Objectives
- Describe motion in terms of changing velocity.
- Compare graphical representations of accelerated and nonaccelerated motions.
- Apply kinematic equations to calculate distance, time, or velocity under conditions of constant acceleration.

Key Term
acceleration

Changes in Velocity

Many bullet trains have a top speed of about 300 km/h. Because a train stops to load and unload passengers, it does not always travel at that top speed. For some of the time the train is in motion, its velocity is either increasing or decreasing. It loses speed as it slows down to stop and gains speed as it pulls away and heads for the next station.

Acceleration is the rate of change of velocity with respect to time.

Similarly, when a shuttle bus approaches a stop, the driver begins to apply the brakes to slow down 5.0 s before actually reaching the stop. The speed changes from 9.0 m/s to 0 m/s over a time interval of 5.0 s. Sometimes, however, the shuttle stops much more quickly. For example, if the driver slams on the brakes to avoid hitting a dog, the bus slows from 9.0 m/s to 0 m/s in just 1.5 s.

Clearly, these two stops are very different, even though the shuttle’s velocity changes by the same amount in both cases. What is different in these two examples is the time interval during which the change in velocity occurs. As you can imagine, this difference has a great effect on the motion of the bus, as well as on the comfort and safety of the passengers. A sudden change in velocity feels very different from a slow, gradual change.

The quantity that describes the rate of change of velocity in a given time interval is called acceleration.

\[
\text{Average Acceleration } \quad a_{\text{avg}} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}
\]

average acceleration = change in velocity / time required for change

Acceleration has dimensions of length divided by time squared. The units of acceleration in SI are meters per second per second, which is written as meters per second squared, as shown below. When measured in these units, acceleration describes how much the velocity changes in each second.

\[
\text{(m/s)}^2 = \frac{\text{m}}{\text{s}^2}
\]

ENGLISH LEARNERS

The word *acceleration* has different meanings in everyday life and in science. Ask students how they use the word *acceleration* when talking to their friends and family. They will likely say that it means “to speed up” or “go faster.” Explain that in science an object accelerates if its velocity changes in any way. So acceleration can mean speeding up, slowing down, or changing direction.
Classroom Practice

AVERAGE ACCELERATION

Find the acceleration of an amusement park ride that falls from rest to a speed of 28 m/s in 3.0 s.

Answer: 9.3 m/s²

PROBLEM GUIDE B

Use this guide to assign problems.

SE = Student Edition Textbook

PW = Sample Problem Set I (online)

PB = Sample Problem Set II (online)

<table>
<thead>
<tr>
<th>Problem</th>
<th>SE, PW, PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆t</td>
<td>Sample, 1–3; Ch. Rvw. 16</td>
</tr>
<tr>
<td>∆v</td>
<td>Sample, 1–4a, 5a, 8b</td>
</tr>
<tr>
<td>aavg</td>
<td>Ch. Rvw. 17, 45</td>
</tr>
</tbody>
</table>

*Challenging Problem

Answers

Practice B
1. 2.2 s
2. 2.0 s
3. 5.4 s
4. \(-3.5 \times 10^{-3}\) m/s²
5. a. 1.4 m/s
   b. 3.1 m/s
Answers

Conceptual Challenge
1. No; The ball could be speeding up from rest.
2. slowing down
3. Jennifer’s acceleration could be positive if she is moving in the negative direction; in this case, the direction of the bike’s velocity is opposite the direction of the bike’s acceleration, so the bike slows down. In mathematical terms, \( a = \frac{\Delta v}{\Delta t} \). If \( v_f \) and \( v_i \) are negative, and if the magnitude of \( v_f \) is less than the magnitude of \( v_i \), then \( \Delta v \) and thus \( a \) are positive.

Differentiated Instruction

**BELOW LEVEL**
Students may have trouble relating velocity-time graphs to the motion of an object. Explain to students that a rising slope on a velocity-time graph means that the velocity is increasing. The steeper the slope, the faster the velocity increases, and the greater the acceleration. A falling slope means the velocity is decreasing. Again, a steeper decrease means a greater acceleration.
Figure 2.3 shows how the signs of the velocity and acceleration can be combined to give a description of an object’s motion. From this table, you can see that a negative acceleration can describe an object that is speeding up (when the velocity is negative) or an object that is slowing down (when the velocity is positive). Use this table to check your answers to problems involving acceleration.

For example, in Figure 2.2 the initial velocity $v_i$ of the train is positive. At point A on the graph, the train’s velocity is still increasing, so its acceleration is positive as well. The first entry in Figure 2.3 shows that in this situation, the train is speeding up. At point C, the velocity is still positive, but it is decreasing, so the train’s acceleration is negative. Figure 2.3 tells you that in this case, the train is slowing down.

### Table 2.3

<table>
<thead>
<tr>
<th>$v_i$</th>
<th>$a$</th>
<th>Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>speeding up</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>speeding up</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>slowing down</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>slowing down</td>
</tr>
<tr>
<td>- or +</td>
<td>0</td>
<td>constant velocity</td>
</tr>
<tr>
<td>0</td>
<td>- or +</td>
<td>speeding up from rest</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>remaining at rest</td>
</tr>
</tbody>
</table>

### Motion with constant acceleration.

Figure 2.4 is a strobe photograph of a ball moving in a straight line with constant acceleration. While the ball was moving, its image was captured ten times in one second, so the time interval between successive images is 0.10 s. As the ball’s velocity increases, the ball travels a greater distance during each time interval. In this example, the velocity increases by exactly the same amount during each time interval. Thus, the acceleration is constant. Because the velocity increases for each time interval, the successive change in displacement for each time interval increases. You can see this in the photograph by noting that the distance between images increases while the time interval between images remains constant. The relationships between displacement, velocity, and constant acceleration are expressed by equations that apply to any object moving with constant acceleration.

**Figure 2.4**

**Motion of a Falling Ball**

The motion in this picture took place in about 1.00 s. In this short time interval, your eyes could only detect a blur. This photo shows what really happens within that time.

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**PRE-AP**

Point out that because the acceleration is constant, the distance that the ball travels in each time interval is equal to the distance it traveled in the previous interval, plus a constant distance. Tell students to make a chart with calculations that demonstrate this fact, given an acceleration of 3 m/s².

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**Demonstration**

**CONSTANT ACCELERATION**

**Purpose** Give several visual examples of constant acceleration.

**Materials** metronome (optional), tile floor (or tape)

**Procedure** Tell students you are going to demonstrate constant velocity and then constant acceleration. Use a metronome (or have students clap at regular intervals) to show time intervals. For the first part (constant velocity), walk in a straight line at a rate of one tile per time interval. (If you do not have a tile floor, use the tape to mark regular intervals on the floor.)

Now show a constant acceleration of one tile per interval for each interval. Walk a distance of one tile in the first interval, two tiles in the second interval, three in the third, and so on.

Finally, show students a constant negative acceleration. Start walking at a rate of four or five tiles per interval, decreasing by one tile per interval with each interval. When you get to zero tiles per interval, you may want to continue by walking backward one tile per interval, then two tiles per interval, and so on. Explain that the acceleration was still present at the velocity of zero tiles per interval, so your velocity continued to change.
Displacement depends on acceleration, initial velocity, and time.

Figure 2.5 is a graph of the ball’s velocity plotted against time. The initial, final, and average velocities are marked on the graph. We know that the average velocity is equal to displacement divided by the time interval.

\[ v_{avg} = \frac{\Delta x}{\Delta t} \]

Displacement with Constant Acceleration

\[ \Delta x = \frac{1}{2} (v_i + v_f) \Delta t \]

Displacement = \( \frac{1}{2} \) (initial velocity + final velocity)(time interval)

DECONSTRUCTING PROBLEMS

Show students that the area under the curve in a graph of velocity versus time equals the displacement during that time interval. Use the simplest case in Figure 2.5, where \( v_i \) equals zero, to illustrate this point. Choose a point on the graph, and draw a vertical line from the \( x \)-axis to the point and a horizontal line from the \( y \)-axis to the point, as shown here.

Use the corresponding velocity and time interval values to find the area of the rectangle \( (A = v_f t_f) \). Point out that the line in the graph bisects the box; thus, the area under the line equals \( \frac{1}{2} v_f t_f \), which is the equation for the displacement of a constantly accelerated object that begins at rest.
Displacement with Constant Acceleration

Sample Problem C A racing car reaches a speed of 42 m/s. It then begins a uniform negative acceleration, using its parachute and braking system, and comes to rest 5.5 s later. Find the distance that the car travels during braking.

1 ANALYZE

Given:

\[ v_i = 42 \text{ m/s} \]
\[ v_f = 0 \text{ m/s} \]
\[ \Delta t = 5.5 \text{ s} \]

Unknown: \[ \Delta x = ? \]

2 SOLVE

Use the equation that relates displacement, initial and final velocities, and the time interval.

\[ \Delta x = \frac{1}{2} (v_i + v_f) \Delta t \]
\[ \Delta x = \frac{1}{2} (42 \text{ m/s} + 0 \text{ m/s})(5.5 \text{ s}) \]
\[ \Delta x = 120 \text{ m} \]

Tips and Tricks
Remember that this equation applies only when acceleration is constant. In this problem, you know that acceleration is constant by the phrase “uniform negative acceleration.” All of the kinematic equations introduced in this chapter are valid only for constant acceleration.

Calculator Solution
The calculator answer is 115.5. However, the velocity and time values have only two significant figures each, so the answer must be reported as 120 m.

Practice

1. A car accelerates uniformly from rest to a speed of 6.6 m/s in 6.5 s. Find the distance the car travels during this time.

2. When Maggie applies the brakes of her car, the car slows uniformly from 15.0 m/s to 0.0 m/s in 2.50 s. How many meters before a stop sign must she apply her brakes in order to stop at the sign?

3. A driver in a car traveling at a speed of 21.8 m/s sees a cat 101 m away on the road. How long will it take for the car to accelerate uniformly to a stop in exactly 99 m?

4. A car enters the freeway with a speed of 6.4 m/s and accelerates uniformly for 3.2 km in 3.5 min. How fast (in m/s) is the car moving after this time?

Answers

Practice C

1. 21 m
2. 18.8 m
3. 9.1 s
4. 24 m/s
Final velocity depends on initial velocity, acceleration, and time.

What if the final velocity of the ball is not known but we still want to calculate the displacement? If we know the initial velocity, the acceleration, and the elapsed time, we can find the final velocity. We can then use this value for the final velocity to find the total displacement of the ball.

By rearranging the equation for acceleration, we can find a value for the final velocity.

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

By adding the initial velocity to both sides of the equation, we get an equation for the final velocity of the ball.

$$a\Delta t + v_i = v_f$$

**Velocity with Constant Acceleration**

$$v_f = v_i + a\Delta t$$

**Displacement with Constant Acceleration**

$$\Delta x = v_i\Delta t + \frac{1}{2}a(\Delta t)^2$$

This equation is useful not only for finding the displacement of an object moving with constant acceleration but also for finding the displacement required for an object to reach a certain speed or to come to a stop. For the latter situation, you need to use both this equation and the equation given above.

**Problem Solving**

**REALITY CHECK**

Be sure that students understand that these equations only work for objects with constant acceleration. For objects with non-constant acceleration, this equation won’t work. One way to show this is by drawing graphs like the one shown in the Teaching Tip, but with a curved line connecting the initial and final velocities.

What happens if the object has a high initial acceleration and then a lower acceleration?
Sample Problem D A plane starting at rest at one end of a runway undergoes a uniform acceleration of 4.8 m/s² for 15 s before takeoff. What is its speed at takeoff? How long must the runway be for the plane to be able to take off?

ANALYZE

Given:

\( v_i = 0 \text{ m/s} \)

\( a = 4.8 \text{ m/s}^2 \)

\( \Delta t = 15 \text{ s} \)

Unknown:

\( v_f = ? \)

\( \Delta x = ? \)

SOLVE

First, use the equation for the velocity of a uniformly accelerated object.

\[ v_f = v_i + a \Delta t \]

\[ v_f = 0 \text{ m/s} + (4.8 \text{ m/s}^2)(15 \text{ s}) \]

\[ v_f = 72 \text{ m/s} \]

Then, use the displacement equation that contains the given variables.

\[ \Delta x = v_f \Delta t + \frac{1}{2} a (\Delta t)^2 \]

\[ \Delta x = (0 \text{ m/s})(15 \text{ s}) + \frac{1}{2} (4.8 \text{ m/s}^2)(15 \text{ s})^2 \]

\[ \Delta x = 540 \text{ m} \]

Practice

1. A car with an initial speed of 6.5 m/s accelerates at a uniform rate of 0.92 m/s² for 3.6 s. Find the final speed and the displacement of the car during this time.

2. An automobile with an initial speed of 4.30 m/s accelerates uniformly at the rate of 3.00 m/s². Find the final speed and the displacement after 5.00 s.

3. A car starts from rest and travels for 5.0 s with a constant acceleration of −1.5 m/s². What is the final velocity of the car? How far does the car travel in this time interval?

4. A driver of a car traveling at 15.0 m/s applies the brakes, causing a uniform acceleration of −2.0 m/s². How long does it take the car to accelerate to a final speed of 10.0 m/s? How far has the car moved during the braking period?

Answers

Practice D

1. 9.8 m/s; 29 m

2. 19.3 m/s; 59.0 m

3. −7.5 m/s; 19 m

4. 2.5 s; 32 m
Final velocity depends on initial velocity, acceleration, and displacement.

So far, all of the equations for motion under uniform acceleration have required knowing the time interval. We can also obtain an expression that relates displacement, velocity, and acceleration without using the time interval. This method involves rearranging one equation to solve for $\Delta t$ and substituting that expression in another equation, making it possible to find the final velocity of a uniformly accelerated object without knowing how long it has been accelerating. Start with the following equation for displacement:

$$\Delta x = \frac{1}{2} (v_i + v_f) \Delta t$$

Now multiply both sides by 2.

$$2\Delta x = (v_i + v_f) \Delta t$$

Next, divide both sides by $(v_i + v_f)$ to solve for $\Delta t$.

$$\frac{2\Delta x}{v_i + v_f} = \Delta t$$

Now that we have an expression for $\Delta t$, we can substitute this expression into the equation for the final velocity.

$$v_f = v_i + a\Delta t$$

$$v_f = v_i + a \left( \frac{2\Delta x}{v_i + v_f} \right)$$

In its present form, this equation is not very helpful because $v_f$ appears on both sides. To solve for $v_f$, first subtract $v_i$ from both sides of the equation.

$$v_f - v_i = a \left( \frac{2\Delta x}{v_i + v_f} \right)$$

Next, multiply both sides by $(v_i + v_f)$ to get all the velocities on the same side of the equation.

$$(v_f - v_i) (v_i + v_f) = 2a\Delta x = v_f^2 - v_i^2$$

Add $v_i^2$ to both sides to solve for $v_f^2$.

**Final Velocity After Any Displacement**

$$v_f^2 = v_i^2 + 2a\Delta x$$

$$(\text{final velocity})^2 = (\text{initial velocity})^2 + 2(\text{acceleration})(\text{displacement})$$

When using this equation, you must take the square root of the right side of the equation to find the final velocity. Remember that the square root may be either positive or negative. If you have been consistent in your use of the sign convention, you will be able to determine which value is the right answer by reasoning based on the direction of the motion.
Final Velocity After Any Displacement

Sample Problem E A person pushing a stroller starts from rest, uniformly accelerating at a rate of 0.500 m/s². What is the velocity of the stroller after it has traveled 4.75 m?

1. **ANALYZE**
   Given: $v_i = 0 \text{ m/s}$
   $a = 0.500 \text{ m/s}^2$
   $\Delta x = 4.75 \text{ m}$
   Unknown: $v_f = ?$
   Diagram:
   Choose a coordinate system. The most convenient one has an origin at the initial location of the stroller. The positive direction is to the right.

2. **PLAN**
   Choose an equation or situation:
   Because the initial velocity, acceleration, and displacement are known, the final velocity can be found by using the following equation:
   $$v_f^2 = v_i^2 + 2a\Delta x$$
   Rearrange the equation to isolate the unknown:
   Take the square root of both sides to isolate $v_f$.
   $$v_f = \pm \sqrt{(v_i)^2 + 2a\Delta x}$$

3. **SOLVE**
   Substitute the values into the equation and solve:
   $$v_f = \pm \sqrt{(0 \text{ m/s})^2 + 2(0.500 \text{ m/s}^2)(4.75 \text{ m})}$$
   $$v_f = +2.18 \text{ m/s}$$

4. **CHECK YOUR WORK**
   The stroller’s velocity after accelerating for 4.75 m is 2.18 m/s to the right.

**Tips and Tricks**

Think about the physical situation to determine whether to keep the positive or negative answer from the square root. In this case, the stroller is speeding up because it starts from rest and ends with a speed of 2.18 m/s. An object that is speeding up and has a positive acceleration must have a positive velocity, as shown in Figure 2.3. So, the final velocity must be positive.

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Problem Solving

REALITY CHECK

Remind students that the sign in Sample Problem E tells you the direction of the stroller. Because the stroller was being pushed with a constant acceleration to the right, then the stroller’s final velocity should be in the same direction—to the right. In addition, because pushing to the right was designated as the positive direction, then the stroller’s velocity will also be positive.
With the four equations presented in this section, it is possible to solve any problem involving one-dimensional motion with uniform acceleration. For your convenience, the equations that are used most often are listed in Figure 2.6. The first column of the table gives the equations in their standard form. For an object initially at rest, \( v_i = 0 \). Using this value for \( v_i \) in the equations in the first column will result in the equations in the second column. It is not necessary to memorize the equations in the second column. If \( v_i = 0 \) in any problem, you will naturally derive this form of the equation. Referring back to the sample problems in this chapter will guide you through using these equations to solve many problems.

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**Practice**

1. Find the velocity after the stroller in Sample Problem E has traveled 6.32 m.
2. A car traveling initially at +7.0 m/s accelerates uniformly at the rate of +0.80 m/s² for a distance of 245 m.
   a. What is its velocity at the end of the acceleration?
   b. What is its velocity after it accelerates for 125 m?
   c. What is its velocity after it accelerates for 67 m?
3. A car accelerates uniformly in a straight line from rest at the rate of 2.3 m/s².
   a. What is the speed of the car after it has traveled 55 m?
   b. How long does it take the car to travel 55 m?
4. A motorboat accelerates uniformly from a velocity of 6.5 m/s to the west to a velocity of 1.5 m/s to the west. If its acceleration was 2.7 m/s² to the east, how far did it travel during the acceleration?
5. An aircraft has a liftoff speed of 33 m/s. What minimum constant acceleration does this require if the aircraft is to be airborne after a takeoff run of 240 m?
6. A certain car is capable of accelerating at a uniform rate of 0.85 m/s². What is the magnitude of the car’s displacement as it accelerates uniformly from a speed of 83 km/h to one of 94 km/h.

**Answers**

**Practice E**

1. +2.51 m/s
2. a. +21 m/s
   b. +16 m/s
   c. +13 m/s
3. a. 16 m/s
   b. 7.0 s
4. 74 m
5. +2.3 m/s²
6. 88 m

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**FIGURE 2.6**

**EQUATIONS FOR CONSTANTLY ACCELERATED STRAIGHT-LINE MOTION**

<table>
<thead>
<tr>
<th>Form to use when accelerating object has an initial velocity</th>
<th>Form to use when object accelerating starts from rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta x = \frac{1}{2} (v_i + v_f) \Delta t )</td>
<td>( \Delta x = \frac{1}{2} v_f \Delta t )</td>
</tr>
<tr>
<td>( v_f = v_i + a \Delta t )</td>
<td>( v_f = a \Delta t )</td>
</tr>
<tr>
<td>( \Delta x = v_f \Delta t + \frac{1}{2} a(\Delta t)^2 )</td>
<td>( \Delta x = \frac{1}{2} a(\Delta t)^2 )</td>
</tr>
<tr>
<td>( v_f^2 = v_i^2 + 2a \Delta x )</td>
<td>( v_f^2 = 2a \Delta x )</td>
</tr>
</tbody>
</table>
**SECTION 2** FORMATIVE ASSESSMENT

**Reviewing Main Ideas**

1. Marissa’s car accelerates uniformly at a rate of $+2.60 \text{ m/s}^2$. How long does it take for Marissa’s car to accelerate from a speed of $24.6 \text{ m/s}$ to a speed of $26.8 \text{ m/s}$?

2. A bowling ball with a negative initial velocity slows down as it rolls down the lane toward the pins. Is the bowling ball’s acceleration positive or negative as it rolls toward the pins?

3. Nathan accelerates his skateboard uniformly along a straight path from rest to $12.5 \text{ m/s}$ in $2.5 \text{ s}$.
   a. What is Nathan’s acceleration?
   b. What is Nathan’s displacement during this time interval?
   c. What is Nathan’s average velocity during this time interval?

**Critical Thinking**

4. Two cars are moving in the same direction in parallel lanes along a highway. At some instant, the instantaneous velocity of car A exceeds the instantaneous velocity of car B. Does this mean that car A’s acceleration is greater than car B’s? Explain, and use examples.

**Interpreting Graphics**

5. The velocity-versus-time graph for a shuttle bus moving along a straight path is shown in Figure 2.7.
   a. Identify the time intervals during which the velocity of the shuttle bus is constant.
   b. Identify the time intervals during which the acceleration of the shuttle bus is constant.
   c. Find the value for the average velocity of the shuttle bus during each time interval identified in b.
   d. Find the acceleration of the shuttle bus during each time interval identified in b.
   e. Identify the times at which the velocity of the shuttle bus is zero.
   f. Identify the times at which the acceleration of the shuttle bus is zero.
   g. Explain what the slope of the graph reveals about the acceleration in each time interval.

6. Is the shuttle bus in item 5 always moving in the same direction? Explain, and refer to the time intervals shown on the graph.

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**Answers to Section Assessment**

1. 0.85 s
2. positive
3. a. $+5.0 \text{ m/s}^2$
   b. $+16 \text{ m}$
   c. $+6.4 \text{ m/s}$
4. No, car A’s acceleration is not necessarily greater than car B’s acceleration. If the two cars are moving in the positive direction, car A could be slowing down (negative acceleration) while car B is speeding up (positive acceleration), even though car A’s velocity is greater than car B’s velocity.
5. a. 0 s to 30 s; 60 s to 125 s; 210 s to 275 s
   b. 0 s to 30 s; 30 s to 60 s; 60 s to 125 s; 125 s to 210 s; 210 s to 275 s; 275 s to 300 s; 300 s to 520 s; 520 s to 580 s
   c. 0 m/s; 1.5 m/s; 0 m/s; 1.5 m/s; 0 m/s; $-0.75 \text{ m/s}$; $-3.25 \text{ m/s}$; $-4.5 \text{ m/s}$
   d. 0 m/s$^2$; 0.1 m/s$^2$; 0 m/s$^2$; $-0.04 \text{ m/s}^2$; 0 m/s$^2$; $-0.06 \text{ m/s}^2$; $-0.02 \text{ m/s}^2$; 0.02 m/s$^2$
   e. 0 to 30 s; 210 to 275 s
   f. 0 s to 30 s; 60 s to 125 s; 210 s to 275 s
   g. When the graph slopes upward, acceleration is positive. When it slopes downward, acceleration is negative.
6. No, the bus is moving in the positive direction from 30 s to 210 s (when velocity is positive) and in the negative direction from 275 s to 600 s (when velocity is negative).