The space shuttle has released a parachute to reduce its speed quickly. The directions of the shuttle's velocity and acceleration are shown by the green ($\vec{\mathbf{v}}$) and gold ($\vec{\mathbf{a}}$) arrows.

Motion is described using the concepts of velocity and acceleration. In the case shown here, the velocity $\vec{\mathbf{v}}$ is to the right, in the direction of motion. The acceleration $\vec{\mathbf{a}}$ is in the opposite direction from the velocity $\vec{\mathbf{v}}$, which means the object is slowing down.

We examine in detail motion with constant acceleration, including the vertical motion of objects falling under gravity.

CHAPTER 2

Describing Motion: Kinematics in One Dimension

CHAPTER-OPENING QUESTION—Guess now!

[*Don't worry about getting the right answer now—you will get another chance later in the Chapter. See also p. 1 of Chapter 1 for more explanation.*]

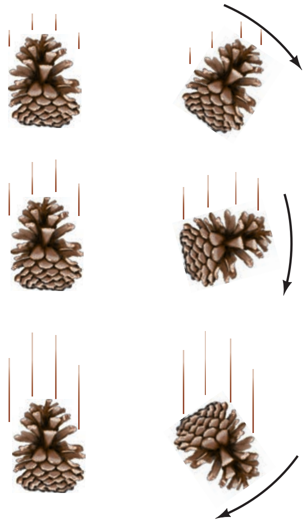
Two small heavy balls have the same diameter but one weighs twice as much as the other. The balls are dropped from a second-story balcony at the exact same time. The time to reach the ground below will be:

(a) twice as long for the lighter ball as for the heavier one.
(b) longer for the lighter ball, but not twice as long.
(c) twice as long for the heavier ball as for the lighter one.
(d) longer for the heavier ball, but not twice as long.
(e) nearly the same for both balls.

CONTENTS

The motion of objects—baseballs, automobiles, joggers, and even the Sun and Moon—is an obvious part of everyday life. It was not until the sixteenth and seventeenth centuries that our modern understanding of motion was established. Many individuals contributed to this understanding, particularly Galileo Galilei (1564–1642) and Isaac Newton (1642–1727).

The study of the motion of objects, and the related concepts of force and energy, form the field called **mechanics**. Mechanics is customarily divided into two parts: **kinematics**, which is the description of how objects move, and **dynamics**, which deals with force and why objects move as they do. This Chapter and the next deal with kinematics.



(a) (b)

FIGURE 2–1 A falling pinecone undergoes (a) pure translation; (b) it is rotating as well as translating.

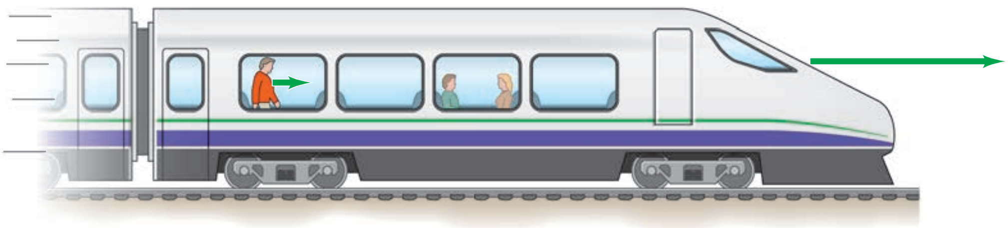
For now we only discuss objects that move without rotating (Fig. 2–1a). Such motion is called **translational motion**. In this Chapter we will be concerned with describing an object that moves along a straight-line path, which is one-dimensional translational motion. In Chapter 3 we will describe translational motion in two (or three) dimensions along paths that are not straight. (Rotation, shown in Fig. 2–1b, is discussed in Chapter 8.)

We will often use the concept, or *model*, of an idealized **particle** which is considered to be a mathematical **point** with no spatial extent (no size). A point particle can undergo only translational motion. The particle model is useful in many real situations where we are interested only in translational motion and the object's size is not significant. For example, we might consider a billiard ball, or even a spacecraft traveling toward the Moon, as a particle for many purposes.

2–1 Reference Frames and Displacement

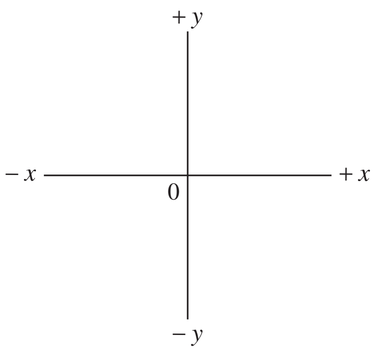
Any measurement of position, distance, or speed must be made with respect to a **reference frame**, or **frame of reference**. For example, while you are on a train traveling at 80 km/h, suppose a person walks past you toward the front of the train at a speed of, say, 5 km/h (Fig. 2–2). This 5 km/h is the person's speed with respect to the train as frame of reference. With respect to the ground, that person is moving at a speed of $80\text{ km/h} + 5\text{ km/h} = 85\text{ km/h}$. It is always important to specify the frame of reference when stating a speed. In everyday life, we usually mean "with respect to the Earth" without even thinking about it, but the reference frame must be specified whenever there might be confusion.

FIGURE 2–2 A person walks toward the front of a train at 5 km/h. The train is moving 80 km/h with respect to the ground, so the walking person's speed, relative to the ground, is 85 km/h.



When specifying the motion of an object, it is important to specify not only the speed but also the direction of motion. Often we can specify a direction by using north, east, south, and west, and by "up" and "down." In physics, we often draw a set of **coordinate axes**, as shown in Fig. 2–3, to represent a frame of reference. We can always place the origin 0, and the directions of the x and y axes, as we like for convenience. The x and y axes are always perpendicular to each other. The **origin** is where $x = 0$, $y = 0$. Objects positioned to the right of the origin of coordinates (0) on the x axis have an x coordinate which we almost always choose to be positive; then points to the left of 0 have a negative x coordinate. The position along the y axis is usually considered positive when above 0, and negative when below 0, although the reverse convention can be used if convenient. Any point on the plane can be specified by giving its x and y coordinates. In three dimensions, a z axis perpendicular to the x and y axes is added.

FIGURE 2–3 Standard set of xy coordinate axes, sometimes called "rectangular coordinates."



For one-dimensional motion, we often choose the x axis as the line along which the motion takes place. Then the **position** of an object at any moment is given by its x coordinate. If the motion is vertical, as for a dropped object, we usually use the y axis.

We need to make a distinction between the *distance* an object has traveled and its **displacement**, which is defined as the *change in position* of the object. That is, *displacement is how far the object is from its starting point*. To see the distinction between total distance and displacement, imagine a person walking 70 m to the east and then turning around and walking back (west) a distance of 30 m (see Fig. 2–4). The total *distance* traveled is 100 m, but the *displacement* is only 40 m since the person is now only 40 m from the starting point.

CAUTION

The displacement may not equal the total distance traveled

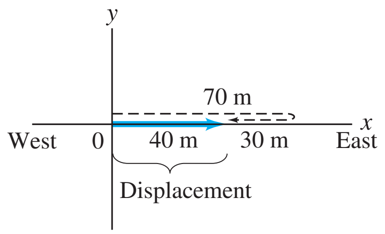


FIGURE 2–4 A person walks 70 m east, then 30 m west. The total distance traveled is 100 m (path is shown dashed in black); but the displacement, shown as a solid blue arrow, is 40 m to the east.

Displacement is a quantity that has both magnitude and direction. Such quantities are called **vectors**, and are represented by arrows in diagrams. For example, in Fig. 2–4, the blue arrow represents the displacement whose magnitude is 40 m and whose direction is to the right (east).

We will deal with vectors more fully in Chapter 3. For now, we deal only with motion in one dimension, along a line. In this case, vectors which point in one direction will be positive (typically to the right along the x axis). Vectors that point in the opposite direction will have a negative sign in front of their magnitude.

Consider the motion of an object over a particular time interval. Suppose that at some initial time, call it t_1, the object is on the x axis at the position x_1 in the coordinate system shown in Fig. 2–5. At some later time, t_2, suppose the object has moved to position x_2. The displacement of our object is $x_2 - x_1$, and is represented by the arrow pointing to the right in Fig. 2–5. It is convenient to write

$$\Delta x = x_2 - x_1,$$

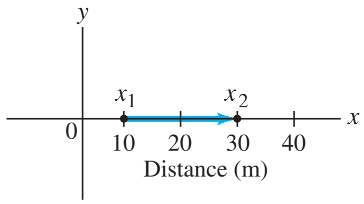


FIGURE 2–5 The arrow represents the displacement $x_2 - x_1$. Distances are in meters.

where the symbol Δ (Greek letter delta) means "change in." Then Δx means "the change in x," or "change in position," which is the displacement. The **change in** any quantity means *the final value of that quantity, minus the initial value*. Suppose $x_1 = 10.0\text{ m}$ and $x_2 = 30.0\text{ m}$, as in Fig. 2–5. Then

$$\Delta x = x_2 - x_1 = 30.0\text{ m} - 10.0\text{ m} = 20.0\text{ m},$$

so the displacement is 20.0 m in the positive direction, Fig. 2–5.

Now consider an object moving to the left as shown in Fig. 2–6. Here the object, a person, starts at $x_1 = 30.0\text{ m}$ and walks to the left to the point $x_2 = 10.0\text{ m}$. In this case her displacement is

$$\Delta x = x_2 - x_1 = 10.0\text{ m} - 30.0\text{ m} = -20.0\text{ m},$$

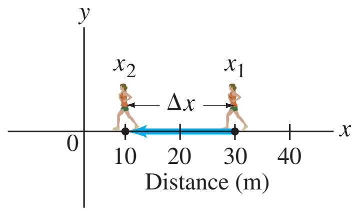


FIGURE 2–6 For the displacement $\Delta x = x_2 - x_1 = 10.0\text{ m} - 30.0\text{ m}$, the displacement vector points left.

and the blue arrow representing the vector displacement points to the left. For one-dimensional motion along the x axis, a vector pointing to the right is positive, whereas a vector pointing to the left has a negative sign.

EXERCISE A An ant starts at $x = 20\text{ cm}$ on a piece of graph paper and walks along the x axis to $x = -20\text{ cm}$. It then turns around and walks back to $x = -10\text{ cm}$. Determine (a) the ant's displacement and (b) the total distance traveled.

2–2 Average Velocity

An important aspect of the motion of a moving object is how *fast* it is moving—its speed or velocity.

The term "speed" refers to how far an object travels in a given time interval, regardless of direction. If a car travels 240 kilometers (km) in 3 hours (h), we say its average speed was 80 km/h. In general, the **average speed** of an object is defined as *the total distance traveled along its path divided by the time it takes to travel this distance*:

$$\text{average speed} = \frac{\text{distance traveled}}{\text{time elapsed}}. \qquad \textbf{(2–1)}$$

The terms "velocity" and "speed" are often used interchangeably in ordinary language. But in physics we make a distinction between the two. Speed is simply a positive number, with units. **Velocity**, on the other hand, is used to signify both the *magnitude* (numerical value) of how fast an object is moving and also the *direction* in which it is moving. Velocity is therefore a *vector*.

There is a second difference between speed and velocity: namely, the *average velocity* is defined in terms of *displacement*, rather than total distance traveled:

$$\text{average velocity} = \frac{\text{displacement}}{\text{time elapsed}} = \frac{\text{final position} - \text{initial position}}{\text{time elapsed}}.$$

CAUTION
Average speed is not necessarily equal to the magnitude of the average velocity

Average speed and average velocity have the same magnitude when the motion is all in one direction. In other cases, they may differ: recall the walk we described earlier, in Fig. 2–4, where a person walked 70 m east and then 30 m west. The total distance traveled was $70\text{ m} + 30\text{ m} = 100\text{ m}$, but the displacement was 40 m. Suppose this walk took 70 s to complete. Then the average speed was:

$$\frac{\text{distance}}{\text{time elapsed}} = \frac{100\text{ m}}{70\text{ s}} = 1.4\text{ m/s}.$$

The magnitude of the average velocity, on the other hand, was:

$$\frac{\text{displacement}}{\text{time elapsed}} = \frac{40\text{ m}}{70\text{ s}} = 0.57\text{ m/s}.$$

To discuss one-dimensional motion of an object in general, suppose that at some moment in time, call it t_1, the object is on the x axis at position x_1 in a coordinate system, and at some later time, t_2, suppose it is at position x_2. The **elapsed time** (= change in time) is $\Delta t = t_2 - t_1$; during this time interval the displacement of our object is $\Delta x = x_2 - x_1$. Then the **average velocity**, defined as *the displacement divided by the elapsed time*, can be written

$$\bar{v} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}, \qquad \text{[average velocity]} \quad \textbf{(2–2)}$$

where v stands for velocity and the bar ($^-$) over the v is a standard symbol meaning "average."

PROBLEM SOLVING
+ or − sign can signify the direction for linear motion

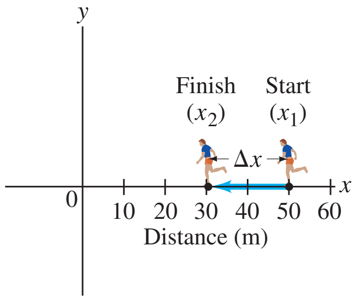
For one-dimensional motion in the usual case of the $+x$ axis to the right, note that if x_2 is less than x_1, the object is moving to the left, and then $\Delta x = x_2 - x_1$ is less than zero. The sign of the displacement, and thus of the average velocity, indicates the direction: the average velocity is positive for an object moving to the right along the x axis and negative when the object moves to the left. The direction of the average velocity is always the same as the direction of the displacement.

CAUTION
Time interval = elapsed time

It is always important to choose (and state) the *elapsed time*, or **time interval**, $t_2 - t_1$, the time that passes during our chosen period of observation.

EXAMPLE 2–1 **Runner's average velocity.** The position of a runner is plotted as moving along the x axis of a coordinate system. During a 3.00-s time interval, the runner's position changes from $x_1 = 50.0\text{ m}$ to $x_2 = 30.5\text{ m}$, as shown in Fig. 2–7. What is the runner's average velocity?

FIGURE 2–7 Example 2–1. A person runs from $x_1 = 50.0\text{ m}$ to $x_2 = 30.5\text{ m}$. The displacement is -19.5 m.



APPROACH We want to find the average velocity, which is the displacement divided by the elapsed time.

SOLUTION The displacement is

$$\begin{aligned}\Delta x &= x_2 - x_1 \\ &= 30.5\text{ m} - 50.0\text{ m} = -19.5\text{ m}.\end{aligned}$$

The elapsed time, or time interval, is given as $\Delta t = 3.00\text{ s}$. The average velocity (Eq. 2–2) is

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{-19.5\text{ m}}{3.00\text{ s}} = -6.50\text{ m/s}.$$

The displacement and average velocity are negative, which tells us that the runner is moving to the left along the x axis, as indicated by the arrow in Fig. 2–7. The runner's average velocity is 6.50 m/s to the left.

EXAMPLE 2–2 **Distance a cyclist travels.** How far can a cyclist travel in 2.5 h along a straight road if her average velocity is 18 km/h?

APPROACH We want to find the distance traveled, so we solve Eq. 2–2 for Δx.

SOLUTION In Eq. 2–2, $\bar{v} = \Delta x/\Delta t$, we multiply both sides by Δt and obtain

$$\Delta x = \bar{v}\,\Delta t = (18\,\mathrm{km/h})(2.5\,\mathrm{h}) = 45\,\mathrm{km}.$$

EXAMPLE 2–3 **Car changes speed.** A car travels at a constant 50 km/h for 100 km. It then speeds up to 100 km/h and is driven another 100 km. What is the car's average speed for the 200-km trip?

APPROACH At 50 km/h, the car takes 2.0 h to travel 100 km. At 100 km/h it takes only 1.0 h to travel 100 km. We use the defintion of average velocity, Eq. 2–2.

SOLUTION Average velocity (Eq. 2–2) is

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{100\,\mathrm{km} + 100\,\mathrm{km}}{2.0\,\mathrm{h} + 1.0\,\mathrm{h}} = 67\,\mathrm{km/h}.$$

NOTE Averaging the two speeds, $(50\,\mathrm{km/h} + 100\,\mathrm{km/h})/2 = 75\,\mathrm{km/h}$, gives a wrong answer. Can you see why? You must use the definition of $\bar{v}$, Eq. 2–2.

2–3 Instantaneous Velocity

If you drive a car along a straight road for 150 km in 2.0 h, the magnitude of your average velocity is 75 km/h. It is unlikely, though, that you were moving at precisely 75 km/h at every instant. To describe this situation we need the concept of *instantaneous velocity*, which is the velocity at any instant of time. (Its magnitude is the number, with units, indicated by a speedometer, Fig. 2–8.) More precisely, the **instantaneous velocity** at any moment is defined as *the average velocity over an infinitesimally short time interval*. That is, Eq. 2–2 is to be evaluated in the limit of Δt becoming extremely small, approaching zero. We can write the definition of instantaneous velocity, v, for one-dimensional motion as

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t}. \qquad \text{[instantaneous velocity]} \quad \textbf{(2–3)}$$

The notation $\lim_{\Delta t \to 0}$ means the ratio $\Delta x/\Delta t$ is to be evaluated in the limit of Δt approaching zero.†

For instantaneous velocity we use the symbol v, whereas for average velocity we use $\bar{v}$, with a bar above. In the rest of this book, when we use the term "velocity" it will refer to instantaneous velocity. When we want to speak of the average velocity, we will make this clear by including the word "average."

Note that the *instantaneous speed* always equals the magnitude of the instantaneous velocity. Why? Because distance traveled and the magnitude of the displacement become the same when they become infinitesimally small.

If an object moves at a uniform (that is, constant) velocity during a particular time interval, then its instantaneous velocity at any instant is the same as its average velocity (see Fig. 2–9a). But in many situations this is not the case. For example, a car may start from rest, speed up to 50 km/h, remain at that velocity for a time, then slow down to 20 km/h in a traffic jam, and finally stop at its destination after traveling a total of 15 km in 30 min. This trip is plotted on the graph of Fig. 2–9b. Also shown on the graph is the average velocity (dashed line), which is $\bar{v} = \Delta x/\Delta t = 15\,\mathrm{km}/0.50\,\mathrm{h} = 30\,\mathrm{km/h}$.

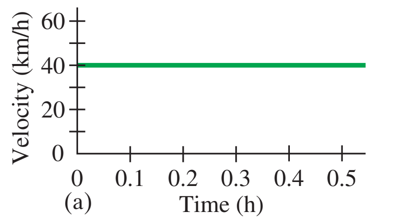
Graphs are often useful for analysis of motion; we discuss additional insights graphs can provide as we go along, especially in Section 2–8.

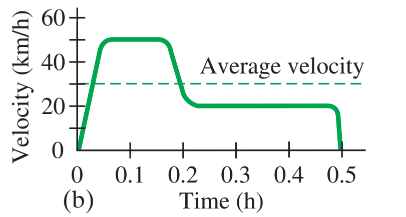
EXERCISE B What is your instantaneous speed at the instant you turn around to move in the opposite direction? (*a*) Depends on how quickly you turn around; (*b*) always zero; (*c*) always negative; (*d*) none of the above.

†We do not simply set $\Delta t = 0$ in this definition, for then Δx would also be zero, and we would have an undetermined number. Rather, we consider the *ratio* $\Delta x/\Delta t$, as a whole. As we let Δt approach zero, Δx approaches zero as well. But the ratio $\Delta x/\Delta t$ approaches some definite value, which is the instantaneous velocity at a given instant.

FIGURE 2–8 Car speedometer showing mi/h in white, and km/h in orange.

FIGURE 2–9 Velocity of a car as a function of time: (a) at constant velocity; (b) with velocity varying in time.





2–4 Acceleration

An object whose velocity is changing is said to be accelerating. For instance, a car whose velocity increases in magnitude from zero to 80 km/h is accelerating. Acceleration specifies how *rapidly* the velocity of an object is changing.

Average acceleration is defined as the change in velocity divided by the time taken to make this change:

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

In symbols, the **average acceleration**, $\bar{a}$, over a time interval $\Delta t = t_2 - t_1$, during which the velocity changes by $\Delta v = v_2 - v_1$, is defined as

$$\bar{a} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t}. \qquad \text{[average acceleration]} \qquad \textbf{(2–4)}$$

We saw that velocity is a vector (it has magnitude and direction), so acceleration is a vector too. But for one dimensional motion, we need only use a plus or minus sign to indicate acceleration direction relative to a chosen coordinate axis. (Usually, right is +, left is −.)

The **instantaneous acceleration**, a, can be defined in analogy to instantaneous velocity as the average acceleration over an infinitesimally short time interval at a given instant:

$$a = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t}. \qquad \text{[instantaneous acceleration]} \qquad \textbf{(2–5)}$$

Here Δv is the very small change in velocity during the very short time interval Δt.

EXAMPLE 2–4 **Average acceleration.** A car accelerates on a straight road from rest to 75 km/h in 5.0 s, Fig. 2–10. What is the magnitude of its average acceleration?

APPROACH Average acceleration is the change in velocity divided by the elapsed time, 5.0 s. The car starts from rest, so $v_1 = 0$. The final velocity is $v_2 = 75\ \text{km/h}$.

SOLUTION From Eq. 2–4, the average acceleration is

$$\bar{a} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{75\ \text{km/h} - 0\ \text{km/h}}{5.0\ \text{s}} = 15\ \frac{\text{km/h}}{\text{s}}.$$

This is read as "fifteen kilometers per hour per second" and means that, on average, the velocity changed by 15 km/h during each second. That is, assuming the acceleration was constant, during the first second the car's velocity increased from zero to 15 km/h. During the next second its velocity increased by another 15 km/h, reaching a velocity of 30 km/h at $t = 2.0\ \text{s}$, and so on. See Fig. 2–10.

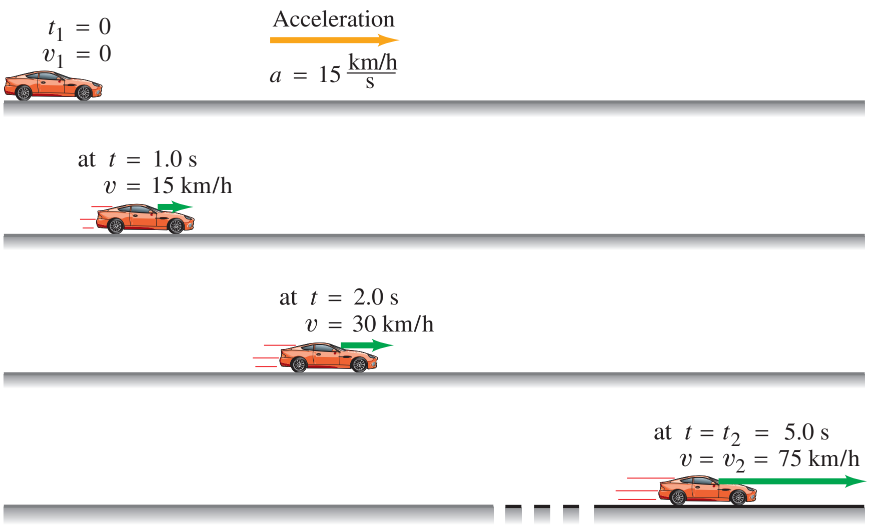


FIGURE 2–10 Example 2–4. The car is shown at the start with $v_1 = 0$ at $t_1 = 0$. The car is shown three more times, at $t = 1.0\ \text{s}$, $t = 2.0\ \text{s}$, and at the end of our time interval, $t_2 = 5.0\ \text{s}$. The green arrows represent the velocity vectors, whose length represents the magnitude of the velocity at that moment. The acceleration vector is the orange arrow, whose magnitude is constant and equals 15 km/h/s or 4.2 m/s^2 (see top of next page). Distances are not to scale.

Our result in Example 2–4 contains two different time units: hours and seconds. We usually prefer to use only seconds. To do so we can change km/h to m/s (see Section 1–6, and Example 1–5):

$$75\ \mathrm{km/h} \;=\; \left(75\,\frac{\cancel{\mathrm{km}}}{\cancel{\mathrm{h}}}\right)\left(\frac{1000\ \mathrm{m}}{1\ \cancel{\mathrm{km}}}\right)\left(\frac{1\ \cancel{\mathrm{h}}}{3600\ \mathrm{s}}\right) \;=\; 21\ \mathrm{m/s}.$$

Then

$$\bar{a} \;=\; \frac{21\ \mathrm{m/s} - 0.0\ \mathrm{m/s}}{5.0\ \mathrm{s}} \;=\; 4.2\,\frac{\mathrm{m/s}}{\mathrm{s}} \;=\; 4.2\,\frac{\mathrm{m}}{\mathrm{s}^2}.$$

We almost always write the units for acceleration as $\mathrm{m/s^2}$ (meters per second squared) instead of m/s/s. This is possible because:

$$\frac{\mathrm{m/s}}{\mathrm{s}} \;=\; \frac{\mathrm{m}}{\mathrm{s\cdot s}} \;=\; \frac{\mathrm{m}}{\mathrm{s}^2}.$$

Note that *acceleration tells us how quickly the velocity changes*, whereas *velocity tells us how quickly the position changes*.

CAUTION
Distinguish velocity from acceleration

CONCEPTUAL EXAMPLE 2–5 **Velocity and acceleration.** (*a*) If the velocity of an object is zero, does it mean that the acceleration is zero? (*b*) If the acceleration is zero, does it mean that the velocity is zero? Think of some examples.

CAUTION
If v or a is zero, is the other zero too?

RESPONSE A zero velocity does not necessarily mean that the acceleration is zero, nor does a zero acceleration mean that the velocity is zero. (*a*) For example, when you put your foot on the gas pedal of your car which is at rest, the velocity starts from zero but the acceleration is not zero since the velocity of the car changes. (How else could your car start forward if its velocity weren't changing—that is, accelerating?) (*b*) As you cruise along a straight highway at a constant velocity of 100 km/h, your acceleration is zero: $a = 0,\ v \neq 0$.

EXAMPLE 2–6 **Car slowing down.** An automobile is moving to the right along a straight highway, which we choose to be the positive x axis (Fig. 2–11). Then the driver steps on the brakes. If the initial velocity (when the driver hits the brakes) is $v_1 = 15.0\ \mathrm{m/s}$, and it takes 5.0 s to slow down to $v_2 = 5.0\ \mathrm{m/s}$, what was the car's average acceleration?

APPROACH We put the given initial and final velocities, and the elapsed time, into Eq. 2–4 for $\bar{a}$.

SOLUTION In Eq. 2–4, we call the initial time $t_1 = 0$, and set $t_2 = 5.0\ \mathrm{s}$:

$$\bar{a} \;=\; \frac{5.0\ \mathrm{m/s} - 15.0\ \mathrm{m/s}}{5.0\ \mathrm{s}} \;=\; -2.0\ \mathrm{m/s^2}.$$

The negative sign appears because the final velocity is less than the initial velocity. In this case the direction of the acceleration is to the left (in the negative x direction)—even though the velocity is always pointing to the right. We say that the acceleration is $2.0\ \mathrm{m/s^2}$ to the left, and it is shown in Fig. 2–11 as an orange arrow.

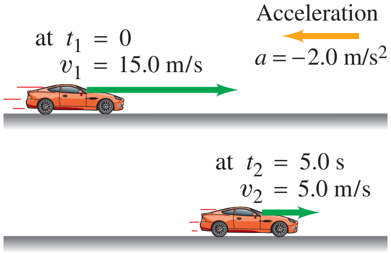


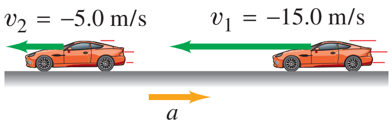
FIGURE 2–11 Example 2–6, showing the position of the car at times t_1 and t_2, as well as the car's velocity represented by the green arrows. The acceleration vector (orange) points to the left because the car slows down as it moves to the right.

Deceleration

When an object is slowing down, we can say it is **decelerating**. But be careful: deceleration does *not* mean that the acceleration is necessarily negative. The velocity of an object moving to the right along the positive x axis is positive; if the object is slowing down (as in Fig. 2–11), the acceleration *is* negative. But the same car moving to the left (decreasing x), and slowing down, has positive acceleration that points to the right, as shown in Fig. 2–12. We have a deceleration whenever the magnitude of the velocity is decreasing; thus the *velocity and acceleration point in opposite directions* when there is deceleration.

FIGURE 2–12 The car of Example 2–6, now moving to the *left* and decelerating. The acceleration is $a = (v_2 - v_1)/\Delta t$, or

$$a = \frac{(-5.0\ \mathrm{m/s}) - (-15.0\ \mathrm{m/s})}{5.0\ \mathrm{s}}$$
$$= \frac{-5.0\ \mathrm{m/s} + 15.0\ \mathrm{m/s}}{5.0\ \mathrm{s}} = +2.0\ \mathrm{m/s^2}.$$



EXERCISE C A car moves along the x axis. What is the sign of the car's acceleration if it is moving in the positive x direction with (*a*) increasing speed or (*b*) decreasing speed? What is the sign of the acceleration if the car moves in the negative x direction with (*c*) increasing speed or (*d*) decreasing speed?

2–5 Motion at Constant Acceleration

We now examine motion in a straight line when the magnitude of the acceleration is constant. In this case, the instantaneous and average accelerations are equal. We use the definitions of average velocity and acceleration to derive a set of valuable equations that relate x, v, a, and t when a is constant, allowing us to determine any one of these variables if we know the others. We can then solve many interesting Problems.

Notation in physics varies from book to book; and different instructors use different notation. We are now going to change our notation, to simplify it a bit for our discussion here of motion at **constant acceleration**. First we choose the initial time in any discussion to be zero, and we call it t_0. That is, $t_1 = t_0 = 0$. (This is effectively starting a stopwatch at t_0.) We can then let $t_2 = t$ be the elapsed time. The initial position (x_1) and the initial velocity (v_1) of an object will now be represented by x_0 and v_0, since they represent x and v at $t = 0$. At time t the position and velocity will be called x and v (rather than x_2 and v_2). The average velocity during the time interval $t - t_0$ will be (Eq. 2–2)

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x - x_0}{t - t_0} = \frac{x - x_0}{t}$$

since we chose $t_0 = 0$. The acceleration, assumed constant in time, is $a = \Delta v / \Delta t$ (Eq. 2–4), so

$$a = \frac{v - v_0}{t}.$$

FIGURE 2–13 An accelerating motorcycle.

A common problem is to determine the velocity of an object after any elapsed time t, when we are given the object's constant acceleration. We can solve such problems† by solving for v in the last equation: first we multiply both sides by t,

$$at = v - v_0 \qquad \text{or} \qquad v - v_0 = at.$$

Then, adding v_0 to both sides, we obtain

$$v = v_0 + at. \qquad \text{[constant acceleration]} \quad \textbf{(2–6)}$$

If an object, such as a motorcycle (Fig. 2–13), starts from rest $(v_0 = 0)$ and accelerates at $4.0\,\mathrm{m/s^2}$, after an elapsed time $t = 6.0\,\mathrm{s}$ its velocity will be $v = 0 + at = (4.0\,\mathrm{m/s^2})(6.0\,\mathrm{s}) = 24\,\mathrm{m/s}$.

Next, let us see how to calculate the position x of an object after a time t when it undergoes constant acceleration. The definition of average velocity (Eq. 2–2) is $\bar{v} = (x - x_0)/t$, which we can rewrite by multiplying both sides by t:

$$x = x_0 + \bar{v}t. \qquad \textbf{(2–7)}$$

Because the velocity increases at a uniform rate, the average velocity, $\bar{v}$, will be midway between the initial and final velocities:

CAUTION

Average velocity, but only if a = constant

$$\bar{v} = \frac{v_0 + v}{2}. \qquad \text{[constant acceleration]} \quad \textbf{(2–8)}$$

(Careful: Equation 2–8 is not necessarily valid if the acceleration is not constant.) We combine the last two Equations with Eq. 2–6 and find, starting with Eq. 2–7,

$$\begin{aligned} x &= x_0 + \bar{v}t \\ &= x_0 + \left(\frac{v_0 + v}{2}\right)t \\ &= x_0 + \left(\frac{v_0 + v_0 + at}{2}\right)t \end{aligned}$$

or

$$x = x_0 + v_0 t + \tfrac{1}{2}at^2. \qquad \text{[constant acceleration]} \quad \textbf{(2–9)}$$

Equations 2–6, 2–8, and 2–9 are three of the four most useful equations for motion at constant acceleration. We now derive the fourth equation, which is useful

†Appendix A–4 summarizes simple algebraic manipulations.

in situations where the time t is not known. We substitute Eq. 2–8 into Eq. 2–7:

$$x = x_0 + \bar{v}t = x_0 + \left(\frac{v + v_0}{2}\right)t.$$

Next we solve Eq. 2–6 for t, obtaining (see Appendix A–4 for a quick review)

$$t = \frac{v - v_0}{a},$$

and substituting this into the previous equation we have

$$x = x_0 + \left(\frac{v + v_0}{2}\right)\left(\frac{v - v_0}{a}\right) = x_0 + \frac{v^2 - v_0^2}{2a}.$$

We solve this for v^2 and obtain

$$v^2 = v_0^2 + 2a(x - x_0), \qquad \text{[constant acceleration]} \qquad \textbf{(2–10)}$$

which is the other useful equation we sought.

We now have four equations relating position, velocity, acceleration, and time, when the acceleration a is constant. We collect these *kinematic equations for constant acceleration* here in one place for future reference (the tan background screen emphasizes their usefulness):

$$v = v_0 + at \qquad [a = \text{constant}] \qquad \textbf{(2–11a)}$$
$$x = x_0 + v_0 t + \tfrac{1}{2}at^2 \qquad [a = \text{constant}] \qquad \textbf{(2–11b)}$$
$$v^2 = v_0^2 + 2a(x - x_0) \qquad [a = \text{constant}] \qquad \textbf{(2–11c)}$$
$$\bar{v} = \frac{v + v_0}{2}. \qquad [a = \text{constant}] \qquad \textbf{(2–11d)}$$

Kinematic equations for constant acceleration (we'll use them a lot)

These useful equations are not valid unless a is a constant. In many cases we can set $x_0 = 0$, and this simplifies the above equations a bit. Note that x represents position (not distance), also that $x - x_0$ is the displacement, and that t is the elapsed time. Equations 2–11 are useful also when a is approximately constant to obtain reasonable estimates.

EXAMPLE 2–7 Runway design. You are designing an airport for small planes. One kind of airplane that might use this airfield must reach a speed before takeoff of at least 27.8 m/s (100 km/h), and can accelerate at 2.00 m/s^2. (a) If the runway is 150 m long, can this airplane reach the required speed for takeoff? (b) If not, what minimum length must the runway have?

PHYSICS APPLIED
Airport design

Known	Wanted
$x_0 = 0$	v
$v_0 = 0$	
$x = 150\,\text{m}$	
$a = 2.00\,\text{m/s}^2$	

APPROACH Assuming the plane's acceleration is constant, we use the kinematic equations for constant acceleration. In (a), we want to find v, and what we are given is shown in the Table in the margin.

SOLUTION (a) Of the above four equations, Eq. 2–11c will give us v when we know v_0, a, x, and x_0:

$$v^2 = v_0^2 + 2a(x - x_0)$$
$$= 0 + 2(2.00\,\text{m/s}^2)(150\,\text{m}) = 600\,\text{m}^2/\text{s}^2$$
$$v = \sqrt{600\,\text{m}^2/\text{s}^2} = 24.5\,\text{m/s}.$$

PROBLEM SOLVING
Equations 2–11 are valid only when the acceleration is constant, which we assume in this Example

This runway length is *not* sufficient, because the minimum speed is not reached.

(b) Now we want to find the minimum runway length, $x - x_0$, for a plane to reach $v = 27.8\,\text{m/s}$, given $a = 2.00\,\text{m/s}^2$. We again use Eq. 2–11c, but rewritten as

$$(x - x_0) = \frac{v^2 - v_0^2}{2a} = \frac{(27.8\,\text{m/s})^2 - 0}{2(2.00\,\text{m/s}^2)} = 193\,\text{m}.$$

A 200-m runway is more appropriate for this plane.

NOTE We did this Example as if the plane were a particle, so we round off our answer to 200 m.

EXERCISE D A car starts from rest and accelerates at a constant $10\,\text{m/s}^2$ during a $\frac{1}{4}$-mile (402 m) race. How fast is the car going at the finish line? (*a*) 8040 m/s; (*b*) 90 m/s; (*c*) 81 m/s; (*d*) 804 m/s.

2–6 Solving Problems

Before doing more worked-out Examples, let us look at how to approach problem solving. First, it is important to note that physics is *not* a collection of equations to be memorized. Simply searching for an equation that might work can lead you to a wrong result and will not help you understand physics (Fig. 2–14). A better approach is to use the following (rough) procedure, which we present as a special "Problem Solving Strategy." (Other such Problem Solving Strategies will be found throughout the book.)

FIGURE 2–14 Read the book, study carefully, and work the Problems using your reasoning abilities.

PROBLEM SOLVING

1. Read and **reread** the whole problem carefully before trying to solve it.
2. Decide what **object** (or objects) you are going to study, and for what **time interval**. You can often choose the initial time to be $t = 0$.
3. **Draw** a **diagram** or picture of the situation, with coordinate axes wherever applicable. [You can place the origin of coordinates and the axes wherever you like to make your calculations easier. You also choose which direction is positive and which is negative. Usually we choose the x axis to the right as positive.]
4. Write down what quantities are "**known**" or "given," and then what you *want* to know. Consider quantities both at the beginning and at the end of the chosen time interval. You may need to "translate" language into physical terms, such as "starts from rest" means $v_0 = 0$.
5. Think about which **principles of physics** apply in this problem. Use common sense and your own experiences. Then plan an approach.
6. Consider which **equations** (and/or definitions) relate the quantities involved. Before using them, be sure their **range of validity** includes your problem (for example, Eqs. 2–11 are valid only when the acceleration is constant). If you find an applicable equation that involves only known quantities and one desired unknown, **solve** the equation algebraically for the unknown. Sometimes several sequential calculations, or a combination of equations, may be needed. It is often preferable to solve algebraically for the desired unknown before putting in numerical values.
7. Carry out the **calculation** if it is a numerical problem. Keep one or two extra digits during the calculations, but round off the final answer(s) to the correct number of significant figures (Section 1–4).
8. Think carefully about the result you obtain: Is it **reasonable**? Does it make sense according to your own intuition and experience? A good check is to do a rough **estimate** using only powers of 10, as discussed in Section 1–7. Often it is preferable to do a rough estimate at the *start* of a numerical problem because it can help you focus your attention on finding a path toward a solution.
9. A very important aspect of doing problems is keeping track of **units**. An equals sign implies the units on each side must be the same, just as the numbers must. If the units do not balance, a mistake has been made. This can serve as a **check** on your solution (but it only tells you if you're wrong, not if you're right). Always use a consistent set of units.

EXAMPLE 2–8 **Acceleration of a car.** How long does it take a car to cross a 30.0-m-wide intersection after the light turns green, if the car accelerates from rest at a constant $2.00\ \mathrm{m/s^2}$?

APPROACH We follow the Problem Solving Strategy on the previous page, step by step.

SOLUTION

1. **Reread** the problem. Be sure you understand what it asks for (here, a time interval: "how long does it take").
2. The **object** under study is the car. We need to choose the **time interval** during which we look at the car's motion: we choose $t = 0$, the initial time, to be the moment the car starts to accelerate from rest $(v_0 = 0)$; the time t is the instant the car has traveled the full 30.0-m width of the intersection.
3. **Draw** a **diagram**: the situation is shown in Fig. 2–15, where the car is shown moving along the positive x axis. We choose $x_0 = 0$ at the front bumper of the car before it starts to move.
4. The "**knowns**" and the "wanted" information are shown in the Table in the margin. Note that "starting from rest" means $v = 0$ at $t = 0$; that is, $v_0 = 0$. The wanted time t is how long it takes the car to travel 30.0 m.
5. The **physics**: the car, starting from rest $(\text{at } t_0 = 0)$, increases in speed as it covers more distance. The acceleration is constant, so we can use the kinematic equations, Eqs. 2–11.
6. **Equations**: we want to find the time, given the distance and acceleration; Eq. 2–11b is perfect since the only unknown quantity is t. Setting $v_0 = 0$ and $x_0 = 0$ in Eq. 2–11b $\left(x = x_0 + v_0 t + \frac{1}{2}at^2\right)$, we have
$$x = \tfrac{1}{2}at^2.$$
We solve for t by multiplying both sides by $\dfrac{2}{a}$:
$$\frac{2x}{a} = t^2.$$
Taking the square root, we get t:
$$t = \sqrt{\frac{2x}{a}}.$$
7. The **calculation**:
$$t = \sqrt{\frac{2x}{a}} = \sqrt{\frac{2(30.0\ \mathrm{m})}{2.00\ \mathrm{m/s^2}}} = 5.48\ \mathrm{s}.$$
This is our answer. Note that the units come out correctly.
8. We can check the **reasonableness** of the answer by doing an alternate calculation: we first find the final velocity
$$v = at = (2.00\ \mathrm{m/s^2})(5.48\ \mathrm{s}) = 10.96\ \mathrm{m/s},$$
and then find the distance traveled
$$x = x_0 + \bar{v}t = 0 + \tfrac{1}{2}(10.96\ \mathrm{m/s} + 0)(5.48\ \mathrm{s}) = 30.0\ \mathrm{m},$$
which checks with our given distance.
9. We checked the **units** in step 7, and they came out correctly (seconds).

NOTE In steps 6 and 7, when we took the square root, we should have written $t = \pm\sqrt{2x/a} = \pm 5.48\ \mathrm{s}$. Mathematically there are two solutions. But the second solution, $t = -5.48\ \mathrm{s}$, is a time *before* our chosen time interval and makes no sense physically. We say it is "unphysical" and ignore it.

PROBLEM SOLVING
"Starting from rest" means $v = 0$ at $t = 0$ [i.e., $v_0 = 0$]

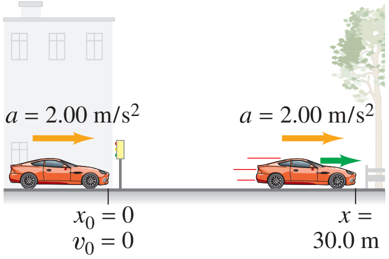


FIGURE 2–15 Example 2–8.

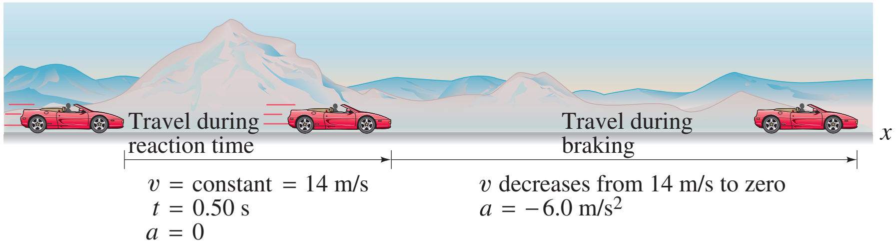
Known	Wanted
$x_0 = 0$	t
$x = 30.0\ \mathrm{m}$	
$a = 2.00\ \mathrm{m/s^2}$	
$v_0 = 0$	

PROBLEM SOLVING
Check your answer

PROBLEM SOLVING
"Unphysical" solutions

We explicitly followed the steps of the Problem Solving Strategy in Example 2–8. In upcoming Examples, we will use our usual "Approach" and "Solution" to avoid being wordy.

FIGURE 2–16 Example 2–9: stopping distance for a braking car.



PHYSICS APPLIED
Car stopping distances

EXAMPLE 2–9 ESTIMATE Braking distances. Estimate the minimum stopping distance for a car, which is important for traffic safety and traffic design. The problem is best dealt with in two parts, two separate time intervals. (1) The first time interval begins when the driver decides to hit the brakes, and ends when the foot touches the brake pedal. This is the "reaction time" during which the speed is constant, so $a = 0$. (2) The second time interval is the actual braking period when the vehicle slows down $(a \neq 0)$ and comes to a stop. The stopping distance depends on the reaction time of the driver, the initial speed of the car (the final speed is zero), and the deceleration of the car. For a dry road and good tires, good brakes can decelerate a car at a rate of about $5\,\mathrm{m/s^2}$ to $8\,\mathrm{m/s^2}$. Calculate the total stopping distance for an initial velocity of 50 km/h $(= 14\,\mathrm{m/s} \approx 31\,\mathrm{mi/h})$ and assume the acceleration of the car is $-6.0\,\mathrm{m/s^2}$ (the minus sign appears because the velocity is taken to be in the positive x direction and its magnitude is decreasing). Reaction time for normal drivers varies from perhaps 0.3 s to about 1.0 s; take it to be 0.50 s.

APPROACH During the "reaction time," part (1), the car moves at constant speed of 14 m/s, so $a = 0$. Once the brakes are applied, part (2), the acceleration is $a = -6.0\,\mathrm{m/s^2}$ and is constant over this time interval. For both parts a is constant, so we can use Eqs. 2–11.

Part 1: Reaction time

Known	Wanted
$t = 0.50\,\mathrm{s}$	x
$v_0 = 14\,\mathrm{m/s}$	
$v = 14\,\mathrm{m/s}$	
$a = 0$	
$x_0 = 0$	

SOLUTION Part (1). We take $x_0 = 0$ for the first time interval, when the driver is reacting (0.50 s): the car travels at a constant speed of 14 m/s so $a = 0$. See Fig. 2–16 and the Table in the margin. To find x, the position of the car at $t = 0.50\,\mathrm{s}$ (when the brakes are applied), we cannot use Eq. 2–11c because x is multiplied by a, which is zero. But Eq. 2–11b works:

$$x = v_0 t + 0 = (14\,\mathrm{m/s})(0.50\,\mathrm{s}) = 7.0\,\mathrm{m}.$$

Thus the car travels 7.0 m during the driver's reaction time, until the instant the brakes are applied. We will use this result as input to part (2).

Part 2: Braking

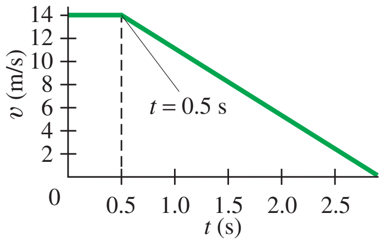
Known	Wanted
$x_0 = 7.0\,\mathrm{m}$	x
$v_0 = 14\,\mathrm{m/s}$	
$v = 0$	
$a = -6.0\,\mathrm{m/s^2}$	

Part (2). During the second time interval, the brakes are applied and the car is brought to rest. The initial position is $x_0 = 7.0\,\mathrm{m}$ (result of part (1)), and other variables are shown in the second Table in the margin. Equation 2–11a doesn't contain x; Eq. 2–11b contains x but also the unknown t. Equation 2–11c, $v^2 - v_0^2 = 2a(x - x_0)$, is what we want; after setting $x_0 = 7.0\,\mathrm{m}$, we solve for x, the final position of the car (when it stops):

$$\begin{aligned} x &= x_0 + \frac{v^2 - v_0^2}{2a} \\ &= 7.0\,\mathrm{m} + \frac{0 - (14\,\mathrm{m/s})^2}{2(-6.0\,\mathrm{m/s^2})} = 7.0\,\mathrm{m} + \frac{-196\,\mathrm{m^2/s^2}}{-12\,\mathrm{m/s^2}} \\ &= 7.0\,\mathrm{m} + 16\,\mathrm{m} = 23\,\mathrm{m}. \end{aligned}$$

The car traveled 7.0 m while the driver was reacting and another 16 m during the braking period before coming to a stop, for a total distance traveled of 23 m. Figure 2–17 shows a graph of v vs. t: v is constant from $t = 0$ until $t = 0.50\,\mathrm{s}$, and after $t = 0.50\,\mathrm{s}$ it decreases linearly to zero.

FIGURE 2–17 Example 2–9. Graph of v vs. t.



NOTE From the equation above for x, we see that the stopping distance after the driver hit the brakes $(= x - x_0)$ increases with the *square* of the initial speed, not just linearly with speed. If you are traveling twice as fast, it takes four times the distance to stop.

FIGURE 2–18 Painting of Galileo demonstrating to the Grand Duke of Tuscany his argument for the action of gravity being uniform acceleration. He used an inclined plane to slow down the action. A ball rolling down the plane still accelerates. Tiny bells placed at equal distances along the inclined plane would ring at shorter time intervals as the ball "fell," indicating that the speed was increasing.

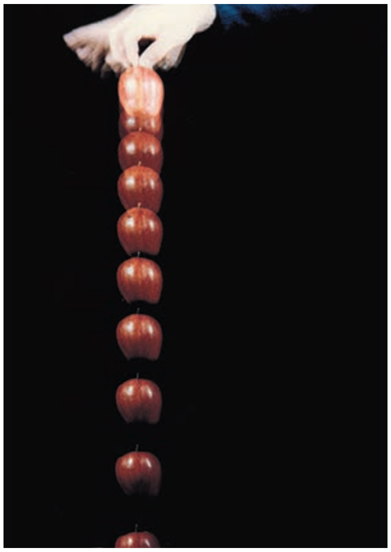


FIGURE 2–19 Multiflash photograph of a falling apple, at equal time intervals. The apple falls farther during each successive interval, which means it is accelerating.

2–7 Freely Falling Objects

One of the most common examples of uniformly accelerated motion is that of an object allowed to fall freely near the Earth's surface. That a falling object is accelerating may not be obvious at first. And beware of thinking, as was widely believed before the time of Galileo (Fig. 2–18), that heavier objects fall faster than lighter objects and that the speed of fall is proportional to how heavy the object is. *The speed of a falling object is* not *proportional to its mass.*

Galileo made use of his new technique of imagining what would happen in idealized (simplified) cases. For free fall, he postulated that *all objects would fall with the same constant acceleration in the absence of air or other resistance*. He showed that this postulate predicts that for an object falling from rest, the distance traveled will be proportional to the square of the time (Fig. 2–19); that is, $d \propto t^2$. We can see this from Eq. 2–11b for constant acceleration; but Galileo was the first to derive this mathematical relation.

To support his claim that falling objects increase in speed as they fall, Galileo made use of a clever argument: a heavy stone dropped from a height of 2 m will drive a stake into the ground much further than will the same stone dropped from a height of only 0.2 m. Clearly, the stone must be moving faster in the former case.

Galileo claimed that *all* objects, light or heavy, fall with the *same* acceleration, at least in the absence of air. If you hold a piece of paper flat and horizontal in one hand, and a heavier object like a baseball in the other, and release them at the same time as in Fig. 2–20a, the heavier object will reach the ground first. But if you repeat the experiment, this time crumpling the paper into a small wad, you will find (see Fig. 2–20b) that the two objects reach the floor at nearly the same time.

Galileo was sure that air acts as a resistance to very light objects that have a large surface area. But in many ordinary circumstances this air resistance is negligible. In a chamber from which the air has been removed, even light objects like a feather or a horizontally held piece of paper will fall with the same acceleration as any other object (see Fig. 2–21). Such a demonstration in vacuum was not possible in Galileo's time, which makes Galileo's achievement all the greater. Galileo is often called the "father of modern science," not only for the *content* of his science (astronomical discoveries, inertia, free fall) but also for his new methods of *doing* science (idealization and simplification, mathematization of theory, theories that have testable consequences, experiments to test theoretical predictions).

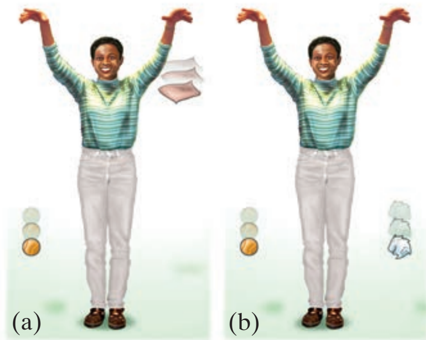
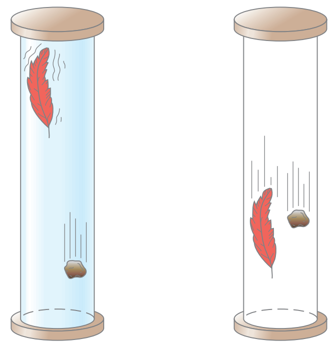


FIGURE 2–20 (a) A ball and a light piece of paper are dropped at the same time. (b) Repeated, with the paper wadded up.

FIGURE 2–21 A rock and a feather are dropped simultaneously (a) in air, (b) in a vacuum.



Air-filled tube (a)

Evacuated tube (b)

Galileo's specific contribution to our understanding of the motion of falling objects can be summarized as follows:

> **at a given location on the Earth and in the absence of air resistance, all objects fall with the same constant acceleration.**

We call this acceleration the **acceleration due to gravity** at the surface of the Earth, and we give it the symbol g. Its magnitude is approximately

$$g = 9.80\ \mathrm{m/s^2}. \qquad \left[\begin{array}{l}\text{acceleration due to gravity}\\ \text{at surface of Earth}\end{array}\right]$$

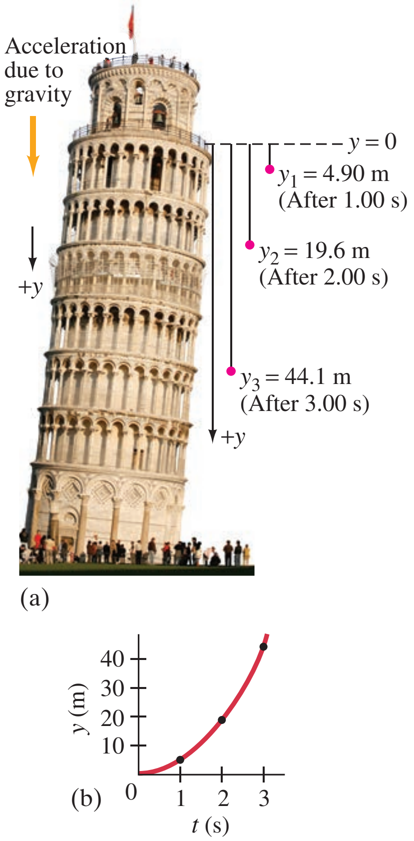
In British units g is about $32\ \mathrm{ft/s^2}$. Actually, g varies slightly according to latitude and elevation on the Earth's surface, but these variations are so small that we will ignore them for most purposes. (Acceleration of gravity in space beyond the Earth's surface is treated in Chapter 5.) The effects of air resistance are often small, and we will neglect them for the most part. However, air resistance will be noticeable even on a reasonably heavy object if the velocity becomes large.† Acceleration due to gravity is a vector, as is any acceleration, and its direction is downward toward the center of the Earth.

When dealing with freely falling objects we can make use of Eqs. 2–11, where for a we use the value of g given above. Also, since the motion is vertical we will substitute y in place of x, and y_0 in place of x_0. We take $y_0 = 0$ unless otherwise specified. *It is arbitrary whether we choose y to be positive in the upward direction or in the downward direction; but we must be consistent about it throughout a problem's solution.*

PROBLEM SOLVING
You can choose y to be positive either up or down

EXERCISE E Return to the Chapter-Opening Question, page 21, and answer it again now, assuming minimal air resistance. Try to explain why you may have answered differently the first time.

FIGURE 2–22 Example 2–10. (a) An object dropped from a tower falls with progressively greater speed and covers greater distance with each successive second. (See also Fig. 2–19.) (b) Graph of y vs. t.



EXAMPLE 2–10 **Falling from a tower.** Suppose that a ball is dropped ($v_0 = 0$) from a tower. How far will it have fallen after a time $t_1 = 1.00\ \mathrm{s}$, $t_2 = 2.00\ \mathrm{s}$, and $t_3 = 3.00\ \mathrm{s}$? Ignore air resistance.

APPROACH Let us take y as positive downward, so the acceleration is $a = g = +9.80\ \mathrm{m/s^2}$. We set $v_0 = 0$ and $y_0 = 0$. We want to find the position y of the ball after three different time intervals. Equation 2–11b, with x replaced by y, relates the given quantities (t, a, and v_0) to the unknown y.

SOLUTION We set $t = t_1 = 1.00\ \mathrm{s}$ in Eq. 2–11b:

$$\begin{aligned} y_1 &= v_0 t_1 + \tfrac{1}{2} a t_1^2 \\ &= 0 + \tfrac{1}{2} a t_1^2 = \tfrac{1}{2}(9.80\ \mathrm{m/s^2})(1.00\ \mathrm{s})^2 = 4.90\ \mathrm{m}. \end{aligned}$$

The ball has fallen a distance of 4.90 m during the time interval $t = 0$ to $t_1 = 1.00\ \mathrm{s}$. Similarly, after 2.00 s $(= t_2)$, the ball's position is

$$y_2 = \tfrac{1}{2} a t_2^2 = \tfrac{1}{2}(9.80\ \mathrm{m/s^2})(2.00\ \mathrm{s})^2 = 19.6\ \mathrm{m}.$$

Finally, after 3.00 s $(= t_3)$, the ball's position is (see Fig. 2–22)

$$y_3 = \tfrac{1}{2} a t_3^2 = \tfrac{1}{2}(9.80\ \mathrm{m/s^2})(3.00\ \mathrm{s})^2 = 44.1\ \mathrm{m}.$$

NOTE Whenever we say "dropped," it means $v_0 = 0$. Note also the graph of y vs. t (Fig. 2–22b): the curve is not straight but bends upward because y is proportional to t^2.

†The speed of an object falling in air (or other fluid) does not increase indefinitely. If the object falls far enough, it will reach a maximum velocity called the **terminal velocity** due to air resistance.

EXAMPLE 2–11 **Thrown down from a tower.** Suppose the ball in Example 2–10 is *thrown* downward with an initial velocity of 3.00 m/s, instead of being dropped. (*a*) What then would be its position after 1.00 s and 2.00 s? (*b*) What would its speed be after 1.00 s and 2.00 s? Compare with the speeds of a dropped ball.

APPROACH Again we use Eq. 2–11b, but now v_0 is not zero, it is $v_0 = 3.00\,\mathrm{m/s}$.

SOLUTION (*a*) At $t_1 = 1.00\,\mathrm{s}$, the position of the ball as given by Eq. 2–11b is

$$y = v_0 t + \tfrac{1}{2}at^2 = (3.00\,\mathrm{m/s})(1.00\,\mathrm{s}) + \tfrac{1}{2}(9.80\,\mathrm{m/s^2})(1.00\,\mathrm{s})^2 = 7.90\,\mathrm{m}.$$

At $t_2 = 2.00\,\mathrm{s}$ (time interval $t = 0$ to $t = 2.00\,\mathrm{s}$), the position is

$$y = v_0 t + \tfrac{1}{2}at^2 = (3.00\,\mathrm{m/s})(2.00\,\mathrm{s}) + \tfrac{1}{2}(9.80\,\mathrm{m/s^2})(2.00\,\mathrm{s})^2 = 25.6\,\mathrm{m}.$$

As expected, the ball falls farther each second than if it were dropped with $v_0 = 0$.

(*b*) The velocity is obtained from Eq. 2–11a:

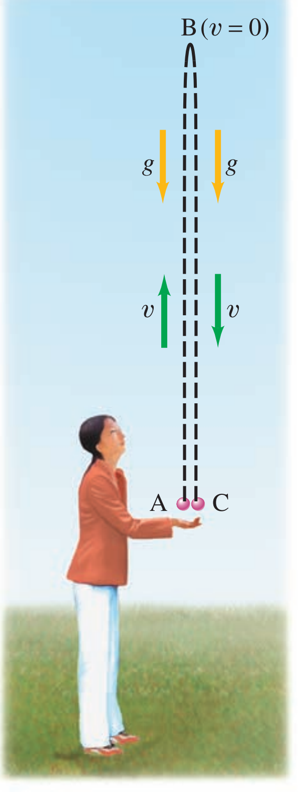
$$\begin{aligned} v &= v_0 + at \\ &= 3.00\,\mathrm{m/s} + (9.80\,\mathrm{m/s^2})(1.00\,\mathrm{s}) = 12.8\,\mathrm{m/s} \quad [\text{at } t_1 = 1.00\,\mathrm{s}] \\ &= 3.00\,\mathrm{m/s} + (9.80\,\mathrm{m/s^2})(2.00\,\mathrm{s}) = 22.6\,\mathrm{m/s}. \quad [\text{at } t_2 = 2.00\,\mathrm{s}] \end{aligned}$$

In Example 2–10, when the ball was dropped $(v_0 = 0)$, the first term (v_0) in these equations was zero, so

$$\begin{aligned} v &= 0 + at \\ &= (9.80\,\mathrm{m/s^2})(1.00\,\mathrm{s}) = 9.80\,\mathrm{m/s} \quad [\text{at } t_1 = 1.00\,\mathrm{s}] \\ &= (9.80\,\mathrm{m/s^2})(2.00\,\mathrm{s}) = 19.6\,\mathrm{m/s}. \quad [\text{at } t_2 = 2.00\,\mathrm{s}] \end{aligned}$$

NOTE For both Examples 2–10 and 2–11, the speed increases linearly in time by 9.80 m/s during each second. But the speed of the downwardly thrown ball at any instant is always 3.00 m/s (its initial speed) higher than that of a dropped ball.

FIGURE 2–23 An object thrown into the air leaves the thrower's hand at A, reaches its maximum height at B, and returns to the original position at C. Examples 2–12, 2–13, 2–14, and 2–15.



EXAMPLE 2–12 **Ball thrown upward.** A person throws a ball *upward* into the air with an initial velocity of 15.0 m/s. Calculate how high it goes. Ignore air resistance.

APPROACH We are not concerned here with the throwing action, but only with the motion of the ball *after* it leaves the thrower's hand (Fig. 2–23) and until it comes back to the hand again. Let us choose y to be positive in the upward direction and negative in the downward direction. (This is a different convention from that used in Examples 2–10 and 2–11, and so illustrates our options.) The acceleration due to gravity is downward and so will have a negative sign, $a = -g = -9.80\,\mathrm{m/s^2}$. As the ball rises, its speed decreases until it reaches the highest point (B in Fig. 2–23), where its speed is zero for an instant; then it descends, with increasing speed.

SOLUTION We consider the time interval from when the ball leaves the thrower's hand until the ball reaches the highest point. To determine the maximum height, we calculate the position of the ball when its velocity equals zero ($v = 0$ at the highest point). At $t = 0$ (point A in Fig. 2–23) we have $y_0 = 0$, $v_0 = 15.0\,\mathrm{m/s}$, and $a = -9.80\,\mathrm{m/s^2}$. At time t (maximum height), $v = 0$, $a = -9.80\,\mathrm{m/s^2}$, and we wish to find y. We use Eq. 2–11c, replacing x with y: $v^2 = v_0^2 + 2ay$. We solve this equation for y:

$$y = \frac{v^2 - v_0^2}{2a} = \frac{0 - (15.0\,\mathrm{m/s})^2}{2(-9.80\,\mathrm{m/s^2})} = 11.5\,\mathrm{m}.$$

The ball reaches a height of 11.5 m above the hand.

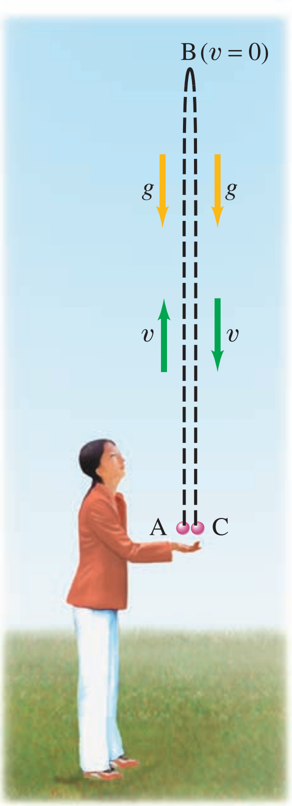


FIGURE 2–23 (Repeated.) An object thrown into the air leaves the thrower's hand at A, reaches its maximum height at B, and returns to the original position at C. Examples 2–12, 2–13, 2–14, and 2–15.

EXAMPLE 2–13 **Ball thrown upward, II.** In Fig. 2–23, Example 2–12, how long is the ball in the air before it comes back to the hand?

APPROACH We need to choose a time interval to calculate how long the ball is in the air before it returns to the hand. We could do this calculation in two parts by first determining the time required for the ball to reach its highest point, and then determining the time it takes to fall back down. However, it is simpler to consider the time interval for the entire motion from A to B to C (Fig. 2–23) in one step and use Eq. 2–11b. We can do this because y is position or displacement, and not the total distance traveled. Thus, at both points A and C, $y = 0$.

SOLUTION We use Eq. 2–11b with $a = -9.80\,\mathrm{m/s^2}$ and find

$$y = y_0 + v_0 t + \tfrac{1}{2}at^2$$
$$0 = 0 + (15.0\,\mathrm{m/s})t + \tfrac{1}{2}\left(-9.80\,\mathrm{m/s^2}\right)t^2.$$

This equation can be factored (we factor out one t):

$$\left(15.0\,\mathrm{m/s} - 4.90\,\mathrm{m/s^2}\,t\right)t = 0.$$

There are two solutions:

$$t = 0 \quad \text{and} \quad t = \frac{15.0\,\mathrm{m/s}}{4.90\,\mathrm{m/s^2}} = 3.06\,\mathrm{s}.$$

The first solution $(t = 0)$ corresponds to the initial point (A) in Fig. 2–23, when the ball was first thrown from $y = 0$. The second solution, $t = 3.06\,\mathrm{s}$, corresponds to point C, when the ball has returned to $y = 0$. Thus the ball is in the air 3.06 s.

NOTE We have ignored air resistance in these last two Examples, which could be significant, so our result is only an approximation to a real, practical situation.

We did not consider the throwing action in these Examples. Why? Because during the throw, the thrower's hand is touching the ball and accelerating the ball at a rate unknown to us—the acceleration is *not* g. We consider only the time when the ball is in the air and the acceleration is equal to g.

Every quadratic equation (where the variable is squared) mathematically produces two solutions. In physics, sometimes only one solution corresponds to the real situation, as in Example 2–8, in which case we ignore the "unphysical" solution. But in Example 2–13, both solutions to our equation in t^2 are physically meaningful: $t = 0$ and $t = 3.06\,\mathrm{s}$.

CAUTION

Quadratic equations have two solutions. Sometimes only one corresponds to reality, sometimes both

CONCEPTUAL EXAMPLE 2–14 **Two possible misconceptions.** Give examples to show the error in these two common misconceptions: (1) that acceleration and velocity are always in the same direction, and (2) that an object thrown upward has zero acceleration at the highest point (B in Fig. 2–23).

RESPONSE Both are wrong. (1) Velocity and acceleration are *not* necessarily in the same direction. When the ball in Fig. 2–23 is moving upward, its velocity is positive (upward), whereas the acceleration is negative (downward). (2) At the highest point (B in Fig. 2–23), the ball has zero velocity for an instant. Is the acceleration also zero at this point? No. The velocity near the top of the arc points upward, then becomes zero for an instant (zero time) at the highest point, and then points downward. Gravity does not stop acting, so $a = -g = -9.80\,\mathrm{m/s^2}$ even there. Thinking that $a = 0$ at point B would lead to the conclusion that upon reaching point B, the ball would stay there: if the acceleration (= rate of change of velocity) were zero, the velocity would stay zero at the highest point, and the ball would stay up there without falling. Remember: the acceleration of gravity always points down toward the Earth, even when the object is moving up.

CAUTION

(1) Velocity and acceleration are not always in the same direction; the acceleration (of gravity) always points down

(2) $a \neq 0$ even at the highest point of a trajectory

EXAMPLE 2–15 **Ball thrown upward, III.** Let us consider again the ball thrown upward of Examples 2–12 and 2–13, and make more calculations. Calculate (*a*) how much time it takes for the ball to reach the maximum height (point B in Fig. 2–23), and (*b*) the velocity of the ball when it returns to the thrower's hand (point C).

APPROACH Again we assume the acceleration is constant, so we can use Eqs. 2–11. We have the maximum height of 11.5 m and initial speed of 15.0 m/s from Example 2–12. Again we take y as positive upward.

SOLUTION (*a*) We consider the time interval between the throw $(t = 0, v_0 = 15.0\,\mathrm{m/s})$ and the top of the path $(y = +11.5\,\mathrm{m},\ v = 0)$, and we want to find t. The acceleration is constant at $a = -g = -9.80\,\mathrm{m/s^2}$. Both Eqs. 2–11a and 2–11b contain the time t with other quantities known. Let us use Eq. 2–11a with $a = -9.80\,\mathrm{m/s^2}$, $v_0 = 15.0\,\mathrm{m/s}$, and $v = 0$:

$$v = v_0 + at;$$

setting $v = 0$ gives $0 = v_0 + at$, which we rearrange to solve for t: $at = -v_0$ or

$$\begin{aligned} t &= -\frac{v_0}{a} \\ &= -\frac{15.0\,\mathrm{m/s}}{-9.80\,\mathrm{m/s^2}} = 1.53\,\mathrm{s}. \end{aligned}$$

This is just half the time it takes the ball to go up and fall back to its original position [3.06 s, calculated in Example 2–13]. Thus it takes the same time to reach the maximum height as to fall back to the starting point.

(*b*) Now we consider the time interval from the throw $(t = 0, v_0 = 15.0\,\mathrm{m/s})$ until the ball's return to the hand, which occurs at $t = 3.06\,\mathrm{s}$ (as calculated in Example 2–13), and we want to find v when $t = 3.06\,\mathrm{s}$:

$$\begin{aligned} v &= v_0 + at \\ &= 15.0\,\mathrm{m/s} - (9.80\,\mathrm{m/s^2})(3.06\,\mathrm{s}) = -15.0\,\mathrm{m/s}. \end{aligned}$$

NOTE The ball has the same speed (magnitude of velocity) when it returns to the starting point as it did initially, but in the opposite direction (this is the meaning of the negative sign). And, as we saw in part (*a*), the time is the same up as down. Thus the motion is *symmetrical* about the maximum height.

PROBLEM SOLVING
Acceleration in g's

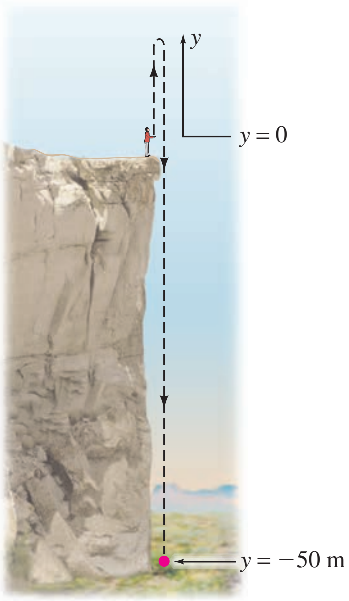
The acceleration of objects such as rockets and fast airplanes is often given as a multiple of $g = 9.80\,\mathrm{m/s^2}$. For example, a plane pulling out of a dive (see Fig. 2–24) and undergoing $3.00\,g$'s would have an acceleration of $(3.00)(9.80\,\mathrm{m/s^2}) = 29.4\,\mathrm{m/s^2}$.

FIGURE 2–24 Several planes, in formation, are just coming out of a downward dive.

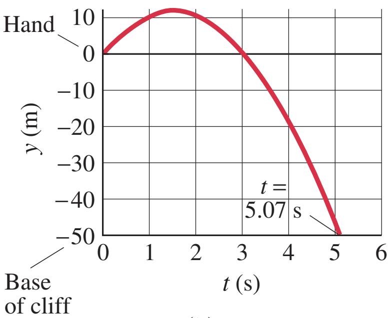
EXERCISE F Two balls are thrown from a cliff. One is thrown directly up, the other directly down. Both balls have the same initial speed, and both hit the ground below the cliff but at different times. Which ball hits the ground at the greater speed: (*a*) the ball thrown upward, (*b*) the ball thrown downward, or (*c*) both the same? Ignore air resistance.

Additional Example—Using the Quadratic Formula

EXAMPLE 2–16 Ball thrown upward at edge of cliff. Suppose that the person of Examples 2–12, 2–13, and 2–15 throws the ball upward at 15.0 m/s while standing on the edge of a cliff, so that the ball can fall to the base of the cliff 50.0 m below, as shown in Fig. 2–25a. (*a*) How long does it take the ball to reach the base of the cliff? (*b*) What is the total distance traveled by the ball? Ignore air resistance (likely to be significant, so our result is an approximation).



(a)



(b)

FIGURE 2–25 Example 2–16. (a) A person stands on the edge of a cliff. A ball is thrown upward, then falls back down past the thrower to the base of the cliff, 50.0 m below. (b) The y vs. t graph.

APPROACH We again use Eq. 2–11b, with y as + upward, but this time we set $y = -50.0\text{ m}$, the bottom of the cliff, which is 50.0 m below the initial position $(y_0 = 0)$; hence the minus sign.

SOLUTION (*a*) We use Eq. 2–11b with $a = -9.80\text{ m/s}^2$, $v_0 = 15.0\text{ m/s}$, $y_0 = 0$, and $y = -50.0\text{ m}$:

$$\begin{aligned} y &= y_0 + v_0 t + \tfrac{1}{2}at^2 \\ -50.0\text{ m} &= 0 + (15.0\text{ m/s})t - \tfrac{1}{2}(9.80\text{ m/s}^2)t^2. \end{aligned}$$

To solve any quadratic equation of the form

$$at^2 + bt + c = 0,$$

where a, b, and c are constants (a is *not* acceleration here), we use the **quadratic formula** (see Appendix A–4):

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

We rewrite our y equation just above in standard form, $at^2 + bt + c = 0$:

$$(4.90\text{ m/s}^2)t^2 - (15.0\text{ m/s})t - (50.0\text{ m}) = 0.$$

Using the quadratic formula, we find as solutions

$$t = 5.07\text{ s}$$

and

$$t = -2.01\text{ s}.$$

The first solution, $t = 5.07\text{ s}$, is the answer we are seeking: the time it takes the ball to rise to its highest point and then fall to the base of the cliff. To rise and fall back to the top of the cliff took 3.06 s (Example 2–13); so it took an additional 2.01 s to fall to the base. But what is the meaning of the other solution, $t = -2.01\text{ s}$? This is a time before the throw, when our calculation begins, so it isn't relevant here. It is outside our chosen time interval, and so is an *unphysical* solution (also in Example 2–8).

CAUTION

Sometimes a solution to a quadratic equation does not apply to the actual physical conditions of the Problem

(*b*) From Example 2–12, the ball moves up 11.5 m, falls 11.5 m back down to the top of the cliff, and then down another 50.0 m to the base of the cliff, for a total distance traveled of 73.0 m. [Note that the *displacement*, however, was −50.0 m.] Figure 2–25b shows the y vs. t graph for this situation.

2–8 Graphical Analysis of Linear Motion

Velocity as Slope

Analysis of motion using graphs can give us additional insight into kinematics. Let us draw a graph of x vs. t, making the choice that at $t = 0$, the position of an object is $x = 0$, and the object is moving at a constant velocity, $v = \bar{v} = 11\ \mathrm{m/s}$ ($40\ \mathrm{km/h}$). Our graph starts at $x = 0$, $t = 0$ (the origin). The graph of the position increases linearly in time because, by Eq. 2–2, $\Delta x = \bar{v}\,\Delta t$ and $\bar{v}$ is a constant. So the graph of x vs. t is a straight line, as shown in Fig. 2–26. The small (shaded) triangle on the graph indicates the **slope** of the straight line:

$$\text{slope} = \frac{\Delta x}{\Delta t}.$$

We see, using the definition of average velocity (Eq. 2–2), that the *slope of the x vs. t graph is equal to the velocity*. And, as can be seen from the small triangle on the graph, $\Delta x/\Delta t = (11\ \mathrm{m})/(1.0\ \mathrm{s}) = 11\ \mathrm{m/s}$, which is the given velocity.

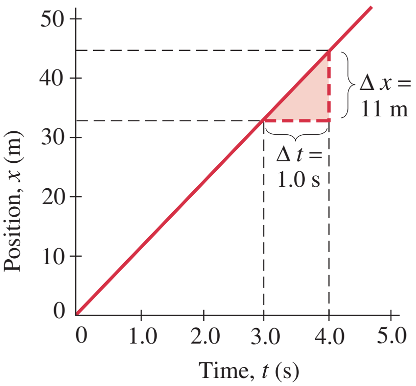
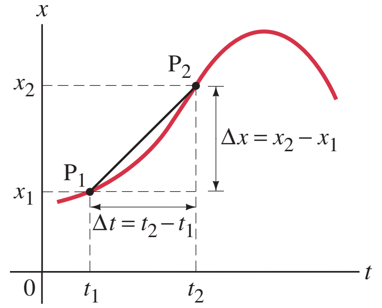


FIGURE 2–26 Graph of position vs. time for an object moving at a constant velocity of 11 m/s.

If the object's velocity changes in time, we might have an x vs. t graph like that shown in Fig. 2–27. (Note that this graph is different from showing the "path" of an object on an x vs. y plot.) Suppose the object is at position x_1 at time t_1, and at position x_2 at time t_2. P_1 and P_2 represent these two points on the graph. A straight line drawn from point $P_1(x_1, t_1)$ to point $P_2(x_2, t_2)$ forms the hypotenuse of a right triangle whose sides are Δx and Δt. The ratio $\Delta x/\Delta t$ is the **slope** of the straight line P_1P_2. But $\Delta x/\Delta t$ is also the average velocity of the object during the time interval $\Delta t = t_2 - t_1$. Therefore, we conclude that the *average velocity of an object during any time interval $\Delta t = t_2 - t_1$ is equal to the slope of the straight line* (or **chord**) connecting the two points (x_1, t_1) and (x_2, t_2) on an x vs. t graph.

FIGURE 2–27 Graph of an object's position x vs. time t. The slope of the straight line P_1P_2 represents the average velocity of the object during the time interval $\Delta t = t_2 - t_1$.



Consider now a time intermediate between t_1 and t_2, call it t_3, at which moment the object is at x_3 (Fig. 2–28). The slope of the straight line P_1P_3 is less than the slope of P_1P_2. Thus the average velocity during the time interval $t_3 - t_1$ is less than during the time interval $t_2 - t_1$.

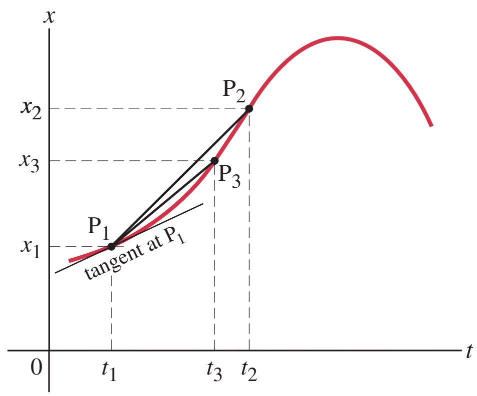


FIGURE 2–28 Same position vs. time curve as in Fig. 2–27. Note that the average velocity over the time interval $t_3 - t_1$ (which is the slope of P_1P_3) is less than the average velocity over the time interval $t_2 - t_1$. The slope of the line tangent to the curve at point P_1 equals the *instantaneous* velocity at time t_1.

Next let us take point P_3 in Fig. 2–28 to be closer and closer to point P_1. That is, we let the interval $t_3 - t_1$, which we now call Δt, to become smaller and smaller. The slope of the line connecting the two points becomes closer and closer to the slope of a line **tangent**† to the curve at point P_1. The average velocity (equal to the slope of the chord) thus approaches the slope of the tangent at point P_1. The definition of the instantaneous velocity (Eq. 2–3) is the limiting value of the average velocity as Δt approaches zero. Thus the *instantaneous velocity equals the slope of the tangent to the curve of x vs. t* at any chosen point (which we can simply call "the slope of the curve" at that point).

PROBLEM SOLVING
Velocity equals slope of x vs. t graph at any instant

†The tangent is a straight line that touches the curve only at the one chosen point, without passing across or through the curve at that point.

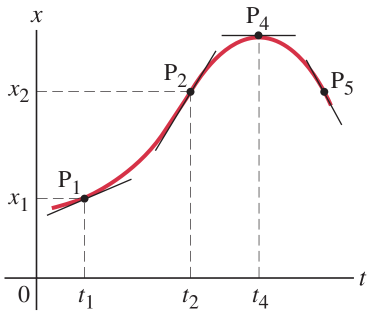
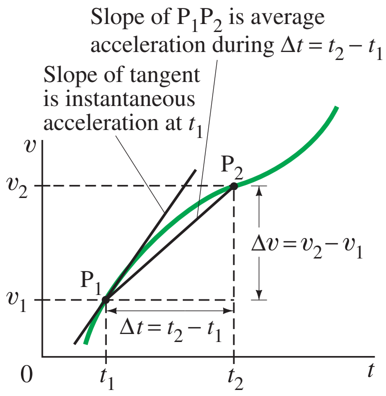


FIGURE 2–29 Same x vs. t curve as in Figs. 2–27 and 2–28, but here showing the slope at four different points: At P_4, the slope is zero, so $v = 0$. At P_5 the slope is negative, so $v < 0$.

We can obtain the velocity of an object at any instant from its graph of x vs. t. For example, in Fig. 2–29 (which shows the same graph as in Figs. 2–27 and 2–28), as our object moves from x_1 to x_2, the slope continually increases, so the velocity is increasing. For times after t_2, the slope begins to decrease and reaches zero $(v = 0)$ where x has its maximum value, at point P_4 in Fig. 2–29. Beyond point P_4, the slope is negative, as for point P_5. The velocity is therefore negative, which makes sense since x is now decreasing—the particle is moving toward decreasing values of x, to the left on a standard xy plot.

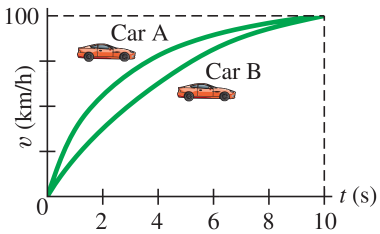
FIGURE 2–30 A graph of velocity v vs. time t. The average acceleration over a time interval $\Delta t = t_2 - t_1$ is the slope of the straight line P_1P_2: $\bar{a} = \Delta v/\Delta t$. The instantaneous acceleration at time t_1 is the slope of the v vs. t curve at that instant.



Slope and Acceleration

We can also draw a graph of the *velocity*, v, vs. time, t, as shown in Fig. 2–30. Then the average acceleration over a time interval $\Delta t = t_2 - t_1$ is represented by the slope of the straight line connecting the two points P_1 and P_2 as shown. [Compare this to the position vs. time graph of Fig. 2–27 for which the slope of the straight line represents the average velocity.] The instantaneous acceleration at any time, say t_1, is the slope of the tangent to the v vs. t curve at that time, which is also shown in Fig. 2–30. Using this fact for the situation graphed in Fig. 2–30, as we go from time t_1 to time t_2 the velocity continually increases, but the acceleration (the rate at which the velocity changes) is decreasing since the slope of the curve is decreasing.

FIGURE 2–31 (below) Example 2–17.



CONCEPTUAL EXAMPLE 2–17 **Analyzing with graphs.** Figure 2–31 shows the velocity as a function of time for two cars accelerating from 0 to 100 km/h in a time of 10.0 s. Compare (*a*) the average acceleration; (*b*) the instantaneous acceleration; and (*c*) the total distance traveled for the two cars.

RESPONSE (*a*) Average acceleration is $\Delta v/\Delta t$. Both cars have the same Δv (100 km/h) over the same time interval $\Delta t = 10.0$ s, so the average acceleration is the same for both cars. (*b*) Instantaneous acceleration is the slope of the tangent to the v vs. t curve. For the first 4 s or so, the top curve (car A) is steeper than the bottom curve, so car A has a greater acceleration during this interval. The bottom curve is steeper during the last 6 s, so car B has the larger acceleration for this period. (*c*) Except at $t = 0$ and $t = 10.0$ s, car A is always going faster than car B. Since it is going faster, it will go farther in the same time.

Summary

[*The Summary that appears at the end of each Chapter in this book gives a brief overview of the main ideas of the Chapter. The Summary* cannot *serve to give an understanding of the material, which can be accomplished only by a detailed reading of the Chapter.*]

Kinematics deals with the description of how objects move. The description of the motion of any object must always be given relative to some particular **reference frame**.

The **displacement** of an object is the change in position of the object.

Average speed is the distance traveled divided by the **elapsed time** or **time interval**, Δt (the time period over which we choose to make our observations). An object's **average velocity** over a particular time interval is

$$\bar{v} = \frac{\Delta x}{\Delta t}, \qquad \textbf{(2–2)}$$

where Δx is the displacement during the time interval Δt.

The **instantaneous velocity**, whose magnitude is the same as the *instantaneous speed*, is defined as the average velocity taken over an infinitesimally short time interval.

Acceleration is the change of velocity per unit time. An object's **average acceleration** over a time interval Δt is

$$\bar{a} = \frac{\Delta v}{\Delta t}, \tag{2–4}$$

where Δv is the change of velocity during the time interval Δt. **Instantaneous acceleration** is the average acceleration taken over an infinitesimally short time interval.

If an object has position x_0 and velocity v_0 at time $t = 0$ and moves in a straight line with **constant acceleration**, the velocity v and position x at a later time t are related to the acceleration a, the initial position x_0, and the initial velocity v_0 by Eqs. 2–11:

$$\begin{aligned} v &= v_0 + at, \\ x &= x_0 + v_0 t + \tfrac{1}{2}at^2, \\ v^2 &= v_0^2 + 2a(x - x_0), \\ \bar{v} &= \frac{v + v_0}{2}. \end{aligned} \tag{2–11}$$

Objects that move vertically near the surface of the Earth, either falling or having been projected vertically up or down, move with the constant downward **acceleration due to gravity**, whose magnitude is $g = 9.80\,\text{m/s}^2$ if air resistance can be ignored. We can apply Eqs. 2–11 for constant acceleration to objects that move up or down freely near the Earth's surface.

The slope of a curve at any point on a graph is the slope of the tangent to the curve at that point. On a graph of position vs. time, the **slope** is equal to the instantaneous velocity. On a graph of velocity vs. time, the slope is the acceleration.

Questions

1. Does a car speedometer measure speed, velocity, or both? Explain.

2. When an object moves with constant velocity, does its average velocity during any time interval differ from its instantaneous velocity at any instant? Explain.

3. If one object has a greater speed than a second object, does the first necessarily have a greater acceleration? Explain, using examples.

4. Compare the acceleration of a motorcycle that accelerates from 80 km/h to 90 km/h with the acceleration of a bicycle that accelerates from rest to 10 km/h in the same time.

5. Can an object have a northward velocity and a southward acceleration? Explain.

6. Can the velocity of an object be negative when its acceleration is positive? What about vice versa? If yes, give examples in each case.

7. Give an example where both the velocity and acceleration are negative.

8. Can an object be increasing in speed as its acceleration decreases? If so, give an example. If not, explain.

9. Two cars emerge side by side from a tunnel. Car A is traveling with a speed of 60 km/h and has an acceleration of 40 km/h/min. Car B has a speed of 40 km/h and has an acceleration of 60 km/h/min. Which car is passing the other as they come out of the tunnel? Explain your reasoning.

10. A baseball player hits a ball straight up into the air. It leaves the bat with a speed of 120 km/h. In the absence of air resistance, how fast would the ball be traveling when it is caught at the same height above the ground as it left the bat? Explain.

11. As a freely falling object speeds up, what is happening to its acceleration—does it increase, decrease, or stay the same? (*a*) Ignore air resistance. (*b*) Consider air resistance.

12. You travel from point A to point B in a car moving at a constant speed of 70 km/h. Then you travel the same distance from point B to another point C, moving at a constant speed of 90 km/h. Is your average speed for the entire trip from A to C equal to 80 km/h? Explain why or why not.

13. Can an object have zero velocity and nonzero acceleration at the same time? Give examples.

14. Can an object have zero acceleration and nonzero velocity at the same time? Give examples.

15. Which of these motions is *not* at constant acceleration: a rock falling from a cliff, an elevator moving from the second floor to the fifth floor making stops along the way, a dish resting on a table? Explain your answers.

16. Describe in words the motion plotted in Fig. 2–32 in terms of velocity, acceleration, etc. [*Hint*: First try to duplicate the motion plotted by walking or moving your hand.]

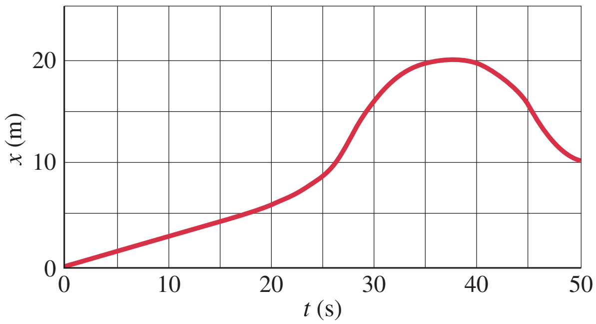


FIGURE 2–32 Question 16.

17. Describe in words the motion of the object graphed in Fig. 2–33.

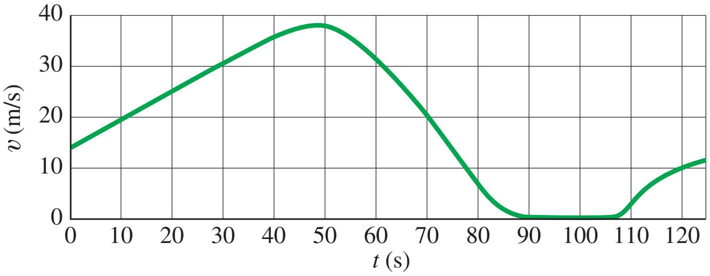


FIGURE 2–33 Question 17.

MisConceptual Questions

[List all answers that are valid.]

1. Which of the following should be part of solving any problem in physics? Select all that apply:
(*a*) Read the problem carefully.
(*b*) Draw a picture of the situation.
(*c*) Write down the variables that are given.
(*d*) Think about which physics principles to apply.
(*e*) Determine which equations can be used to apply the correct physics principles.
(*f*) Check the units when you have completed your calculation.
(*g*) Consider whether your answer is reasonable.

2. In which of the following cases does a car have a negative velocity and a positive acceleration? A car that is traveling in the
(*a*) $-x$ direction at a constant 20 m/s.
(*b*) $-x$ direction increasing in speed.
(*c*) $+x$ direction increasing in speed.
(*d*) $-x$ direction decreasing in speed.
(*e*) $+x$ direction decreasing in speed.

3. At time $t = 0$ an object is traveling to the right along the $+x$ axis at a speed of 10.0 m/s with acceleration $-2.0\ \mathrm{m/s^2}$. Which statement is true?
(*a*) The object will slow down, eventually coming to a complete stop.
(*b*) The object cannot have a negative acceleration and be moving to the right.
(*c*) The object will continue to move to the right, slowing down but never coming to a complete stop.
(*d*) The object will slow down, momentarily stopping, then pick up speed moving to the left.

4. A ball is thrown straight up. What are the velocity and acceleration of the ball at the highest point in its path?
(*a*) $v = 0,\ a = 0$.
(*b*) $v = 0,\ a = 9.8\ \mathrm{m/s^2}$ up.
(*c*) $v = 0,\ a = 9.8\ \mathrm{m/s^2}$ down.
(*d*) $v = 9.8$ m/s up, $a = 0$.
(*e*) $v = 9.8$ m/s down, $a = 0$.

5. You drop a rock off a bridge. When the rock has fallen 4 m, you drop a second rock. As the two rocks continue to fall, what happens to their velocities?
(*a*) Both increase at the same rate.
(*b*) The velocity of the first rock increases faster than the velocity of the second.
(*c*) The velocity of the second rock increases faster than the velocity of the first.
(*d*) Both velocities stay constant.

6. You drive 4 km at 30 km/h and then another 4 km at 50 km/h. What is your average speed for the whole 8-km trip?
(*a*) More than 40 km/h.
(*b*) Equal to 40 km/h.
(*c*) Less than 40 km/h.
(*d*) Not enough information.

7. A ball is dropped from the top of a tall building. At the same instant, a second ball is thrown upward from ground level. When the two balls pass one another, one on the way up, the other on the way down, compare the magnitudes of their acceleration:
(*a*) The acceleration of the dropped ball is greater.
(*b*) The acceleration of the ball thrown upward is greater.
(*c*) The acceleration of both balls is the same.
(*d*) The acceleration changes during the motion, so you cannot predict the exact value when the two balls pass each other.
(*e*) The accelerations are in opposite directions.

8. A ball is thrown downward at a speed of 20 m/s. Choosing the $+y$ axis pointing up and neglecting air resistance, which equation(s) could be used to solve for other variables? The acceleration due to gravity is $g = 9.8\ \mathrm{m/s^2}$ downward.
(*a*) $v = (20\ \mathrm{m/s}) - gt$.
(*b*) $y = y_0 + (-20\ \mathrm{m/s})t - (1/2)gt^2$.
(*c*) $v^2 = (20\ \mathrm{m/s})^2 - 2g(y - y_0)$.
(*d*) $(20\ \mathrm{m/s}) = (v + v_0)/2$.
(*e*) All of the above.

9. A car travels along the x axis with increasing speed. We don't know if to the left or the right. Which of the graphs in Fig. 2–34 most closely represents the motion of the car?

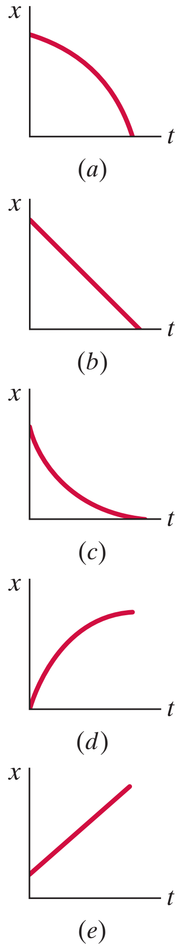


FIGURE 2–34 MisConceptual Question 9.

Problems

[*The Problems at the end of each Chapter are ranked* I, II, *or* III *according to estimated difficulty, with level* I *Problems being easiest. Level* III *are meant as challenges for the best students. The Problems are arranged by Section, meaning that the reader should have read up to and including that Section, but not only that Section—Problems often depend on earlier material. Next is a set of "General Problems" not arranged by Section and not ranked. Finally, there are "Search and Learn" Problems that require rereading parts of the Chapter and sometimes earlier Chapters.*]

(Note: *In Problems, assume a number like* 6.4 *is accurate to* $\pm$ 0.1; *and* 950 *is* $\pm$ 10 *unless* 950 *is said to be "precisely" or "very nearly"* 950, *in which case assume* 950 $\pm$ 1. *See Section 1–4.*)

2–1 to 2–3 Speed and Velocity

1. (I) If you are driving 95 km/h along a straight road and you look to the side for 2.0 s, how far do you travel during this inattentive period?
2. (I) What must your car's average speed be in order to travel 235 km in 2.75 h?
3. (I) A particle at $t_1 = -2.0\,\mathrm{s}$ is at $x_1 = 4.8\,\mathrm{cm}$ and at $t_2 = 4.5\,\mathrm{s}$ is at $x_2 = 8.5\,\mathrm{cm}$. What is its average velocity over this time interval? Can you calculate its average speed from these data? Why or why not?
4. (I) A rolling ball moves from $x_1 = 8.4\,\mathrm{cm}$ to $x_2 = -4.2\,\mathrm{cm}$ during the time from $t_1 = 3.0\,\mathrm{s}$ to $t_2 = 6.1\,\mathrm{s}$. What is its average velocity over this time interval?
5. (I) A bird can fly 25 km/h. How long does it take to fly 3.5 km?
6. (II) According to a rule-of-thumb, each five seconds between a lightning flash and the following thunder gives the distance to the flash in miles. (*a*) Assuming that the flash of light arrives in essentially no time at all, estimate the speed of sound in m/s from this rule. (*b*) What would be the rule for kilometers?
7. (II) You are driving home from school steadily at 95 km/h for 180 km. It then begins to rain and you slow to 65 km/h. You arrive home after driving 4.5 h. (*a*) How far is your hometown from school? (*b*) What was your average speed?
8. (II) A horse trots away from its trainer in a straight line, moving 38 m away in 9.0 s. It then turns abruptly and gallops halfway back in 1.8 s. Calculate (*a*) its average speed and (*b*) its average velocity for the entire trip, using "away from the trainer" as the positive direction.
9. (II) A person jogs eight complete laps around a 400-m track in a total time of 14.5 min. Calculate (*a*) the average speed and (*b*) the average velocity, in m/s.
10. (II) Every year the Earth travels about 10^9 km as it orbits the Sun. What is Earth's average speed in km/h?
11. (II) A car traveling 95 km/h is 210 m behind a truck traveling 75 km/h. How long will it take the car to reach the truck?
12. (II) Calculate the average speed and average velocity of a complete round trip in which the outgoing 250 km is covered at 95 km/h, followed by a 1.0-h lunch break, and the return 250 km is covered at 55 km/h.
13. (II) Two locomotives approach each other on parallel tracks. Each has a speed of 155 km/h with respect to the ground. If they are initially 8.5 km apart, how long will it be before they reach each other? (See Fig. 2–35.)

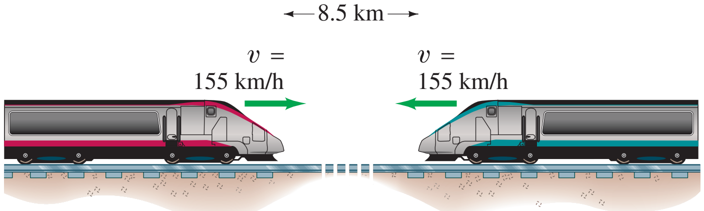


FIGURE 2–35 Problem 13.

14. (II) Digital bits on a 12.0-cm diameter audio CD are encoded along an outward spiraling path that starts at radius $R_1 = 2.5\,\mathrm{cm}$ and finishes at radius $R_2 = 5.8\,\mathrm{cm}$. The distance between the centers of neighboring spiral-windings is $1.6\,\mu\mathrm{m}$ $(= 1.6 \times 10^{-6}\,\mathrm{m})$. (*a*) Determine the total length of the spiraling path. [*Hint*: Imagine "unwinding" the spiral into a straight path of width $1.6\,\mu\mathrm{m}$, and note that the original spiral and the straight path both occupy the same area.] (*b*) To read information, a CD player adjusts the rotation of the CD so that the player's readout laser moves along the spiral path at a constant speed of about 1.2 m/s. Estimate the maximum playing time of such a CD.
15. (III) A bowling ball traveling with constant speed hits the pins at the end of a bowling lane 16.5 m long. The bowler hears the sound of the ball hitting the pins 2.80 s after the ball is released from his hands. What is the speed of the ball, assuming the speed of sound is 340 m/s?
16. (III) An automobile traveling 95 km/h overtakes a 1.30-km-long train traveling in the same direction on a track parallel to the road. If the train's speed is 75 km/h, how long does it take the car to pass it, and how far will the car have traveled in this time? See Fig. 2–36. What are the results if the car and train are traveling in opposite directions?

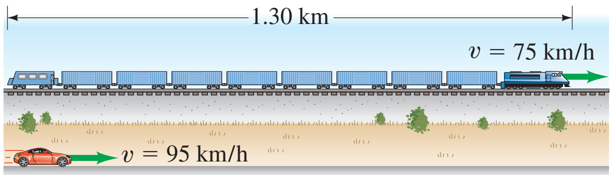


FIGURE 2–36 Problem 16.

2–4 Acceleration

17. (I) A sports car accelerates from rest to 95 km/h in 4.3 s. What is its average acceleration in $\mathrm{m/s^2}$?
18. (I) A sprinter accelerates from rest to 9.00 m/s in 1.38 s. What is her acceleration in (*a*) $\mathrm{m/s^2}$; (*b*) $\mathrm{km/h^2}$?
19. (II) A sports car moving at constant velocity travels 120 m in 5.0 s. If it then brakes and comes to a stop in 4.0 s, what is the magnitude of its acceleration (assumed constant) in $\mathrm{m/s^2}$, and in g's $(g = 9.80\,\mathrm{m/s^2})$?

20. (II) At highway speeds, a particular automobile is capable of an acceleration of about $1.8\ \mathrm{m/s^2}$. At this rate, how long does it take to accelerate from 65 km/h to 120 km/h?

21. (II) A car moving in a straight line starts at $x = 0$ at $t = 0$. It passes the point $x = 25.0\ \mathrm{m}$ with a speed of 11.0 m/s at $t = 3.00\ \mathrm{s}$. It passes the point $x = 385\ \mathrm{m}$ with a speed of 45.0 m/s at $t = 20.0\ \mathrm{s}$. Find (*a*) the average velocity, and (*b*) the average acceleration, between $t = 3.00\ \mathrm{s}$ and $t = 20.0\ \mathrm{s}$.

2–5 and 2–6 Motion at Constant Acceleration

22. (I) A car slows down from 28 m/s to rest in a distance of 88 m. What was its acceleration, assumed constant?

23. (I) A car accelerates from 14 m/s to 21 m/s in 6.0 s. What was its acceleration? How far did it travel in this time? Assume constant acceleration.

24. (I) A light plane must reach a speed of 35 m/s for takeoff. How long a runway is needed if the (constant) acceleration is $3.0\ \mathrm{m/s^2}$?

25. (II) A baseball pitcher throws a baseball with a speed of 43 m/s. Estimate the average acceleration of the ball during the throwing motion. In throwing the baseball, the pitcher accelerates it through a displacement of about 3.5 m, from behind the body to the point where it is released (Fig. 2–37).

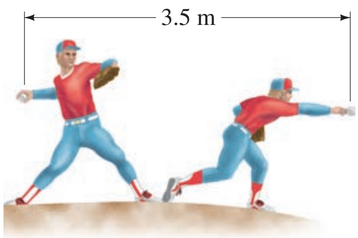


FIGURE 2–37 Problem 25.

26. (II) A world-class sprinter can reach a top speed (of about 11.5 m/s) in the first 18.0 m of a race. What is the average acceleration of this sprinter and how long does it take her to reach that speed?

27. (II) A car slows down uniformly from a speed of 28.0 m/s to rest in 8.00 s. How far did it travel in that time?

28. (II) In coming to a stop, a car leaves skid marks 65 m long on the highway. Assuming a deceleration of $4.00\ \mathrm{m/s^2}$, estimate the speed of the car just before braking.

29. (II) A car traveling 75 km/h slows down at a constant $0.50\ \mathrm{m/s^2}$ just by "letting up on the gas." Calculate (*a*) the distance the car coasts before it stops, (*b*) the time it takes to stop, and (*c*) the distance it travels during the first and fifth seconds.

30. (II) Determine the stopping distances for an automobile going a constant initial speed of 95 km/h and human reaction time of 0.40 s: (*a*) for an acceleration $a = -3.0\ \mathrm{m/s^2}$; (*b*) for $a = -6.0\ \mathrm{m/s^2}$.

31. (II) A driver is traveling 18.0 m/s when she sees a red light ahead. Her car is capable of decelerating at a rate of $3.65\ \mathrm{m/s^2}$. If it takes her 0.350 s to get the brakes on and she is 20.0 m from the intersection when she sees the light, will she be able to stop in time? How far from the beginning of the intersection will she be, and in what direction?

32. (II) A 75-m-long train begins uniform acceleration from rest. The front of the train has a speed of 18 m/s when it passes a railway worker who is standing 180 m from where the front of the train started. What will be the speed of the last car as it passes the worker? (See Fig. 2–38.)

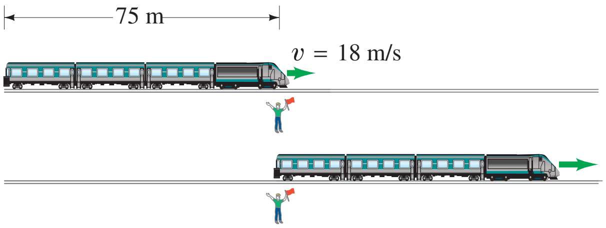


FIGURE 2–38 Problem 32.

33. (II) A space vehicle accelerates uniformly from 85 m/s at $t = 0$ to 162 m/s at $t = 10.0\ \mathrm{s}$. How far did it move between $t = 2.0\ \mathrm{s}$ and $t = 6.0\ \mathrm{s}$?

34. (III) A fugitive tries to hop on a freight train traveling at a constant speed of 5.0 m/s. Just as an empty box car passes him, the fugitive starts from rest and accelerates at $a = 1.4\ \mathrm{m/s^2}$ to his maximum speed of 6.0 m/s, which he then maintains. (*a*) How long does it take him to catch up to the empty box car? (*b*) What is the distance traveled to reach the box car?

35. (III) Mary and Sally are in a foot race (Fig. 2–39). When Mary is 22 m from the finish line, she has a speed of 4.0 m/s and is 5.0 m behind Sally, who has a speed of 5.0 m/s. Sally thinks she has an easy win and so, during the remaining portion of the race, decelerates at a constant rate of $0.40\ \mathrm{m/s^2}$ to the finish line. What constant acceleration does Mary now need during the remaining portion of the race, if she wishes to cross the finish line side-by-side with Sally?

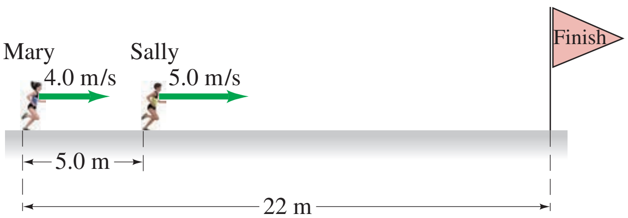


FIGURE 2–39 Problem 35.

36. (III) An unmarked police car traveling a constant 95 km/h is passed by a speeder traveling 135 km/h. Precisely 1.00 s after the speeder passes, the police officer steps on the accelerator; if the police car's acceleration is $2.60\ \mathrm{m/s^2}$, how much time passes before the police car overtakes the speeder (assumed moving at constant speed)?

2–7 Freely Falling Objects (neglect air resistance)

37. (I) A stone is dropped from the top of a cliff. It is seen to hit the ground below after 3.55 s. How high is the cliff?

38. (I) Estimate (*a*) how long it took King Kong to fall straight down from the top of the Empire State Building (380 m high), and (*b*) his velocity just before "landing."

39. (II) A ball player catches a ball 3.4 s after throwing it vertically upward. With what speed did he throw it, and what height did it reach?

40. (II) A baseball is hit almost straight up into the air with a speed of 25 m/s. Estimate (*a*) how high it goes, (*b*) how long it is in the air. (*c*) What factors make this an estimate?

41. (II) The best rebounders in basketball have a vertical leap (that is, the vertical movement of a fixed point on their body) of about 120 cm. (*a*) What is their initial "launch" speed off the ground? (*b*) How long are they in the air?

42. (II) An object starts from rest and falls under the influence of gravity. Draw graphs of (*a*) its speed and (*b*) the distance it has fallen, as a function of time from $t = 0$ to $t = 5.00$ s. Ignore air resistance.

43. (II) A stone is thrown vertically upward with a speed of 24.0 m/s. (*a*) How fast is it moving when it is at a height of 13.0 m? (*b*) How much time is required to reach this height? (*c*) Why are there two answers to (*b*)?

44. (II) For an object falling freely from rest, show that the distance traveled *during* each successive second increases in the ratio of successive odd integers (1, 3, 5, etc.). (This was first shown by Galileo.) See Figs. 2–19 and 2–22.

45. (II) A rocket rises vertically, from rest, with an acceleration of $3.2\ \mathrm{m/s^2}$ until it runs out of fuel at an altitude of 775 m. After this point, its acceleration is that of gravity, downward. (*a*) What is the velocity of the rocket when it runs out of fuel? (*b*) How long does it take to reach this point? (*c*) What maximum altitude does the rocket reach? (*d*) How much time (total) does it take to reach maximum altitude? (*e*) With what velocity does it strike the Earth? (*f*) How long (total) is it in the air?

46. (II) A helicopter is ascending vertically with a speed of 5.40 m/s. At a height of 105 m above the Earth, a package is dropped from the helicopter. How much time does it take for the package to reach the ground? [*Hint*: What is v_0 for the package?]

47. (II) Roger sees water balloons fall past his window. He notices that each balloon strikes the sidewalk 0.83 s after passing his window. Roger's room is on the third floor, 15 m above the sidewalk. (*a*) How fast are the balloons traveling when they pass Roger's window? (*b*) Assuming the balloons are being released from rest, from what floor are they being released? Each floor of the dorm is 5.0 m high.

48. (II) Suppose you adjust your garden hose nozzle for a fast stream of water. You point the nozzle vertically upward at a height of 1.8 m above the ground (Fig. 2–40). When you quickly turn off the nozzle, you hear the water striking the ground next to you for another 2.5 s. What is the water speed as it leaves the nozzle?

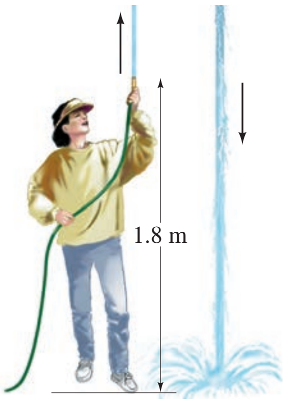


FIGURE 2–40 Problem 48.

49. (III) A falling stone takes 0.31 s to travel past a window 2.2 m tall (Fig. 2–41). From what height above the top of the window did the stone fall?

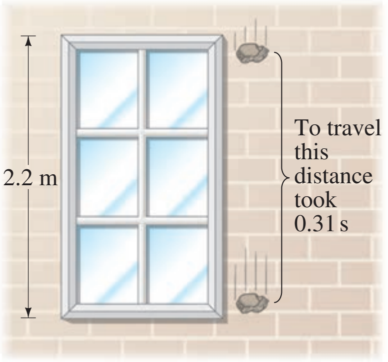


FIGURE 2–41 Problem 49.

50. (III) A rock is dropped from a sea cliff, and the sound of it striking the ocean is heard 3.4 s later. If the speed of sound is 340 m/s, how high is the cliff?

2–8 Graphical Analysis

51. (II) Figure 2–42 shows the velocity of a train as a function of time. (*a*) At what time was its velocity greatest? (*b*) During what periods, if any, was the velocity constant? (*c*) During what periods, if any, was the acceleration constant? (*d*) When was the magnitude of the acceleration greatest?

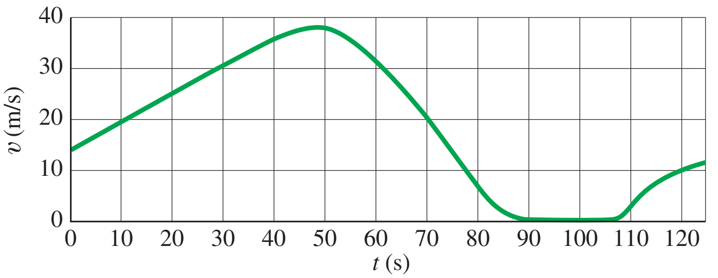


FIGURE 2–42 Problem 51.

52. (II) A sports car accelerates approximately as shown in the velocity–time graph of Fig. 2–43. (The short flat spots in the curve represent manual shifting of the gears.) Estimate the car's average acceleration in (*a*) second gear and (*b*) fourth gear.

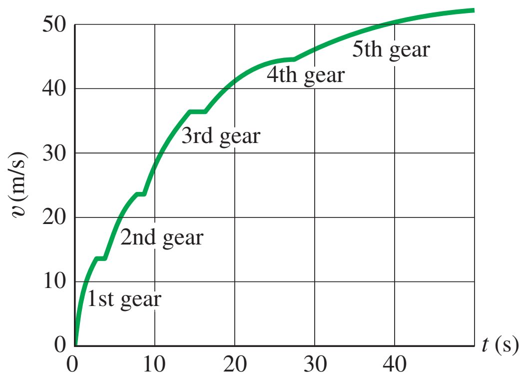


FIGURE 2–43 Problem 52. The velocity of a car as a function of time, starting from a dead stop. The flat spots in the curve represent gear shifts.

53. (II) The position of a rabbit along a straight tunnel as a function of time is plotted in Fig. 2–44. What is its instantaneous velocity (*a*) at $t = 10.0\,\mathrm{s}$ and (*b*) at $t = 30.0\,\mathrm{s}$? What is its average velocity (*c*) between $t = 0$ and $t = 5.0\,\mathrm{s}$, (*d*) between $t = 25.0\,\mathrm{s}$ and $t = 30.0\,\mathrm{s}$, and (*e*) between $t = 40.0\,\mathrm{s}$ and $t = 50.0\,\mathrm{s}$?

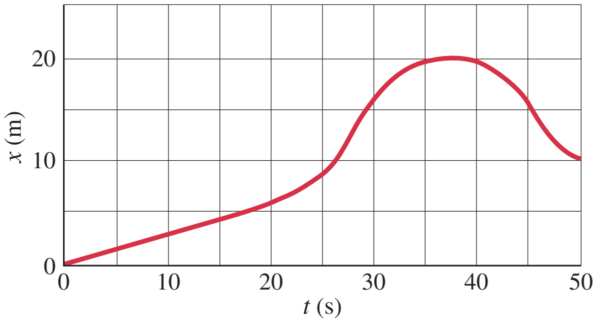


FIGURE 2–44 Problems 53, 54, and 55.

54. (II) In Fig. 2–44, (*a*) during what time periods, if any, is the velocity constant? (*b*) At what time is the velocity greatest? (*c*) At what time, if any, is the velocity zero? (*d*) Does the object move in one direction or in both directions during the time shown?

55. (III) Sketch the v vs. t graph for the object whose displacement as a function of time is given by Fig. 2–44.

General Problems

56. The acceleration due to gravity on the Moon is about one-sixth what it is on Earth. If an object is thrown vertically upward on the Moon, how many times higher will it go than it would on Earth, assuming the same initial velocity?

57. A person who is properly restrained by an over-the-shoulder seat belt has a good chance of surviving a car collision if the deceleration does not exceed 30 "g's" $(1.00\,g = 9.80\,\mathrm{m/s^2})$. Assuming uniform deceleration at 30 g's, calculate the distance over which the front end of the car must be designed to collapse if a crash brings the car to rest from 95 km/h.

58. A person jumps out a fourth-story window 18.0 m above a firefighter's safety net. The survivor stretches the net 1.0 m before coming to rest, Fig. 2–45. (*a*) What was the average deceleration experienced by the survivor when she was slowed to rest by the net? (*b*) What would you do to make it "safer" (that is, to generate a smaller deceleration): would you stiffen or loosen the net? Explain.

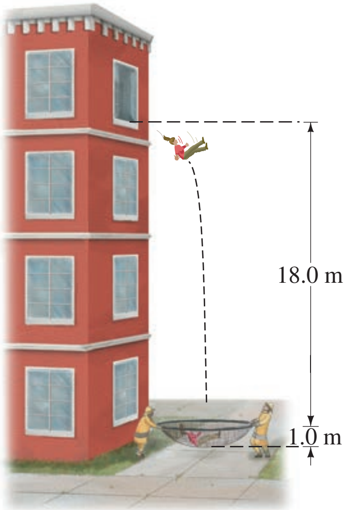


FIGURE 2–45 Problem 58.

59. A bicyclist in the Tour de France crests a mountain pass as he moves at 15 km/h. At the bottom, 4.0 km farther, his speed is 65 km/h. Estimate his average acceleration (in $\mathrm{m/s^2}$) while riding down the mountain.

60. Consider the street pattern shown in Fig. 2–46. Each intersection has a traffic signal, and the speed limit is 40 km/h. Suppose you are driving from the west at the speed limit. When you are 10.0 m from the first intersection, all the lights turn green. The lights are green for 13.0 s each. (*a*) Calculate the time needed to reach the third stoplight. Can you make it through all three lights without stopping? (*b*) Another car was stopped at the first light when all the lights turned green. It can accelerate at the rate of $2.00\,\mathrm{m/s^2}$ to the speed limit. Can the second car make it through all three lights without stopping? By how many seconds would it make it, or not make it?

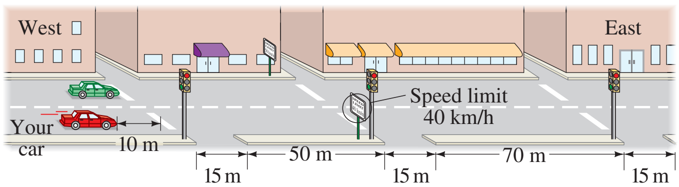


FIGURE 2–46 Problem 60.

61. An airplane travels 2100 km at a speed of 720 km/h, and then encounters a tailwind that boosts its speed to 990 km/h for the next 2800 km. What was the total time for the trip? What was the average speed of the plane for this trip? [*Hint*: Does Eq. 2–11d apply?]

62. A stone is dropped from the roof of a high building. A second stone is dropped 1.30 s later. How far apart are the stones when the second one has reached a speed of 12.0 m/s?

63. A person jumps off a diving board 4.0 m above the water's surface into a deep pool. The person's downward motion stops 2.0 m below the surface of the water. Estimate the average deceleration of the person while under the water.

64. In putting, the force with which a golfer strikes a ball is planned so that the ball will stop within some small distance of the cup, say 1.0 m long or short, in case the putt is missed. Accomplishing this from an uphill lie (that is, putting the ball downhill, see Fig. 2–47) is more difficult than from a downhill lie. To see why, assume that on a particular green the ball decelerates constantly at $1.8\ \mathrm{m/s^2}$ going downhill, and constantly at $2.6\ \mathrm{m/s^2}$ going uphill. Suppose we have an uphill lie 7.0 m from the cup. Calculate the allowable range of initial velocities we may impart to the ball so that it stops in the range 1.0 m short to 1.0 m long of the cup. Do the same for a downhill lie 7.0 m from the cup. What in your results suggests that the downhill putt is more difficult?

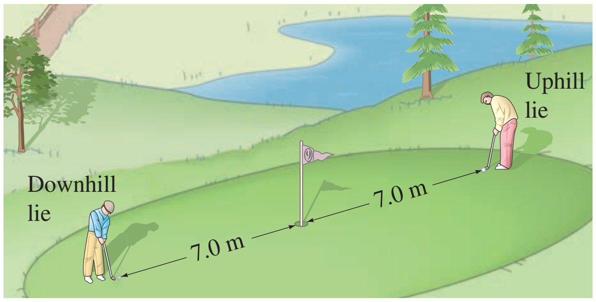


FIGURE 2–47 Problem 64.

65. A stone is thrown vertically upward with a speed of 15.5 m/s from the edge of a cliff 75.0 m high (Fig. 2–48). (*a*) How much later does it reach the bottom of the cliff? (*b*) What is its speed just before hitting? (*c*) What total distance did it travel?

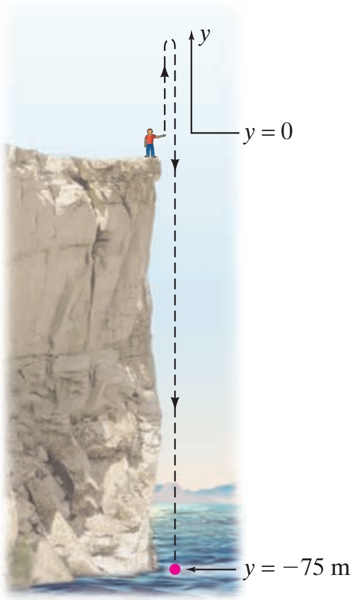


FIGURE 2–48 Problem 65.

66. In the design of a **rapid transit system**, it is necessary to balance the average speed of a train against the distance between station stops. The more stops there are, the slower the train's average speed. To get an idea of this problem, calculate the time it takes a train to make a 15.0-km trip in two situations: (*a*) the stations at which the trains must stop are 3.0 km apart (a total of 6 stations, including those at the ends); and (*b*) the stations are 5.0 km apart (4 stations total). Assume that at each station the train accelerates at a rate of $1.1\ \mathrm{m/s^2}$ until it reaches 95 km/h, then stays at this speed until its brakes are applied for arrival at the next station, at which time it decelerates at $-2.0\ \mathrm{m/s^2}$. Assume it stops at each intermediate station for 22 s.

67. A person driving her car at 35 km/h approaches an intersection just as the traffic light turns yellow. She knows that the yellow light lasts only 2.0 s before turning to red, and she is 28 m away from the near side of the intersection (Fig. 2–49). Should she try to stop, or should she speed up to cross the intersection before the light turns red? The intersection is 15 m wide. Her car's maximum deceleration is $-5.8\ \mathrm{m/s^2}$, whereas it can accelerate from 45 km/h to 65 km/h in 6.0 s. Ignore the length of her car and her reaction time.

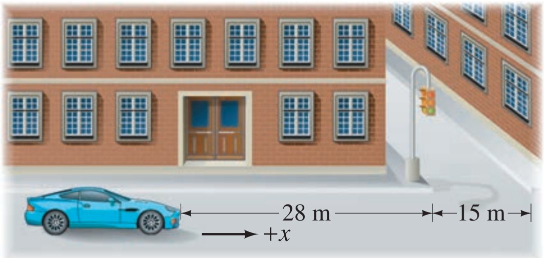


FIGURE 2–49 Problem 67.

68. A car is behind a truck going 18 m/s on the highway. The car's driver looks for an opportunity to pass, guessing that his car can accelerate at $0.60\ \mathrm{m/s^2}$ and that he has to cover the 20-m length of the truck, plus 10-m extra space at the rear of the truck and 10 m more at the front of it. In the oncoming lane, he sees a car approaching, probably at the speed limit, 25 m/s (55 mph). He estimates that the car is about 500 m away. Should he attempt the pass? Give details.

69. Agent Bond is standing on a bridge, 15 m above the road below, and his pursuers are getting too close for comfort. He spots a flatbed truck approaching at 25 m/s, which he measures by knowing that the telephone poles the truck is passing are 25 m apart in this region. The roof of the truck is 3.5 m above the road, and Bond quickly calculates how many poles away the truck should be when he drops down from the bridge onto the truck, making his getaway. How many poles is it?

70. A conveyor belt is used to send burgers through a grilling machine. If the grilling machine is 1.2 m long and the burgers require 2.8 min to cook, how fast must the conveyor belt travel? If the burgers are spaced 25 cm apart, what is the rate of burger production (in burgers/min)?

71. Two students are asked to find the height of a particular building using a barometer. Instead of using the barometer as an altitude measuring device, they take it to the roof of the building and drop it off, timing its fall. One student reports a fall time of 2.0 s, and the other, 2.3 s. What % difference does the 0.3 s make for the estimates of the building's height?

72. Two children are playing on two trampolines. The first child bounces up one-and-a-half times higher than the second child. The initial speed up of the second child is 4.0 m/s. (*a*) Find the maximum height the second child reaches. (*b*) What is the initial speed of the first child? (*c*) How long was the first child in the air?

73. If there were no air resistance, how long would it take a free-falling skydiver to fall from a plane at 3200 m to an altitude of 450 m, where she will open her parachute? What would her speed be at 450 m? (In reality, the air resistance will restrict her speed to perhaps 150 km/h.)

74. You stand at the top of a cliff while your friend stands on the ground below you. You drop a ball from rest and see that she catches it 1.4 s later. Your friend then throws the ball up to you, such that it just comes to rest in your hand. What is the speed with which your friend threw the ball?

75. On an audio compact disc (CD), digital bits of information are encoded sequentially along a spiral path. Each bit occupies about 0.28 μm. A CD player's readout laser scans along the spiral's sequence of bits at a constant speed of about 1.2 m/s as the CD spins. (*a*) Determine the number N of digital bits that a CD player reads every second. (*b*) The audio information is sent to each of the two loudspeakers 44,100 times per second. Each of these samplings requires 16 bits, and so you might expect the required bit rate for a CD player to be

$$N_0 = 2\left(44{,}100\,\frac{\text{samplings}}{\text{s}}\right)\left(16\,\frac{\text{bits}}{\text{sampling}}\right) = 1.4 \times 10^6\,\frac{\text{bits}}{\text{s}},$$

where the 2 is for the 2 loudspeakers (the 2 stereo channels). Note that N_0 is less than the number N of bits actually read per second by a CD player. The excess number of bits $(= N - N_0)$ is needed for encoding and error-correction. What percentage of the bits on a CD are dedicated to encoding and error-correction?

Search and Learn

1. Discuss two conditions given in Section 2–7 for being able to use a constant acceleration of magnitude $g = 9.8\ \text{m/s}^2$. Give an example in which one of these conditions would not be met and would not even be a reasonable approximation of motion.

2. In a lecture demonstration, a 3.0-m-long vertical string with ten bolts tied to it at equal intervals is dropped from the ceiling of the lecture hall. The string falls on a tin plate, and the class hears the clink of each bolt as it hits the plate. (*a*) The sounds will not occur at equal time intervals. Why? (*b*) Will the time between clinks increase or decrease as the string falls? (*c*) How could the bolts be tied so that the clinks occur at equal intervals? (Assume the string is vertical with the bottom bolt touching the tin plate when the string is released.)

3. The position of a ball rolling in a straight line is given by $x = 2.0 - 3.6t + 1.7t^2$, where x is in meters and t in seconds. (*a*) What do the numbers 2.0, 3.6, and 1.7 refer to? (*b*) What are the units of each of these numbers? (*c*) Determine the position of the ball at $t = 1.0$ s, 2.0 s, and 3.0 s. (*d*) What is the average velocity over the interval $t = 1.0$ s to $t = 3.0$ s?

ANSWERS TO EXERCISES

A: (*a*) displacement $= -30$ cm; (*b*) total distance $= 50$ cm.
B: (*b*).
C: (*a*) +; (*b*) −; (*c*) −; (*d*) +.
D: (*b*).
E: (*e*).
F: (*c*).