11.3 Acceleration

**Reading Focus**

**Key Concepts**
- How are changes in velocity described?
- How can you calculate acceleration?
- How does a speed-time graph indicate acceleration?
- What is instantaneous acceleration?

**Vocabulary**
- acceleration
- free fall
- constant acceleration
- linear graph
- nonlinear graph

**Figure 11** The basketball constantly changes velocity as it rises and falls.

A basketball constantly changes velocity during a game. The player in Figure 11 dribbles the ball down the court, and the ball speeds up as it falls and slows down as it rises. As she passes the ball, it flies through the air and suddenly stops when a teammate catches it. The velocity of the ball increases again as it is thrown toward the basket.

But the rate at which velocity changes is also important. Imagine a basketball player running down the court and slowly coming to a stop. Now imagine the player running down the court and stopping suddenly. If the player stops slowly, his or her velocity changes slowly. If the player stops suddenly, his or her velocity changes quickly. The ball handler’s teammates must position themselves to assist the drive or to take a pass. Opposing team members want to prevent the ball handler from reaching the basket. Each player must anticipate the ball handler’s motion.

Velocity changes frequently, not only in a basketball game, but throughout our physical world. Describing changes in velocity, and how fast they occur, is a necessary part of describing motion.

**What Is Acceleration?**

The rate at which velocity changes is called **acceleration**. Recall that velocity is a combination of speed and direction. **Acceleration** can be described as changes in speed, changes in direction, or changes in both. Acceleration is a vector.
Changes in Speed  We often use the word _acceleration_ to describe situations in which the speed of an object is increasing. A television news-caster describing the liftoff of a rocket-launched space shuttle, for example, might exclaim, “That shuttle is really accelerating!” We understand that the newscaster is describing the spacecraft’s quickly increasing speed as it clears its launch pad and rises through the atmosphere. Scientifically, however, acceleration applies to any change in an object’s velocity. This change may be either an increase or a decrease in speed. Acceleration can be caused by positive (increasing) change in speed or by negative (decreasing) change in speed.

For example, suppose that you are sitting on a bus waiting at a stoplight. The light turns green and the bus moves forward. You feel the acceleration as you are pushed back against your seat. The acceleration is the result of an increase in the speed of the bus. As the bus moves down the street at a constant speed, its acceleration is zero. You no longer feel pushed toward your seat. When the bus approaches another stoplight, it begins to slow down. Again, its speed is changing, so the bus is accelerating. You feel pulled away from your seat. Acceleration results from increases or decreases in speed. As the bus slows to a stop, it experiences negative acceleration, also known as deceleration. Deceleration is an acceleration that slows an object’s speed.

An example of acceleration due to change in speed is _free fall_, the movement of an object toward Earth solely because of gravity. Recall that the unit for velocity is meters per second. The unit for acceleration, then, is meters per second per second. This unit is typically written as meters per second squared (m/s$^2$). Objects falling near Earth’s surface accelerate downward at a rate of 9.8 m/s$^2$. Each second an object is in free fall, its velocity increases downward by 9.8 meters per second. Imagine the stone in Figure 12 falling from the mouth of the well. After 1 second, the stone will be falling at about 9.8 m/s. After 2 seconds, the stone will be going faster by 9.8 m/s. Its speed will now be downward at 19.6 m/s. The change in the stone’s speed is 9.8 m/s$^2$, the acceleration due to gravity.

**Figure 12** The velocity of an object in free fall increases 9.8 m/s each second.
Changes in Direction  Acceleration isn’t always the result of changes in speed. You can accelerate even if your speed is constant. You experience this type of acceleration if you ride a bicycle around a curve. Although you may have a constant speed, your change in direction means you are accelerating. You also may have experienced this type of acceleration if you have ridden on a carousel like the one in Figure 13. A horse on the carousel is traveling at a constant speed, but it is accelerating because its direction is constantly changing.

Changes in Speed and Direction  Sometimes motion is characterized by changes in both speed and direction at the same time. You experience this type of motion if you ride on a roller coaster like the one in Figure 14. The roller coaster ride starts out slowly as the cars travel up the steeply inclined rails. The cars reach the top of the incline. Suddenly they plummet toward the ground and then whip around a curve. You are thrown backward, forward, and sideways as your velocity increases, decreases, and changes direction. Your acceleration is constantly changing because of changes in the speed and direction of the cars of the roller coaster.

Similarly, passengers in a car moving at the posted speed limit along a winding road experience rapidly changing acceleration. The car may enter a long curve at the same time that it slows to maintain a safe interval behind another car. The car is accelerating both because it is changing direction and because its speed is decreasing.
**Constant Acceleration** The velocity of an object moving in a straight line changes at a constant rate when the object is experiencing constant acceleration. **Constant acceleration** is a steady change in velocity. That is, the velocity of the object changes by the same amount each second. An example of constant acceleration is illustrated by the jet airplane shown in Figure 15. The airplane’s acceleration may be constant during a portion of its takeoff.

**Calculating Acceleration**

Acceleration is the rate at which velocity changes. You calculate acceleration for straight-line motion by dividing the change in velocity by the total time. If \( a \) is the acceleration, \( v_i \) is the initial velocity, \( v_f \) is the final velocity, and \( t \) is total time, then this equation can be written as follows.

\[
\text{Acceleration} = \frac{v_f - v_i}{t}
\]

Notice in this formula that velocity is in the numerator and time is in the denominator. If the velocity increases, the numerator is positive and thus the acceleration is also positive. For example, if you are coasting downhill on a bicycle, your velocity increases and your acceleration is positive. If the velocity decreases, then the numerator is negative and the acceleration is also negative. For example, if you continue coasting after you reach the bottom of the hill, your velocity decreases and your acceleration is negative.

Remember that acceleration and velocity are both vector quantities. Thus, if an object moving at constant speed changes its direction of travel, there is still acceleration. In other words, the acceleration can occur even if the speed is constant. Think about a car moving at a constant speed as it rounds a curve. Because its direction is changing, the car is accelerating.

To determine a change in velocity, subtract one velocity vector from another. If the motion is in a straight line, however, the velocity can be treated as speed. You can then find acceleration from the change in speed divided by the time.

**Figure 15** Constant acceleration during takeoff results in changes to an aircraft’s velocity that are in a constant direction.
Chapter 11

Calculating Acceleration

A ball rolls down a ramp, starting from rest. After 2 seconds, its velocity is 6 meters per second. What is the acceleration of the ball?

1. Read and Understand
   What information are you given?
   - Time = 2 s
   - Starting velocity = 0 m/s
   - Ending velocity = 6 m/s

2. Plan and Solve
   What unknown are you trying to calculate?
   - Acceleration

3. Look Back and Check
   Is your answer reasonable?
   Objects in free fall accelerate at a rate of 9.8 m/s². The ramp is not very steep. An acceleration of 3 m/s² seems reasonable.

Graphs of Accelerated Motion

You can use a graph to calculate acceleration. For example, consider a downhill skier who is moving in a straight line. After traveling down the hill for 1 second, the skier’s speed is 4 meters per second. In the next second the speed increases by an additional 4 meters per second, so the skier’s acceleration is 4 m/s². Figure 16 is a graph of the skier’s speed.

The slope of a speed-time graph is acceleration. This slope is change in speed divided by change in time.

Additional Problems

1. A sprinter accelerates from the starting block to a speed of 8.0 m/s in 4.0 s. What is the magnitude of the sprinter’s acceleration? (2.0 m/s²)
2. A car is traveling at 14 m/s. Stepping on the gas pedal causes the car to accelerate at 2.0 m/s². How long does the driver have to step on the pedal to reach a speed of 18 m/s? (2.0 s)

Logical, Portfolio
Speed-Time Graphs  The skier’s speed increased at a constant rate because the skier was moving down the hill with constant acceleration. Constant acceleration is represented on a speed–time graph by a straight line. The graph in Figure 16 is an example of a linear graph, in which the displayed data form straight-line parts. The slope of the line is the acceleration.

Constant negative acceleration decreases speed. A speed-time graph of the motion of a bicycle slowing to a stop is shown in Figure 17. The horizontal line segment represents constant speed. The line segment sloping downward represents the bicycle slowing down. The change in speed is negative, so the slope of the line is negative.

Figure 16 The slope of a speed-time graph indicates acceleration. A positive slope shows that the skier’s acceleration is positive.

Graphs of Accelerated Motion

Use Visuals

Figure 17 Ask students the following questions about the speed-time graph in Figure 17. What are the units on the vertical axis? (m/s) What are the units on the horizontal axis? (s) What would be the units of the slope of a line on this graph? (m/s/s, or m/s^2) Remind students that the bike represents the motion of a mountain biker in the photograph. Ask students, Is the bike moving at time zero? (Yes) How fast is it moving at that time? (5 m/s) What happens to the bike after 10 seconds? (It starts to slow down.) How would you describe the acceleration of the bike from that point on? (The acceleration is constant and negative.) Visual, Logical

Build Math Skills

Finding Slope on a Graph  Remind students that the slope of a line on a graph is found by dividing the difference of two points on the vertical axis by the corresponding points on the horizontal axis. The two points used to find the slope should be chosen as far apart on the line as possible.

Have students calculate the slope of the line on the graph in Figure 16. Tell them also to include the units in their calculation. (4 m/s^2) Now have them calculate the slope of the line between 10 and 20 seconds on the graph in Figure 17. (0.5 m/s^2)

Logical

Direct students to the Math Skills in the Skills and Reference Handbook at the end of the student text for additional help.
Instantaneous Acceleration

Integrate Math

Differential calculus is the branch of mathematics that physicists use when considering instantaneous quantities, such as instantaneous speed or instantaneous acceleration. When you use calculus to determine acceleration, you can take the difference in velocities over smaller and smaller time intervals until the time interval becomes, in effect, infinitely small. The slope of a curved line is equal to the slope of a line drawn tangent to a point on the plotted curve. Graphically, this is like finding the slope of a line connecting two points on a speed-time graph, but then moving the points closer and closer together until you have the slope of a line tangent to the curve at a single point on the graph. In this case, the slope of the line represents the instantaneous acceleration at that point.

Logical, Visual

3 ASSESS

Evaluate Understanding

Ask students to sketch a speed-time graph of a car starting from rest, accelerating up to the speed limit, maintaining that speed, then slowing again to a stop.

Reteach

Use the graphs on page 347 to reteach the concepts in the section. Ask students to identify which kind of acceleration cannot be shown on the graphs. (A change in direction)

Math Practice

Solutions

8. \( a = \frac{(v_f - v_i)}{t} = \frac{(25 \text{ m/s} - 0 \text{ m/s})}{(30.0 \text{ s})} = 0.83 \text{ m/s}^2 \)

9. \( a = \frac{(v_f - v_i)}{t} = \frac{(30.0 \text{ m/s} - 25 \text{ m/s})}{(10.0 \text{ s})} = 0.50 \text{ m/s}^2 \)

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 11.3.

Distance-Time Graphs

Accelerated motion is represented by a curved line on a distance-time graph. In a nonlinear graph, a curve connects the data points that are plotted. Figure 18 is a distance-time graph. The data in this graph are for a ball dropped from rest toward the ground.

Compare the slope of the curve during the first second to the slope of the curve during the fourth second. Notice that the slope is much greater during the fourth second than it is during the first second. Because the slope represents the speed of the ball, an increasing slope means that the speed is increasing. An increasing speed means that the ball is accelerating.

Instantaneous Acceleration

Acceleration is rarely constant, and motion is rarely in a straight line. A skateboarder moving along a half-pipe changes speed and direction. As a result, her acceleration changes. At each moment she is accelerating, but her instantaneous acceleration is always changing. Instantaneous acceleration is how fast a velocity is changing at a specific instant.

Acceleration involves a change in velocity or direction or both, so the vector of the skateboarder’s acceleration can point in any direction. The vector’s length depends on how fast she is changing her velocity. At every moment she has an instantaneous acceleration, even if she is standing still and the acceleration vector is zero.

Section 11.3 Assessment

Reviewing Concepts

1. Describe three types of changes in velocity.
2. What is the equation for acceleration?
3. What shows acceleration on a speed-time graph?
4. Define instantaneous acceleration.

Critical Thinking

5. Comparing and Contrasting How are deceleration and acceleration related?
6. Applying Concepts Two trains leave a station at the same time. Train A travels at a constant speed of 16 m/s. Train B starts at 8.0 m/s but accelerates constantly at 1.0 m/s². After 10.0 seconds, which train has the greater speed?
7. Inferring Suppose you plot the distance traveled by an object at various times and you discover that the graph is not a straight line. What does this indicate about the object’s acceleration?
8. A train moves from rest to a speed of 25 m/s in 30.0 seconds. What is the magnitude of its acceleration?
9. A car traveling at a speed of 25 m/s increases its speed to 30.0 m/s in 10.0 seconds. What is the magnitude of its acceleration?

Section 11.3 (continued)

Instantaneous Acceleration

Changes in velocity can be described as changes in speed, changes in direction, or changes in both (or, an increase in speed, a decrease in speed, or a change in direction).

1. \( a = \frac{(v_f - v_i)}{t} \)
2. \( a = \frac{(v_f - v_i)}{t} \)
3. The slope of the line on a speed-time graph gives the acceleration.
4. Instantaneous acceleration is how fast the velocity is changing at a specific instant.
5. Deceleration is a special case of acceleration in which the speed of an object is decreasing.
6. \( a = \frac{v}{t} + at = 8.0 \text{ m/s} + (1.0 \text{ m/s}^2)(10.0 \text{ s}) = 8.0 \text{ m/s} + 10.0 \text{ m/s} = 18 \text{ m/s} \)
7. The graph indicates that the object is accelerating.