CHAPTER 3
Accelerated Motion

BIGIDEA  Acceleration is the rate of change in an object’s velocity.

SECTIONS
1  Acceleration
2  Motion with Constant Acceleration
3  Free Fall

LaunchLAB  iLab Station
GRAPHING MOTION
How does a graph showing constant speed compare to a graph of an object that is accelerating?

WATCH THIS!
SKATEBOARD PHYSICS
How does a trip to your local skate park involve physics? You might be surprised! Explore acceleration as skateboarders show off their best moves.

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Physics 4 You

As an airplane takes off, its speed changes from 5 m/s on the runway to nearly 300 m/s once it’s in the air. If you’ve ever ridden on an airplane, you’ve felt the seat push against your back as the plane rapidly accelerates.

Nonuniform Motion Diagrams

An object in uniform motion moves along a straight line with an unchanging velocity, but few objects move this way all the time. More common is nonuniform motion, in which velocity is changing. In this chapter, you will study nonuniform motion along a straight line. Examples include balls rolling down hills, cars braking to a stop, and falling objects. In later chapters you will analyze nonuniform motion that is not confined to a straight line, such as motion along a circular path and the motion of thrown objects, such as baseballs.

Describing nonuniform motion You can feel a difference between uniform and nonuniform motion. Uniform motion feels smooth. If you close your eyes, it feels as if you are not moving at all. In contrast, when you move around a curve or up and down a roller coaster hill, you feel pushed or pulled.

How would you describe the motion of the person in Figure 1? In the first diagram, the person is motionless, but in the others, her position is changing in different ways. What information do the diagrams contain that could be used to distinguish the different types of motion? Notice the distances between successive positions. Because there is only one image of the person in the first diagram, you can conclude that she is at rest. The distances between images in the second diagram are the same because the jogger is in uniform motion; she moves at a constant velocity. In the remaining two diagrams, the distance between successive positions changes. The change in distance increases if the jogger speeds up. The change decreases if the jogger slows down.
**Particle model diagram** What does a particle model motion diagram look like for an object with changing velocity? Figure 2 shows particle model motion diagrams below the motion diagrams of the jogger when she is speeding up and slowing down. There are two major indicators of the change in velocity in this form of the motion diagram. The change in the spacing of the dots and the differences in the lengths of the velocity vectors indicate the changes in velocity. If an object speeds up, each subsequent velocity vector is longer, and the spacing between dots increases. If the object slows down, each vector is shorter than the previous one, and the spacing between dots decreases. Both types of motion diagrams indicate how an object’s velocity is changing.

**READING CHECK** Analyze What do increasing and decreasing lengths of velocity vectors indicate on a motion diagram?

**Displaying acceleration on a motion diagram** For a motion diagram to give a full picture of an object’s movement, it should contain information about the rate at which the object’s velocity is changing. The rate at which an object’s velocity changes is called the **acceleration** of the object. By including acceleration vectors on a motion diagram, you can indicate the rate of change for the velocity.

Figure 3 shows a particle motion diagram for an object with increasing velocity. Notice that the lengths of the red velocity vectors get longer from left to right along the diagram. The figure also describes how to use the diagram to draw an acceleration vector for the motion. The acceleration vector that describes the increasing velocity is shown in violet on the diagram.

Notice in the figure that if the object’s acceleration is constant, you can determine the length and direction of an acceleration vector by subtracting two consecutive velocity vectors and dividing by the time interval. That is, first find the change in velocity, $Δv = v_f - v_i = v_i + (−v_i)$, where $v_i$ and $v_f$ refer to the velocities at the beginning and the end of the chosen time interval. Then divide by the time interval ($Δt$). The time interval between each dot in Figure 3 is 1 s. You can draw the acceleration vector from the tail of the final velocity vector to the tip of the initial velocity vector.

**Finding Acceleration Vectors**

1. First, draw $v_i$. Below that, draw $v_i$ with its tail aligned with the tip of $v_f$. The acceleration vector $a$ is the same as $Δv$ divided by the time interval.

2. Notice in the figure that if the object's acceleration is constant, you can determine the length and direction of an acceleration vector by subtracting two consecutive velocity vectors and dividing by the time interval. That is, first find the change in velocity, $Δv = v_f - v_i = v_i + (−v_i)$, where $v_i$ and $v_f$ refer to the velocities at the beginning and the end of the chosen time interval. Then divide by the time interval ($Δt$). The time interval between each dot in Figure 3 is 1 s. You can draw the acceleration vector from the tail of the final velocity vector to the tip of the initial velocity vector.

**Figure 3** For constant acceleration, an acceleration vector on a particle model diagram is the difference in the two velocity vectors divided by the time interval: $a = \frac{Δv}{Δt}$.

**Analyze** Can you draw an acceleration vector for two successive velocity vectors that are the same length and direction? Explain.
Direction of Acceleration

Consider the four situations shown in Figure 4 in which an object can accelerate by changing speed. The first motion diagram shows the car moving in the positive direction and speeding up. The second motion diagram shows the car moving in the positive direction and slowing down. The third shows the car speeding up in the negative direction, and the fourth shows the car slowing down as it moves in the negative direction. The figure also shows the velocity vectors for the second time interval of each diagram, along with the corresponding acceleration vectors. Note that $\Delta t$ is equal to 1 s.

In the first and third situations, when the car is speeding up, the velocity and acceleration vectors point in the same direction. In the other two situations, in which the acceleration vector is in the opposite direction from the velocity vectors, the car is slowing down. In other words, when the car’s acceleration is in the same direction as its velocity, the car’s speed increases. When they are in opposite directions, the speed of the car decreases.

Both the direction of an object’s velocity and its direction of acceleration are needed to determine whether it is speeding up or slowing down. An object has a positive acceleration when the acceleration vector points in the positive direction and a negative acceleration when the acceleration vector points in the negative direction. It is important to notice that the sign of acceleration alone does not indicate whether the object is speeding up or slowing down.

**READING CHECK** Describe the motion of an object if its velocity and acceleration vectors have opposite signs.
Velocity-Time Graphs

Just as it was useful to graph position versus time, it also is useful to plot velocity versus time. On a velocity-time graph, or $v$-$t$ graph, velocity is plotted on the vertical axis and time is plotted on the horizontal axis.

**Slope** The velocity-time graph for a car that started at rest and sped up along a straight stretch of road is shown in Figure 5. The positive direction has been chosen to be the same as that of the car’s motion. Notice that the graph is a straight line. This means the car sped up at a constant rate. The rate at which the car’s velocity changed can be found by calculating the slope of the velocity-time graph.

The graph shows that the slope is 5.00 (m/s)/s, which is commonly written as 5 m/s$^2$. Consider the time interval between 4.00 s and 5.00 s. At 4.00 s, the car’s velocity was 20.0 m/s in the positive direction. At 5.00 s, the car was traveling at 25.0 m/s in the same direction. Thus, in 1.00 s, the car’s velocity increased by 5.0 m/s in the positive direction. When the velocity of an object changes at a constant rate, it has a constant acceleration.

**Reading velocity-time graphs** The motions of five runners are shown in Figure 6. Assume that the positive direction is east. The slopes of Graphs A and E are zero. Thus, the accelerations are zero. Both graphs show motion at a constant velocity—Graph A to the east and Graph E to the west. Graph B shows motion with a positive velocity eastward. Its slope indicates a constant, positive acceleration. You can infer that the speed increases because velocity and acceleration are positive. Graph C has a negative slope. It shows motion that begins with a positive velocity, slows down, and then stops. This means the acceleration and the velocity are in opposite directions. The point at which Graphs C and B cross shows that the runners’ velocities are equal at that time. It does not, however, identify their positions.

Graph D indicates motion that starts out toward the west, slows down, for an instant has zero velocity, and then moves east with increasing speed. The slope of Graph D is positive. Because velocity and acceleration are initially in opposite directions, the speed decreases to zero at the time the graph crosses the x-axis. After that time, velocity and acceleration are in the same direction, and the speed increases.

**Reading Check** Describe the meaning of a line crossing the x-axis in a velocity-time graph.

![Figure 5](image)

**Figure 5** You can determine acceleration from a velocity-time graph by calculating the slope of the data. The slope is the rise divided by the run using any two points on the line.

![Figure 6](image)

**Figure 6** Because east is chosen as the positive direction on the graph, velocity is positive if the line is above the horizontal axis and negative if the line is below it. Acceleration is positive if the line is slanted upward on the graph. Acceleration is negative if the line is slanted downward on the graph. A horizontal line indicates constant velocity and zero acceleration.
Average and Instantaneous Acceleration

How does it feel differently if the car you ride in accelerates a little or if it accelerates a lot? As with velocity, the acceleration of most moving objects continually changes. If you want to describe an object’s acceleration, it is often more convenient to describe the overall change in velocity during a certain time interval rather than describing the continual change.

The **average acceleration** of an object is its change in velocity during some measurable time interval divided by that time interval. Average acceleration is measured in meters per second per second (m/s/s), or simply meters per second squared (m/s²). A car might accelerate quickly at times and more slowly at times. Just as average velocity depends only on the starting and ending displacement, average acceleration depends only on the starting and ending velocity during a time interval. **Figure 7** shows a graph of motion in which the acceleration is changing. The average acceleration during a certain time interval is determined just as it is in **Figure 5** for constant acceleration. Notice, however, that because the line is curved, the average acceleration in this graph varies depending on the time interval that you choose.

The change in an object’s velocity at an instant of time is called **instantaneous acceleration**. You can determine the instantaneous acceleration of an object by drawing a tangent line on the velocity-time graph at the point of time in which you are interested. The slope of this line is equal to the instantaneous acceleration. Most of the situations considered in this textbook assume an ideal case of constant acceleration. When the acceleration is the same at all points during a time interval, the average acceleration and the instantaneous accelerations are equal.

**READING CHECK** Contrast How is instantaneous acceleration different from average acceleration?
Calculating Acceleration

How can you describe the acceleration of an object mathematically? Recall that the acceleration of an object is the slope of that object's velocity v. time graph. On a velocity v. time graph, slope equals Δv/Δt.

**AVERAGE ACCELERATION**

Average acceleration is defined as the change in velocity divided by the time it takes to make that change.

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

Suppose you run wind sprints back and forth across the gym. You first run at a speed of 4.0 m/s toward the wall. Then, 10.0 s later, your speed is 4.0 m/s as you run away from the wall. What is your average acceleration if the positive direction is toward the wall?

\[ \bar{a} \equiv \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i} = \frac{-4.0 \text{ m/s} - 4.0 \text{ m/s}}{10.0 \text{ s}} = -0.80 \text{ m/s}^2 \]

**EXAMPLE PROBLEM 1**

**VELOCITY AND ACCELERATION** How would you describe the sprinter’s velocity and acceleration as shown on the graph?

1. **ANALYZE AND SKETCH THE PROBLEM**

   From the graph, note that the magnitude of the sprinter’s velocity starts at zero, increases rapidly for the first few seconds, and then, after reaching about 10.0 m/s, remains almost constant.

   **KNOWN**
   - v = varies
   **UNKNOWN**
   - a = ?

2. **SOLVE FOR THE UNKNOWN**

   Draw tangents to the curve at two points. Choose \( t = 1.00 \) s and \( t = 5.00 \) s.

   Solve for magnitude of the acceleration at 1.00 s:

   \[ a = \frac{\text{rise}}{\text{run}} = \frac{10.0 \text{ m/s} - 6.0 \text{ m/s}}{2.4 \text{ s} - 1.00 \text{ s}} = 2.9 \text{ m/s}^2 \]

   Solve for the magnitude of the instantaneous acceleration at 5.0 s:

   \[ a = \frac{\text{rise}}{\text{run}} = \frac{10.3 \text{ m/s} - 10.0 \text{ m/s}}{10.0 \text{ s} - 0.00 \text{ s}} = 0.030 \text{ m/s}^2 = 0.030 \text{ m/s}^2 \]

   The acceleration is not constant because its magnitude changes from 2.9 m/s\(^2\) at 1.0 s to 0.030 m/s\(^2\) at 5.0 s.

   The acceleration is in the direction chosen to be positive because both values are positive.

3. **EVALUATE THE ANSWER**

   **Are the units correct?** Acceleration is measured in m/s\(^2\).
EXAMPLE PROBLEM 2

ACCELERATION Describe a ball’s motion as it rolls up a slanted driveway. It starts at 2.50 m/s, slows down for 5.00 s, stops for an instant, and then rolls back down. The positive direction is chosen to be up the driveway. The origin is where the motion begins. What are the sign and the magnitude of the ball’s acceleration as it rolls up the driveway?

1 ANALYZE AND SKETCH THE PROBLEM
- Sketch the situation.
- Draw the coordinate system based on the motion diagram.

2 SOLVE FOR THE UNKNOWN
Find the acceleration from the slope of the graph. Solve for the change in velocity and the time taken to make that change.

\[
\Delta v = v_f - v_i
\]
\[
= 0.00 \text{ m/s} - 2.50 \text{ m/s} = -2.50 \text{ m/s}
\]

\[
\Delta t = t_f - t_i
\]
\[
= 5.00 \text{ s} - 0.00 \text{ s} = 5.00 \text{ s}
\]

Solve for the acceleration.

\[
\bar{a} \equiv \frac{\Delta v}{\Delta t} = (-2.50 \text{ m/s}) / 5.00 \text{ s}
\]
\[
= -0.500 \text{ m/s}^2 \text{ or } 0.500 \text{ m/s}^2 \text{ down the driveway}
\]

3 EVALUATE THE ANSWER
- Are the units correct? Acceleration is measured in m/s².
- Do the directions make sense? As the ball slows down, the direction of acceleration is opposite that of velocity.
Acceleration with Constant Speed

Think again about running wind sprints across the gym. Notice that your speed is the same as you move toward the wall of the gym and as you move away from it. In both cases, you are running at a speed of 4.0 m/s. How is it possible for you to be accelerating?

Acceleration can occur even when speed is constant. The average acceleration for the entire trip you make toward the wall of the gym and back again is \(-0.80 \text{ m/s}^2\). The negative sign indicates that the direction of your acceleration is away from the wall because the positive direction was chosen as toward the wall. The velocity changes from positive to negative when the direction of motion changes. A change in velocity results in acceleration. Thus, acceleration can also be associated with a change in the direction of motion.

READING CHECK Explain how it is possible for an object to accelerate when the object is traveling at a constant speed.

5. A race car’s forward velocity increases from 4.0 m/s to 36 m/s over a 4.0-s time interval. What is its average acceleration?

6. The race car in the previous problem slows from 36 m/s to 15 m/s over 3.0 s. What is its average acceleration?

7. A bus is moving west at 25 m/s when the driver steps on the brakes and brings the bus to a stop in 3.0 s.
   a. What is the average acceleration of the bus while braking?
   b. If the bus took twice as long to stop, how would the acceleration compare with what you found in part a?

8. A car is coasting backward downhill at a speed of 3.0 m/s when the driver gets the engine started. After 2.5 s, the car is moving uphill at 4.5 m/s. If uphill is chosen as the positive direction, what is the car’s average acceleration?

9. Rohith has been jogging east toward the bus stop at 3.5 m/s when he looks at his watch and sees that he has plenty of time before the bus arrives. Over the next 10.0 s, he slows his pace to a leisurely 0.75 m/s. What was his average acceleration during this 10.0 s?

10. CHALLENGE If the rate of continental drift were to abruptly slow from 1.0 cm/y to 0.5 cm/y over the time interval of a year, what would be the average acceleration?

11. MAIN IDEA What are three ways an object can accelerate?

12. Position-Time and Velocity-Time Graphs Two joggers run at a constant velocity of 7.5 m/s east. Figure 10 shows the positions of both joggers at time \(t = 0\).
   a. What would be the difference(s) in the position-time graphs of their motion?
   b. What would be the difference(s) in their velocity-time graphs?

13. Velocity-Time Graph Sketch a velocity-time graph for a car that goes east at 25 m/s for 100 s, then west at 25 m/s for another 100 s.

14. Average Velocity and Average Acceleration A canoeist paddles upstream at a velocity of 2.0 m/s for 4.0 s and then floats downstream at 4.0 m/s for 4.0 s.
   a. What is the average velocity of the canoe during the 8.0-s time interval?
   b. What is the average acceleration of the canoe during the 8.0-s time interval?

15. Critical Thinking A police officer clocked a driver going 32 km/h over the speed limit just as the driver passed a slower car. When the officer stopped the car, the driver argued that the other driver should get a ticket as well. The driver said that the cars must have been going the same speed because they were observed next to each other. Is the driver correct? Explain with a sketch and a motion diagram.

**Figure 10**

-15 m West

- origin

- 15 m East
Suppose a car is moving along a road and suddenly the driver sees a fallen tree blocking the way ahead. Will the driver be able to stop in time? It all depends on how effectively the car’s brakes can cause the car to accelerate in the direction opposite its motion.

### Position with Constant Acceleration

If an object experiences constant acceleration, its velocity changes at a constant rate. How does its position change? The positions at different times of a car with constant acceleration are graphed in Figure 11. The graph shows that the car’s motion is not uniform. The displacements for equal time intervals on the graph get larger and larger. As a result, the slope of the line in Figure 11 gets steeper as time goes on. For an object with constant acceleration, the position-time graph is a parabola.

The slopes from the position-time graph in Figure 11 have been used to create the velocity-time graph on the left in Figure 12. For an object with constant acceleration, the velocity-time graph is a straight line.

A unique position-time graph cannot be created using a velocity-time graph because it does not contain information about position. It does, however, contain information about displacement. Recall that for an object moving at a constant velocity, the velocity is the displacement divided by the time interval. The displacement is then the product of the velocity and the time interval. On the right graph in Figure 12 on the next page, \( v \) is the height of the plotted line above the horizontal axis, and \( \Delta t \) is the width of the shaded triangle. The area is \( \frac{1}{2} v \Delta t \), or \( \Delta x \). Thus, the area under the \( v-t \) graph equals the displacement.

**READING CHECK** Identify What is the shape of a position-time graph of an object traveling with constant acceleration?

![Position v. Time](image)

**Figure 11** The slope of a position-time graph changes with time for an object with constant acceleration.
Velocity with Average Acceleration

You have read that the equation for average velocity can be algebraically rearranged to show the new position after a period of time, given the initial position and the average velocity. The definition of average acceleration can be manipulated similarly to show the new velocity after a period of time, given the initial velocity and the average acceleration.

If you know an object’s average acceleration during a time interval, you can use it to determine how much the velocity changed during that time. You can rewrite the definition of average acceleration \( \bar{a} \equiv \frac{\Delta v}{\Delta t} \) as follows:

\[
\Delta v = \bar{a} \Delta t
\]

The equation for final velocity with average acceleration can be written:

**FINAL VELOCITY WITH AVERAGE ACCELERATION**

The final velocity is equal to the initial velocity plus the product of the average acceleration and the time interval.

\[
v_f = v_i + \bar{a} \Delta t
\]

In cases when the acceleration is constant, the average acceleration \( \bar{a} \) is the same as the instantaneous acceleration \( a \). This equation can be rearranged to find the time at which an object with constant acceleration has a given velocity. You can also use it to calculate the initial velocity of an object when both a velocity and the time at which it occurred are given.

**PRACTICE PROBLEMS**

16. A golf ball rolls up a hill toward a miniature-golf hole. Assume the direction toward the hole is positive.
   a. If the golf ball starts with a speed of 2.0 m/s and slows at a constant rate of 0.50 m/s\(^2\), what is its velocity after 2.0 s?
   b. What is the golf ball’s velocity if the constant acceleration continues for 6.0 s?
   c. Describe the motion of the golf ball in words and with a motion diagram.

17. A bus traveling 30.0 km/h east has a constant increase in speed of 1.5 m/s\(^2\). What is its velocity 6.8 s later?

18. If a car accelerates from rest at a constant rate of 5.5 m/s\(^2\) north, how long will it take for the car to reach a velocity of 28 m/s north?

19. CHALLENGE A car slows from 22 m/s to 3.0 m/s at a constant rate of 2.1 m/s\(^2\). How many seconds are required before the car is traveling at a forward velocity of 3.0 m/s?
EXAMPLE PROBLEM 3

FINDING DISPLACEMENT FROM A VELOCITY-TIME GRAPH  The velocity-time graph at the right shows the motion of an airplane. Find the displacement of the airplane for Δt = 1.0 s and for Δt = 2.0 s. Let the positive direction be forward.

1 ANALYZE AND SKETCH THE PROBLEM

- The displacement is the area under the v-t graph.
- The time intervals begin at t = 0.0 s.

KNOWN  UNKNOWN
v = +75 m/s  Δx = ?
Δt = 1.0 s
Δt = 2.0 s

2 SOLVE FOR THE UNKNOWN

Use the relationship among displacement, velocity, and time interval to find Δx during Δt = 1.0 s.

Δx = vΔt
  = (+75 m/s)(1.0 s)  ▼ Substitute v = +75 m/s, Δt = 1.0 s.
  = +75 m

Use the same relationship to find Δx during Δt = 2.0 s.

Δx = vΔt
  = (+75 m/s)(2.0 s)  ▼ Substitute v = +75 m/s, Δt = 2.0 s.
  = +150 m

3 EVALUATE THE ANSWER

- Are the units correct? Displacement is measured in meters.
- Do the signs make sense? The positive sign agrees with the graph.
- Is the magnitude realistic? Moving a distance of about one football field per second is reasonable for an airplane.

PRACTICE PROBLEMS

20. The graph in Figure 13 describes the motion of two bicyclists, Akiko and Brian, who start from rest and travel north, increasing their speed with a constant acceleration. What was the total displacement of each bicyclist during the time shown for each?  Hint: Use the area of a triangle: area = \( \frac{1}{2} \) (base)(height).

21. The motion of two people, Carlos and Diana, moving south along a straight path is described by the graph in Figure 14. What is the total displacement of each person during the 4.0-s interval shown on the graph?

22. CHALLENGE  A car, just pulling onto a straight stretch of highway, has a constant acceleration from 0 m/s to 25 m/s west in 12 s.

a. Draw a v-t graph of the car’s motion.

b. Use the graph to determine the car’s displacement during the 12.0-s time interval.

c. Another car is traveling along the same stretch of highway. It travels the same distance in the same time as the first car, but its velocity is constant. Draw a v-t graph for this car’s motion.

d. Explain how you knew this car’s velocity.
Motion with an initial nonzero velocity The graph in Figure 15 describes constant acceleration that started with an initial velocity of $v_i$. To determine the displacement, you can divide the area under the graph into a rectangle and a triangle. The total area is then:

$$\Delta x = \Delta x_{\text{rectangle}} + \Delta x_{\text{triangle}} = v_i (\Delta t) + \left(\frac{1}{2}\right) a \Delta t^2$$

Substituting $a \Delta t$ for the change in velocity in the equation yields:

$$\Delta x = \Delta x_{\text{rectangle}} + \Delta x_{\text{triangle}} = v_i (\Delta t) + \left(\frac{1}{2}\right) a (\Delta t)^2$$

When the initial or final position of the object is known, the equation can be written as follows:

$$x_f - x_i = v_i(\Delta t) + \left(\frac{1}{2}\right) a (\Delta t)^2$$

or

$$x_i + v_i(\Delta t) + \left(\frac{1}{2}\right) a (\Delta t)^2$$

If the initial time is $t_i = 0$, the equation then becomes the following.

**POSITION WITH AVERAGE ACCELERATION**

An object’s final position is equal to the sum of its initial position, the product of the initial velocity and the final time, and half the product of the acceleration and the square of the final time.

$$x_f = x_i + v_i t_f + \left(\frac{1}{2}\right) a t_f^2$$

**An Alternative Equation**

Often, it is useful to relate position, velocity, and constant acceleration without including time. Rearrange the equation

$$v_f = v_i + a t_f$$

to solve for time: $t_f = \frac{v_f - v_i}{a}$.

You can then rewrite the position with average acceleration equation by substituting $t_f$ to obtain the following:

$$x_f = x_i + v_i \left(\frac{v_f - v_i}{a}\right) + \left(\frac{1}{2}\right) a \left(\frac{v_f - v_i}{a}\right)^2$$

This equation can be solved for the velocity ($v_f$) at any position ($x_f$).

**VELOCITY WITH CONSTANT ACCELERATION**

The square of the final velocity equals the sum of the square of the initial velocity and twice the product of the acceleration and the displacement since the initial time.

$$v_f^2 = v_i^2 + 2a (x_f - x_i)$$
EXAMPLE PROBLEM 4

DISPLACEMENT An automobile starts at rest and accelerates at 3.5 m/s² after a traffic light turns green. How far will it have gone when it is traveling at 25 m/s?

1 ANALYZE AND SKETCH THE PROBLEM
• Sketch the situation.
• Establish coordinate axes. Let the positive direction be to the right.
• Draw a motion diagram.

KNOWN UNKOWN
\[ x_i = 0.00 \text{ m} \]
\[ v_i = 0.00 \text{ m/s} \]
\[ v_f = +25 \text{ m/s} \]
\[ a = +3.5 \text{ m/s}^2 \]

2 SOLVE FOR THE UNKNOWN
Use the relationship among velocity, acceleration, and displacement to find \( x_f \).
\[ v_f^2 = v_i^2 + 2a(x_f - x_i) \]
\[ x_f = x_i + \frac{v_f^2 - v_i^2}{2a} \]
\[ = 0.00 + \frac{(25 \text{ m/s})^2 - (0.00 \text{ m/s})^2}{2(+3.5 \text{ m/s}^2)} \]
\[ = +89 \text{ m} \]

3 EVALUATE THE ANSWER
• Are the units correct? Position is measured in meters.
• Does the sign make sense? The positive sign agrees with both the pictorial and physical models.
• Is the magnitude realistic? The displacement is almost the length of a football field. The result is reasonable because 25 m/s (about 55 mph) is fast.

23. A skateboarder is moving at a constant speed of 1.75 m/s when she starts up an incline that causes her to slow down with a constant acceleration of \(-0.20 \text{ m/s}^2\). How much time passes from when she begins to slow down until she begins to move back down the incline?

24. A race car travels on a straight racetrack with a forward velocity of 44 m/s and slows at a constant rate to a velocity of 22 m/s over 11 s. How far does it move during this time?

25. A car accelerates at a constant rate from 15 m/s to 25 m/s while it travels a distance of 125 m. How long does it take to achieve the final speed?

26. A bike rider pedals with constant acceleration to reach a velocity of 7.5 m/s north over a time of 4.5 s. During the period of acceleration, the bike's displacement is 19 m north. What was the initial velocity of the bike?

27. CHALLENGE The car in Figure 16 travels west with a forward acceleration of 0.22 m/s². What was the car’s velocity (\( v \)) at point \( x_i \) if it travels a distance of 350 m in 18.4 s?
EXAMPLE PROBLEM 5

TWO-PART MOTION You are driving a car, traveling at a constant velocity of 25 m/s along a straight road, when you see a child suddenly run onto the road. It takes 0.45 s for you to react and apply the brakes. As a result, the car slows with a steady acceleration of 8.5 m/s² in the direction opposite your motion and comes to a stop. What is the total displacement of the car before it stops?

1 ANALYZE AND SKETCH THE PROBLEM
- Sketch the situation.
- Choose a coordinate system with the motion of the car in the positive direction.
- Draw the motion diagram, and label \( v \) and \( a \).

KNOWN
- \( v_{\text{reacting}} = +25 \text{ m/s} \)
- \( t_{\text{reacting}} = 0.45 \text{ s} \)
- \( a_{\text{braking}} = -8.5 \text{ m/s}^2 \)
- \( v_{i, \text{braking}} = +25 \text{ m/s} \)
- \( v_{f, \text{braking}} = 0.00 \text{ m/s} \)

UNKNOWN
- \( x_{\text{reacting}} = ? \)
- \( x_{\text{braking}} = ? \)
- \( x_{\text{total}} = ? \)

2 SOLVE FOR THE UNKNOWN
Reacting:
Use the relationship among displacement, velocity, and time interval to find the displacement of the car as it travels at a constant speed.

\[
x_{\text{reacting}} = v_{\text{reacting}} t_{\text{reacting}}
\]

\[
x_{\text{reacting}} = (+25 \text{ m/s})(0.45 \text{ s}) = +11 \text{ m}
\]

Braking:
Use the relationship among velocity, acceleration, and displacement to find the displacement of the car while it is braking.

\[
v_{f, \text{braking}}^2 = v_{\text{reacting}}^2 + 2a_{\text{braking}}(x_{\text{braking}})
\]

Solve for \( x_{\text{braking}} \):

\[
x_{\text{braking}} = \frac{v_{f, \text{braking}}^2 - v_{\text{reacting}}^2}{2a_{\text{braking}}}
\]

\[
= \frac{(0.00 \text{ m/s})^2 - (+25 \text{ m/s})^2}{2(-8.5 \text{ m/s}^2)}
\]

\[
= +37 \text{ m}
\]

The total displacement is the sum of the reaction displacement and the braking displacement.

Solve for \( x_{\text{total}} \):

\[
x_{\text{total}} = x_{\text{reacting}} + x_{\text{braking}}
\]

\[
= +11 \text{ m} + 37 \text{ m}
\]

\[
= +48 \text{ m}
\]

3 EVALUATE THE ANSWER
- Are the units correct? Displacement is measured in meters.
- Do the signs make sense? Both \( x_{\text{reacting}} \) and \( x_{\text{braking}} \) are positive, as they should be.
- Is the magnitude realistic? The braking displacement is small because the magnitude of the acceleration is large.
PRACTICE PROBLEMS

28. A car with an initial velocity of 24.5 m/s east has an acceleration of 4.2 m/s² west. What is its displacement at the moment that its velocity is 18.3 m/s east?

29. A man runs along the path shown in Figure 17. From point A to point B, he runs at a forward velocity of 4.5 m/s for 15.0 min. From point B to point C, he runs up a hill. He slows down at a constant rate of 0.050 m/s² for 90.0 s and comes to a stop at point C. What was the total distance the man ran?

30. You start your bicycle ride at the top of a hill. You coast down the hill at a constant acceleration of 2.00 m/s². When you get to the bottom of the hill, you are moving at 18.0 m/s, and you pedal to maintain that speed. If you continue at this speed for 1.00 min, how far will you have gone from the time you left the hilltop?

31. Sunee is training for a 5.0-km race. She starts out her training run by moving at a constant pace of 4.3 m/s for 19 min. Then she accelerates at a constant rate until she crosses the finish line 19.4 s later. What is her acceleration during the last portion of the training run?

32. CHALLENGE Sekazi is learning to ride a bike without training wheels. His father pushes him with a constant acceleration of 0.50 m/s² east for 6.0 s. Sekazi then travels at 3.0 m/s east for another 6.0 s before falling. What is Sekazi’s displacement? Solve this problem by constructing a velocity-time graph for Sekazi’s motion and computing the area underneath the graphed line.

PRACTICE PROBLEMS

Do additional problems. Online Practice

SECTION 2 REVIEW

33. MAIN IDEA If you were given initial and final velocities and the constant acceleration of an object, and you were asked to find the displacement, what mathematical relationship would you use?

34. Acceleration A woman driving west along a straight road at a speed of 23 m/s sees a deer on the road ahead. She applies the brakes when she is 210 m from the deer. If the deer does not move and the car stops right before it hits the deer, what is the acceleration provided by the car’s brakes?

35. Distance The airplane in Figure 18 starts from rest and accelerates east at a constant 3.00 m/s² for 30.0 s before leaving the ground.

a. What was the plane’s displacement (Δx)?

b. How fast was the airplane going when it took off?

Figure 18

36. Distance An in-line skater first accelerates from 0.0 m/s to 5.0 m/s in 4.5 s, then continues at this constant speed for another 4.5 s. What is the total distance traveled by the in-line skater?

37. Final Velocity A plane travels a distance of 5.0 × 10² m north while being accelerated uniformly from rest at the rate of 5.0 m/s². What final velocity does it attain?

38. Final Velocity An airplane accelerated uniformly from rest at the rate of 5.0 m/s² south for 14 s. What final velocity did it attain?

39. Graphs A sprinter walks up to the starting blocks at a constant speed and positions herself for the start of the race. She waits until she hears the starting pistol go off and then accelerates rapidly until she attains a constant velocity. She maintains this velocity until she crosses the finish line, and then she slows to a walk, taking more time to slow down than she did to speed up at the beginning of the race. Sketch a velocity-time and a position-time graph to represent her motion. Draw them one above the other using the same time scale. Indicate on your position-time graph where the starting blocks and finish line are.

40. Critical Thinking Describe how you could calculate the acceleration of an automobile. Specify the measuring instruments and the procedures you would use.
Galileo’s Discovery

Which falls with more acceleration, a piece of paper or your physics book? If you hold one in each hand and release them, the book hits the ground first. Do heavier objects accelerate more as they fall? Try dropping them again, but first place the paper flat on the book. Without air pushing against it, the paper falls as fast as the book. For a lightweight object such as paper, collisions with particles of air have a greater effect than they do on a heavy book.

To understand falling objects, first consider the case in which air does not have an appreciable effect on motion. Recall that gravity is an attraction between objects. **Free fall** is the motion of an object when gravity is the only significant force acting on it.

About 400 years ago, Galileo Galilei discovered that, neglecting the effect of the air, all objects in free fall have the same acceleration. It doesn’t matter what they are made of or how much they weigh. The acceleration of an object due only to the effect of gravity is known as **free-fall acceleration**. Figure 19 depicts the results of a 1971 free-fall experiment on the Moon in which astronauts verified Galileo’s results.

Near Earth’s surface, free-fall acceleration is about 9.8 m/s² downward (which is equal to about 22 mph/s downward). Think about the skydivers above. Each second the skydivers fall, their downward velocity increases by 9.8 m/s. When analyzing free fall, whether you treat the acceleration as positive or negative depends on the coordinate system you use. If you define upward as the positive direction, then the free-fall acceleration is negative. If you decide that downward is the positive direction, then free-fall acceleration is positive.

**Figure 19** In 1971 astronaut David Scott dropped a hammer and a feather at the same time from the same height above the Moon’s surface. The hammer’s mass was greater, but both objects hit the ground at the same time because the Moon has gravity but no air.
Free-Fall Acceleration

Galileo’s discovery explains why parachutists can form a ring in midair. Regardless of their masses, they fall with the same acceleration. To understand the acceleration that occurs during free fall, look at the multiflash photo of a dropped ball in Figure 20. The time interval between the images is 0.06 s. The distance between each pair of images increases, so the speed is increasing. If the upward direction is positive, then the velocity is becoming more and more negative.

Ball thrown upward Instead of a dropped ball, could this photo also illustrate a ball thrown upward? Suppose you throw a ball upward with a speed of 20.0 m/s. If you choose upward to be positive, then the ball starts at the bottom of the photo with a positive velocity. The acceleration is \( a = -9.8 \) m/s\(^2\). Because velocity and acceleration are in opposite directions, the speed of the ball decreases. If you think of the bottom of the photo as the start, this agrees with the multiflash photo.

Rising and falling motion After 1 s, the ball’s velocity is reduced by 9.8 m/s, so it now is traveling at +10.2 m/s. After 2 s, the velocity is +0.4 m/s, and the ball still is moving upward. What happens during the next second? The ball’s velocity is reduced by another 9.8 m/s and equals −9.4 m/s. The ball now is moving downward. After 4 s, the velocity is −19.2 m/s, meaning the ball is falling even faster.

Velocity-time graph The \( v-t \) graph for the ball as it goes up and down is shown in Figure 21. The straight line sloping downward does not mean that the speed is always decreasing. The speed decreases as the ball rises and increases as it falls. At around 2 s, the velocity changes smoothly from positive to negative. As the ball falls, its speed increases in the negative direction. The figure also shows a closer view of the \( v-t \) graph. At an instant of time, near 2.04 s, the velocity is zero.

Figure 21 The velocity-time graph describes the change in the ball’s speed as it rises and falls. The graph on the right gives a close-up view of the change in velocity at the top of the ball’s trajectory. Analyze What would the graph look like if downward were chosen as the positive direction?

FREE FALL

How can you use the motion of a falling object to estimate free-fall acceleration?

iLab Station

Figure 20 Because of free-fall acceleration, the speed of this falling ball increases 9.8 m/s each second.
Position-time graph Look at the position-time graphs in Figure 22. These graphs show how the ball’s height changes as it rises and falls. If an object is moving with constant acceleration, its position-time graph forms a parabola. Because the ball is rising and falling, its graph is an inverted parabola. The shape of the graph shows the progression of time. It does not mean that the ball’s path was in the shape of a parabola. The close-up graph on the right shows that at about 2.04 s, the ball reaches its maximum height.

Maximum height Compare the close-up graphs in Figure 21 and Figure 22. Just before the ball reaches its maximum height, its velocity is decreasing in the negative direction. At the instant of time when its height is maximum, its velocity is zero. Just after it reaches its maximum height, the ball’s velocity is increasing in the negative direction.

Acceleration The slope of the line on the velocity-time graph in Figure 21 is constant at $-9.8 \text{ m/s}^2$. This shows that the ball’s free-fall acceleration is 9.8 m/s$^2$ in the downward direction the entire time the ball is rising and falling.

It may seem that the acceleration should be zero at the top of the trajectory, but this is not the case. At the top of the flight, the ball’s velocity is 0 m/s. If its acceleration were also zero, the ball’s velocity would not change and would remain at 0 m/s. The ball would not gain any downward velocity and would simply hover in the air. Have you ever seen that happen? Objects tossed in the air on Earth always fall, so you know the acceleration of an object at the top of its flight must not be zero. Further, because the object falls down, you know the acceleration must be downward.

READING CHECK Analyze If you throw a ball straight up, what are its velocity and acceleration at the uppermost point of its path?
Free-fall rides Amusement parks use the concept of acceleration to design rides that give the riders the sensation of free fall. These types of rides usually consist of three parts: the ride to the top, momentary suspension, and the fall downward. Motors provide the force needed to move the cars to the top of the ride. When the cars are in free fall, the most massive rider and the least massive rider will have the same acceleration.

Suppose the free-fall ride shown in Figure 23 starts from the top at rest and is in free fall for 1.5 s. What would be its velocity at the end of 1.5 s? Choose a coordinate system with a positive axis upward and the origin at the initial position of the car.

Because the car starts at rest, \( v_i \) would be equal to 0.0 m/s. To calculate the final velocity, use the equation for velocity with constant acceleration.

\[
v_f = v_i + at_f
\]

\[
v_f = 0.0 \text{ m/s} + (-9.8 \text{ m/s}^2)(1.5 \text{ s})
\]

\[
v_f = -15 \text{ m/s}
\]

How far do people on the ride fall during this time? Use the equation for displacement when time and constant acceleration are known.

\[
x_f = x_i + v_i t_f + \left(\frac{1}{2}\right)at_f^2
\]

\[
x_f = 0.0 \text{ m} + (0.0 \text{ m/s})(1.5 \text{ s}) + \left(\frac{1}{2}\right)(-9.8 \text{ m/s}^2)(1.5 \text{ s})^2
\]

\[
x_f = -11 \text{ m}
\]

Figure 23 The people on this amusement-park ride experience free-fall acceleration.

PRACTICE PROBLEMS

41. A construction worker accidentally drops a brick from a high scaffold.
   a. What is the velocity of the brick after 4.0 s?
   b. How far does the brick fall during this time?

42. Suppose for the previous problem you choose your coordinate system so that the opposite direction is positive.
   a. What is the brick's velocity after 4.0 s?
   b. How far does the brick fall during this time?

43. A student drops a ball from a window 3.5 m above the sidewalk. How fast is it moving when it hits the sidewalk?

44. A tennis ball is thrown straight up with an initial speed of 22.5 m/s. It is caught at the same distance above the ground.
   a. How high does the ball rise?
   b. How long does the ball remain in the air?
   Hint: The time it takes the ball to rise equals the time it takes to fall.

45. You decide to flip a coin to determine whether to do your physics or English homework first. The coin is flipped straight up.
   a. What are the velocity and acceleration of the coin at the top of its trajectory?
   b. If the coin reaches a high point of 0.25 m above where you released it, what was its initial speed?
   c. If you catch it at the same height as you released it, how much time did it spend in the air?

46. CHALLENGE A basketball player is holding a ball in her hands at a height of 1.5 m above the ground. She drops the ball, and it bounces several times. After the first bounce, the ball only returns to a height of 0.75 m. After the second bounce, the ball only returns to a height of 0.25 m.
   a. Suppose downward is the positive direction. What would the shape of a velocity-time graph look like for the first two bounces?
   b. What would be the shape of a position-time graph for the first two bounces?
Variations in Free Fall

When astronaut David Scott performed his free-fall experiment on the Moon, the hammer and the feather did not fall with an acceleration of magnitude 9.8 m/s$^2$. The value 9.8 m/s$^2$ is free-fall acceleration only near Earth’s surface. The magnitude of free-fall acceleration on the Moon is approximately 1.6 m/s$^2$, which is about one-sixth its value on Earth.

When you study force and motion, you will learn about factors that affect the value of free-fall acceleration. One factor is the mass of the object, such as Earth or the Moon, that is responsible for the acceleration. Free-fall acceleration is not as great near the Moon as near Earth because the Moon has much less mass.

Free-fall acceleration also depends on the distance from the object responsible for it. The rings drawn around Earth in Figure 24 show how free-fall acceleration decreases with distance from Earth. It is important to understand, however, that variations in free-fall acceleration at different locations on Earth’s surface are very small, even with great variations in elevation. In New York City, for example, the magnitude of free-fall acceleration is about 9.81 m/s$^2$. In Denver, Colorado, it is about 9.79 m/s$^2$, despite a change in elevation of almost 1600 m greater. For calculations in this book, a value of 9.8 m/s$^2$ will be used for free-fall acceleration.

**SECTION 3 REVIEW**

47. **MAIN IDEA** Suppose you hold a book in one hand and a flat sheet of paper in another hand. You drop them both, and they fall to the ground. Explain why the falling book is a good example of free fall, but the paper is not.

48. **Final Velocity** Your sister drops your house keys down to you from the second-floor window, as shown in Figure 25. What is the velocity of the keys when you catch them?

Figure 25

49. **Free-Fall Ride** Suppose a free-fall ride at an amusement park starts at rest and is in free fall. What is the velocity of the ride after 2.3 s? How far do people on the ride fall during the 2.3-s time period?

50. **Maximum Height and Flight Time** The free-fall acceleration on Mars is about one-third that on Earth. Suppose you throw a ball upward with the same velocity on Mars as on Earth.

   a. How would the ball’s maximum height compare to that on Earth?

   b. How would its flight time compare?

51. **Velocity and Acceleration** Suppose you throw a ball straight up into the air. Describe the changes in the velocity of the ball. Describe the changes in the acceleration of the ball.

52. **Critical Thinking** A ball thrown vertically upward continues upward until it reaches a certain position, and then falls downward. The ball’s velocity is instantaneously zero at that highest point. Is the ball accelerating at that point? Devise an experiment to prove or disprove your answer.

Section 3 • Free Fall
Going Down?

Amusement-Park Thrill Rides
Your stomach jumps as you plummet 100 m downward. Just when you think you might smash into the ground, the breaks kick in and the amusement-park ride brings you to a slow and safe stop. “Let’s go again!” cries your friend.

It’s all about acceleration. Whether it’s the 100-m plunge of a drop tower or the gentle up-and-down action of a carousel ride, the thrills of many amusement-park rides are based on the same principle—changes in velocity are exciting. Thrill rides take advantage of accelerations due to both changes in speed and changes in direction. A roller coaster is exciting because of accelerations produced by hills, loops, and banked turns, as shown in Figure 1.

Rides that use free-fall acceleration Many rides use free-fall acceleration to generate thrills. Drop-tower rides let passengers experience free fall and then carefully slow their descent just before they reach the ground. Pendulum rides, such as the one in Figure 2, act like giant swings. Passengers experience a stomach-churning moment as the pendulum reaches the top of its swing and begins to move downward. Passengers on a roller coaster experience a similar moment at the top of a hill.

FIGURE 1 Passengers accelerate as they move around a banked turn of a roller coaster. Acceleration is also part of what provides the excitement in a series of loops.

FIGURE 2 Passengers sit in the pendulum of this pirate ship–themed ride, which swings back and forth like the pendulum on a grandfather clock.

Research amusement-park ride design online. Design your own ride and present your design to the class. Identify points during the ride where the passengers accelerate.
CHAPTER 3

STUDY GUIDE

BIG IDEA Acceleration is the rate of change in an object’s velocity.

SECTION 1 Acceleration

MAIN IDEA An object accelerates when its velocity changes—that is, when it speeds up, slows down, or changes direction.

• Acceleration is the rate at which an object’s velocity changes.

• Velocity and acceleration are not the same thing. An object moving with constant velocity has zero acceleration. When the velocity and the acceleration of an object are in the same direction, the object speeds up; when they are in opposite directions, the object slows down.

• You can use a velocity-time graph to find the velocity and the acceleration of an object. The average acceleration of an object is the slope of its velocity-time graph.

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

SECTION 2 Motion with Constant Acceleration

MAIN IDEA For an object with constant acceleration, the relationships among position, velocity, acceleration, and time can be described by graphs and equations.

• If an object is moving with constant acceleration, its position-time graph is a parabola, and its velocity-time graph is a straight line.

• The area under an object’s velocity-time graph is its displacement.

• In motion with constant acceleration, position, velocity, acceleration, and time are related:

\[ v_f = v_i + a \Delta t \]
\[ x_f = x_i + v_i t + \frac{1}{2} a t^2 \]
\[ v_f^2 = v_i^2 + 2a(x_f - x_i) \]

SECTION 3 Free Fall

MAIN IDEA The acceleration of an object in free fall is due to gravity alone.

• Free-fall acceleration on Earth is about 9.8 m/s² downward. The sign associated with free-fall acceleration in equations depends on the choice of the coordinate system.

• When an object is in free fall, gravity is the only force acting on it. Equations for motion with constant acceleration can be used to solve problems involving objects in free fall.
SECTION 1  Acceleration

Mastering Concepts

53. BIGIDEA  How are velocity and acceleration related?

54. Give an example of each of the following:
   a. an object that is slowing down but has a positive acceleration
   b. an object that is speeding up but has a negative acceleration
   c. an object that is moving at a constant speed but has an acceleration

55. Figure 26 shows the velocity-time graph for an automobile on a test track. Describe how the velocity changes with time.

![Velocity v. Time Graph](image)

56. If the velocity-time graph of an object moving on a straight path is a line parallel to the horizontal axis, what can you conclude about its acceleration?

Mastering Problems

57. Ranking Task  Rank the following objects according to the magnitude of the acceleration, from least to greatest. Specifically indicate any ties.
   A. A falling acorn accelerates from 0.50 m/s to 10.3 m/s in 1.0 s.
   B. A car accelerates from 20 m/s to rest in 1.0 s.
   C. A centipede accelerates from 0.40 cm/s to 2.0 cm/s in 0.50 s.
   D. While being hit, a golf ball accelerates from rest to 4.3 m/s in 0.40 s.
   E. A jogger accelerates from 2.0 m/s to 1.0 m/s in 8.3 s.

58. Problem Posing  Complete this problem so that it can be solved using the concept listed: “Angela is playing basketball . . .”
   a. acceleration
   b. speed

Table 1  Velocity v. Time

<table>
<thead>
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<th>Velocity (m/s)</th>
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<tbody>
<tr>
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<td>−4.00</td>
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<tr>
<td>12.0</td>
<td>−8.00</td>
</tr>
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</table>

59. The graph in Figure 27 describes the motion of an object moving east along a straight path. Find the acceleration of the object at each of these times:
   a. during the first 5.0 min of travel
   b. between 5.0 min and 10.0 min
   c. between 10.0 min and 15.0 min
   d. between 20.0 min and 25.0 min

![Velocity v. Time Graph](image)

60. Plot a velocity-time graph using the information in Table 1, and answer the following questions:
   a. During what time interval is the object speeding up? Slowing down?
   b. At what time does the object reverse direction?
   c. How does the average acceleration of the object between 0.0 s and 2.0 s differ from the average acceleration between 7.0 s and 12.0 s?
61. Determine the final velocity of a proton that has an initial forward velocity of $2.35 \times 10^5$ m/s and then is accelerated uniformly in an electric field at the rate of $-1.10 \times 10^{12}$ m/s² for $1.50 \times 10^{-7}$ s.

62. Ranking Task Marco wants to buy the used sports car with the greatest acceleration. Car A can go from 0 m/s to 17.9 m/s in 4.0 s. Car B can accelerate from 0 m/s to 22.4 m/s in 3.5 s. Car C can go from 0 to 26.8 m/s in 6.0 s. Rank the three cars from greatest acceleration to least. Indicate if any are the same.

SECTION 2
Motion with Constant Acceleration

Mastering Concepts

63. What quantity does the area under a velocity-time graph represent?

64. Reverse Problem Write a physics problem with real-life objects for which the graph in Figure 28 would be part of the solution.

SECTION 3
Free Fall

Mastering Concepts

69. Explain why an aluminum ball and a steel ball of similar size and shape, dropped from the same height, reach the ground at the same time.

70. Give some examples of falling objects for which air resistance can and cannot be ignored.

Mastering Problems

71. Suppose an astronaut drops a feather from a height of 1.2 m above the surface of the Moon. If the free-fall acceleration on the Moon is $1.62 \text{ m/s}^2$ downward, how long does it take the feather to hit the Moon’s surface?

72. A stone that starts at rest is in free fall for 8.0 s.
   a. Calculate the stone’s velocity after 8.0 s.
   b. What is the stone’s displacement during this time?

73. A bag is dropped from a hovering helicopter. The bag has fallen for 2.0 s. What is the bag’s velocity? How far has the bag fallen? Ignore air resistance.

74. You throw a ball downward from a window at a speed of 2.0 m/s. How fast will it be moving when it hits the sidewalk 2.5 m below?

75. If you throw the ball in the previous problem up instead of down, how fast will it be moving when it hits the sidewalk?
76. **Beanbag** You throw a beanbag in the air and catch it 2.2 s later at the same place at which you threw it.
   a. How high did it go?
   b. What was its initial velocity?

## Applying Concepts

77. **Croquet** A croquet ball, after being hit by a mallet, slows down and stops. Do the velocity and the acceleration of the ball have the same signs?

78. Explain how you would walk to produce each of the position-time graphs in **Figure 30**.

![Figure 30](image)

79. If you were given a table of velocities of an object at various times, how would you determine whether the acceleration was constant?

80. Look back at the graph in **Figure 26**. The three notches in the graph occur where the driver changed gears. Describe the changes in velocity and acceleration of the car while in first gear. Is the acceleration just before a gear change larger or smaller than the acceleration just after the change? Explain your answer.

81. An object shot straight up rises for 7.0 s before it reaches its maximum height. A second object falling from rest takes 7.0 s to reach the ground. Compare the displacements of the two objects during this time interval.

82. Draw a velocity-time graph for each of the graphs in **Figure 31**.

![Figure 31](image)

83. **The Moon** The value of free-fall acceleration on the Moon is about one-sixth of its value on Earth.
   a. Would a ball dropped by an astronaut hit the surface of the Moon with a greater, equal, or lesser speed than that of a ball dropped from the same height to Earth?
   b. Would it take the ball more, less, or equal time to fall?

84. **Jupiter** An object on the planet Jupiter has about three times the free-fall acceleration as on Earth. Suppose a ball could be thrown vertically upward with the same initial velocity on Earth and on Jupiter. Neglect the effects of Jupiter’s atmospheric resistance, and assume that gravity is the only force on the ball.
   a. How would the maximum height reached by the ball on Jupiter compare to the maximum height reached on Earth?
   b. If the ball on Jupiter were thrown with an initial velocity that is three times greater, how would this affect your answer to part a?

85. Rock A is dropped from a cliff, and rock B is thrown upward from the same position.
   a. When they reach the ground at the bottom of the cliff, which rock has a greater velocity?
   b. Which has a greater acceleration?
   c. Which arrives first?

## Mixed Review

86. Suppose a spaceship far from any star or planet had a uniform forward acceleration from 65.0 m/s to 162.0 m/s in 10.0 s. How far would the spaceship move?

87. **Figure 32** is a multiflash photo of a horizontally moving ball. What information about the photo would you need and what measurements would you make to estimate the acceleration?

![Figure 32](image)

88. **Bicycle** A bicycle accelerates from 0.0 m/s to 4.0 m/s in 4.0 s. What distance does it travel?

89. A weather balloon is floating at a constant height above Earth when it releases a pack of instruments.
   a. If the pack hits the ground with a downward velocity of 73.5 m/s, how far did the pack fall?
   b. How long did it take for the pack to fall?
90. The total distance a steel ball rolls down an incline at various times is given in Table 2.
   a. Draw a position-time graph of the motion of the ball. When setting up the axes, use five divisions for each 10 m of travel on the x-axis. Use five divisions for 1 s of time on the t-axis.
   b. Calculate the distance the ball has rolled at the end of 2.2 s.

<table>
<thead>
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<th>Position (m)</th>
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<tr>
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<td>50.0</td>
</tr>
</tbody>
</table>

91. Engineers are developing new types of guns that might someday be used to launch satellites as if they were bullets. One such gun can give a small object a forward velocity of 3.5 km/s while moving it through a distance of only 2.0 cm.
   a. What acceleration does the gun give this object?
   b. Over what time interval does the acceleration take place?

92. Safety Barriers  Highway safety engineers build soft barriers, such as the one shown in Figure 33, so that cars hitting them will slow down at a safe rate. Suppose a car traveling at 110 km/h hits the barrier, and the barrier decreases the car’s velocity at a rate of 32 m/s². What distance would the car travel along the barrier before coming to a stop?

93. Baseball  A baseball pitcher throws a fastball at a speed of 44 m/s. The ball has constant acceleration as the pitcher holds it in his hand and moves it through an almost straight-line distance of 3.5 m. Calculate the acceleration. Compare this acceleration to the free-fall acceleration on Earth.

94. Sleds  Rocket-powered sleds are used to test the responses of humans to acceleration. Starting from rest, one sled can reach a speed of 444 m/s in 1.80 s and can be brought to a stop again in 2.15 s.
   a. Calculate the acceleration of the sled when starting, and compare it to the magnitude of free-fall acceleration, 9.8 m/s².
   b. Find the acceleration of the sled as it is braking, and compare it to the magnitude of free-fall acceleration.

95. The forward velocity of a car changes over an 8.0-s time period, as shown in Table 3.
   a. Plot the velocity-time graph of the motion.
   b. What is the car’s displacement in the first 2.0 s?
   c. What is the car’s displacement in the first 4.0 s?
   d. What is the displacement of the car during the entire 8.0 s?
   e. Find the slope of the line between t = 0.0 s and t = 4.0 s. What does this slope represent?
   f. Find the slope of the line between t = 5.0 s and t = 7.0 s. What does this slope indicate?

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Velocity (m/s)</th>
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</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>1.0</td>
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<td>6.0</td>
<td>20.0</td>
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<tr>
<td>7.0</td>
<td>20.0</td>
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<tr>
<td>8.0</td>
<td>20.0</td>
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</table>

96. A truck is stopped at a stoplight. When the light turns green, the truck accelerates at 2.5 m/s². At the same instant, a car passes the truck going at a constant 15 m/s. Where and when does the truck catch up with the car?
97. Karate  The position-time and velocity-time graphs of George's fist breaking a wooden board during karate practice are shown in Figure 34.

a. Use the velocity-time graph to describe the motion of George's fist during the first 10 ms.

b. Estimate the slope of the velocity-time graph to determine the acceleration of his fist when it suddenly stops.

c. Express the acceleration as a multiple of the magnitude of free-fall acceleration, 9.8 m/s².

d. Determine the area under the velocity-time curve to find the displacement of the fist in the first 6 ms. Compare this with the position-time graph.

98. Cargo  A helicopter is rising at 5.0 m/s when a bag of its cargo is dropped. The bag falls for 2.0 s.

a. What is the bag's velocity?

b. How far has the bag fallen?

c. How far below the helicopter is the bag?

Thinking Critically

99. Beware  Design a probeware lab to measure the distance an accelerated object moves over time. Use equal time intervals so that you can plot velocity over time as well as distance. A pulley at the edge of a table with a mass attached is a good way to achieve uniform acceleration. Suggested materials include a motion detector, lab cart, string, pulley, C-clamp, and masses. Generate position-time and velocity-time graphs using different masses on the pulley. How does the change in mass affect your graphs?

100. Analyze and Conclude  Which (if either) has the greater acceleration: a car that increases its speed from 50 km/h to 60 km/h or a bike that goes from 0 km/h to 10 km/h in the same time? Explain.

101. Analyze and Conclude  An express train traveling at 36.0 m/s is accidentally sidetracked onto a local train track. The express engineer spots a local train exactly 1.00×10² m ahead on the same track and traveling in the same direction. The local engineer is unaware of the situation. The express engineer jams on the brakes and slows the express train at a constant rate of 3.00 m/s². If the speed of the local train is 11.0 m/s, will the express train be able to stop in time, or will there be a collision? To solve this problem, take the position of the express train when the engineer first sights the local train as a point of origin. Next, keeping in mind that the local train has exactly a 1.00×10² m lead, calculate how far each train is from the origin at the end of the 12.0 s it would take the express train to stop (accelerate at −3.00 m/s² from 36 m/s to 0 m/s).

a. On the basis of your calculations, would you conclude that a collision will occur?

b. To check the calculations from part a and to verify your conclusion, take the position of the express train when the engineer first sights the local train as the point of origin and calculate the position of each train at the end of each second after the sighting. Make a table showing the distance of each train from the origin at the end of each second. Plot these positions on the same graph and draw two lines. Compare your graph to your answer to part a.

Writing in Physics

102. Research and describe Galileo's contributions to physics.

103. Research the maximum acceleration a human body can withstand without blacking out. Discuss how this impacts the design of three common entertainment or transportation devices.

Cumulative Review

104. Solve the following problems. Express your answers in scientific notation.

a. 6.2×10⁻⁴ m + 5.7×10⁻³ m

b. 8.7×10⁸ km − 3.4×10⁷ km

c. (9.21×10⁻⁵ cm)(1.83×10⁸ cm)

d. \( \frac{2.63×10^{-6} \text{ m}}{4.08×10^8 \text{ s}} \)

105. The equation below describes an object's motion. Create the corresponding position-time graph and motion diagram. Then write a physics problem that could be solved using that equation. Be creative.

\[ x = (35.0 \text{ m/s}) t - 5.0 \text{ m} \]
**MULTIPLE CHOICE**

Use the following information to answer the first two questions.

A ball rolls down a hill with a constant acceleration of 2.0 m/s². The ball starts at rest and travels for 4.0 s before it reaches the bottom of the hill.

1. How far did the ball travel during this time?
   A. 8.0 m
   B. 12 m
   C. 16 m
   D. 20 m

2. What was the ball’s speed at the bottom of the hill?
   A. 2.0 m/s
   B. 8.0 m/s
   C. 12 m/s
   D. 16 m/s

3. A driver of a car enters a new 110-km/h speed zone on the highway. The driver begins to accelerate immediately and reaches 110 km/h after driving 500 m. If the original speed was 80 km/h, what was the driver’s forward acceleration?
   A. 0.44 m/s²
   B. 0.60 m/s²
   C. 8.4 m/s²
   D. 9.8 m/s²

4. A flowerpot falls off a balcony 85 m above the street. How long does it take to hit the ground?
   A. 4.2 s
   B. 8.3 s
   C. 8.7 s
   D. 17 s

5. A rock climber’s shoe loosens a rock, and her climbing buddy at the bottom of the cliff notices that the rock takes 3.20 s to fall to the ground. How high up the cliff is the rock climber?
   A. 15.0 m
   B. 31.0 m
   C. 50.0 m
   D. 1.00 × 10² m

6. A car traveling at 91.0 km/h approaches the turnoff for a restaurant 30.0 m ahead. If the driver slams on the brakes with an acceleration of −6.40 m/s², what will be her stopping distance?
   A. 14.0 m
   B. 29.0 m
   C. 50.0 m
   D. 100.0 m

7. What is the correct formula manipulation to find acceleration when using the equation \( v_f^2 = v_i^2 + 2ax \)?
   A. \( \frac{v_f^2 - v_i^2}{x} \)
   B. \( \frac{v_f^2 + v_i^2}{2x} \)
   C. \( \frac{(v_f + v_i)^2}{2x} \)
   D. \( \frac{v_f^2 - v_i^2}{2x} \)

8. The graph below shows the motion of a farmer’s truck. What is the truck’s total displacement? Assume north is the positive direction.
   A. 150 m south
   B. 125 m north
   C. 300 m north
   D. 600 m south

9. How can the instantaneous acceleration of an object with varying acceleration be calculated?
   A. by calculating the slope of the tangent on a position-time graph
   B. by calculating the area under the graph on a position-time graph
   C. by calculating the area under the graph on a velocity-time graph
   D. by calculating the slope of the tangent on a velocity-time graph

**FREE RESPONSE**

10. Graph the following data, and then show calculations for acceleration and displacement after 12.0 s on the graph.

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<tr>
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<th>Velocity (m/s)</th>
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<tbody>
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**NEED EXTRA HELP?**

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<th>3</th>
<th>4</th>
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