thick. The bullet strikes the board with a speed of 420 m/s and emerges with a speed of 280 m/s. (a) What is the average acceleration of the bullet through the board? (b) What is the total time that the bullet is in contact with the board? (c) What thickness of board (calculated to 0.1 cm) would it take to stop the bullet, assuming the acceleration through all boards is the same?

59. A student throws a set of keys vertically upward to his fraternity brother, who is in a window 4.00 m above. The brother’s outstretched hand catches the keys 1.50 s later. (a) With what initial velocity were the keys thrown? (b) What was the velocity of the keys just before they were caught?

60. A student throws a set of keys vertically upward to his fraternity brother, who is in a window a distance h above. The brother’s outstretched hand catches the keys on their way up a time t later. (a) With what initial velocity were the keys thrown? (b) What was the velocity of the keys just before they were caught? (Answers should be in terms of h, g, and t.)

61. It has been claimed that an insect called the frog-hopper (Philaenus spumarius) is the best jumper in the animal kingdom. This insect can accelerate at 4 000 m/s² over a distance of 2.0 mm as it straightens its specially designed “jumping legs.” (a) Assuming a uniform acceleration, what is the velocity of the insect after it has accelerated through this short distance, and how long did it take to reach that velocity? (b) How high would the insect jump if air resistance could be ignored? Note that the actual height obtained is about 0.7 m, so air resistance is important here.

62. A ranger in a national park is driving at 35.0 mi/h when a deer jumps into the road 200 ft ahead of the vehicle. After a reaction time t, the ranger applies the brakes to produce an acceleration a = −9.00 ft/s². What is the maximum reaction time allowed if she is to avoid hitting the deer?

63. A ball is thrown upward from the ground with an initial speed of 25 m/s; at the same instant, another ball is dropped from a building 15 m high. After how long will the balls be at the same height?

64. To pass a physical education class at a university, a student must run 1.0 mi in 12 min. After running for 10 min, she still has 500 yd to go. If her maximum acceleration is 0.15 m/s², can she make it? If the answer is no, determine what acceleration she would need to be successful.

65. Two students are on a balcony 19.6 m above the street. One student throws a ball vertically downward at 14.7 m/s; at the same instant, the other student throws a ball ver-
Two students are on a balcony a distance \( h \) above the street. One student throws a ball vertically downward at a speed \( v_0 \); at the same time, the other student throws a ball vertically upward at the same speed. Answer the following symbolically in terms of \( v_0 \), \( g \), \( h \), and \( t \). (a) Write the kinematic equation for the \( y \)-coordinate of each ball. (b) Set the equations found in part (a) equal to height 0 and solve each for \( t \) symbolically using the quadratic formula. What is the difference in the two balls’ time in the air? (c) Use the time-independent kinematics equation to find the velocity of each ball as it strikes the ground. (d) How far apart are the balls at a time \( t \) after they are released and before they strike the ground?

You drop a ball from a window on an upper floor of a building and it is caught by a friend on the ground when the ball is moving with speed \( v_f \). You now repeat the drop, but you have a friend on the street below throw another ball upward at speed \( v_0 \) exactly at the same time that you drop your ball from the window. The two balls are initially separated by 28.7 m. (a) At what time do they pass each other? (b) At what location do they pass each other relative to the window?

The driver of a truck slams on the brakes when he sees a tree blocking the road. The truck slows down uniformly with an acceleration of \(-5.60 \text{ m/s}^2\) for 4.20 s, making skid marks 62.4 m long that end at the tree. With what speed does the truck then strike the tree?

Emily challenges her husband, David, to catch a $1 bill. She holds the bill vertically as in Figure P2.69, with the center of the bill between David’s index finger and thumb. David must catch the bill after Emily releases it without moving his hand downward. If his reaction time is 0.2 s, will he succeed? Explain your reasoning. (This challenge is a good trick you might want to try with your friends.)

A mountain climber stands at the top of a 50.0-m cliff that overhangs a calm pool of water. She throws two stones vertically downward 1.00 s apart and observes that they cause a single splash. The first stone had an initial velocity of \(-2.00 \text{ m/s}\). (a) How long after release of the first stone did the two stones hit the water? (b) What initial velocity must the second stone have had, given that they hit the water simultaneously? (c) What was the velocity of each stone at the instant it hit the water?

An ice sled powered by a rocket engine starts from rest on a large frozen lake and accelerates at \(+40 \text{ ft/s}^2\). After some time \( t_f \), the rocket engine is shut down and the sled moves with constant velocity \( v \) for a time \( t_c \). If the total distance traveled by the sled is 17 500 ft and the total time is 90 s, find (a) the times \( t_f \) and \( t_c \) and (b) the velocity \( v \). At the 17 500-ft mark, the sled begins to accelerate at \(-20 \text{ ft/s}^2\). (c) What is the final position of the sled when it comes to rest? (d) How long does it take to come to rest?

In Bosnia, the ultimate test of a young man’s courage used to be to jump off a 400-year-old bridge (now destroyed) into the River Neretva, 23 m below the bridge. (a) How long did the jump last? (b) How fast was the jumper traveling upon impact with the river? (c) If the speed of sound in air is 340 m/s, how long after the jumper took off did a spectator on the bridge hear the splash?

A person sees a lightning bolt pass close to an airplane that is flying in the distance. The person hears thunder 5.0 s after seeing the bolt and sees the airplane overhead 10 s after hearing the thunder. The speed of sound in air is 1 100 ft/s. (a) Find the distance of the airplane from the person at the instant of the bolt. (Neglect the time it takes the light to travel from the bolt to the eye.) (b) Assuming the plane travels with a constant speed toward the person, find the velocity of the airplane. (c) Look up the speed of light in air and defend the approximation used in part (a).

A glider on an air track carries a flag of length \( L \) through a stationary photogate, which measures the time interval \( \Delta t \) during which the flag blocks a beam of infrared light passing across the photogate. The ratio \( v_g = L/\Delta t \) is the average velocity of the glider over this part of its motion. Suppose the glider moves with constant acceleration. (a) Is \( v_g \) necessarily equal to the instantaneous velocity of the glider when it is halfway through the photogate in space? Explain. (b) Is \( v_g \) equal to the instantaneous velocity of the glider when it is halfway through the photogate in time? Explain.

A stuntman sitting on a tree limb wishes to drop vertically onto a horse galloping under the tree. The constant speed of the horse is 10.0 m/s, and the man is initially 3.00 m above the level of the saddle. (a) What must be the horizontal distance between the saddle and the limb when the man makes his move? (b) How long is he in the air?