11.1 Distance and Displacement

**Key Concepts**
- What is needed to describe motion completely?
- How are distance and displacement different?
- How do you add displacements?

**Vocabulary**
- frame of reference
- relative motion
- distance
- vector
- resultant vector

**Reading Strategy**
**Predicting** Copy the table below and write a definition for frame of reference in your own words. After you read the section, compare your definition to the scientific definition and explain why the frame of reference is important.

<table>
<thead>
<tr>
<th>Frame of reference</th>
<th>Frame of reference actually means</th>
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<tbody>
<tr>
<td>a.</td>
<td>b.</td>
</tr>
</tbody>
</table>

On a spring day a butterfly flutters past. First it flies quickly, then slowly, and then it pauses to drink nectar from a flower. The butterfly’s path involves a great deal of motion. How fast is the butterfly moving? Is it flying toward the flower or away from it? These are the kinds of questions you must answer to describe the butterfly’s motion. To describe motion, you must state the direction the object is moving as well as how fast the object is moving. You must also tell its location at a certain time.

**Choosing a Frame of Reference**

How fast is the butterfly in Figure 1 moving? Remember that the butterfly is moving on Earth, but Earth itself is moving as it spins on its axis and revolves around the sun. If you consider this motion, the butterfly is moving very, very fast! To describe motion accurately and completely, a frame of reference is necessary. The necessary ingredient of a description of motion—a frame of reference—is a system of objects that are not moving with respect to one another. The answer to “How fast is the butterfly moving?” depends on which frame of reference you use to measure motion. How do you decide which frame of reference to use when describing the butterfly’s movement?

Figure 1 You must choose a frame of reference to tell how fast the butterfly is moving.

Applying Concepts Identify a good frame of reference to use when describing the butterfly’s motion.

**Section Resources**
- **Print**
  - Laboratory Manual, Investigation 11A
  - Reading and Study Workbook With Math Support, Section 11.1
  - Transparencies, Chapter Pretest and Section 11.1
- **Technology**
  - Interactive textbook, Section 11.1
  - Presentation Pro CD-ROM, Chapter Pretest and Section 11.1
  - Go Online, NSTA SciLinks, Comparing frames of reference
How Fast Are You Moving? How fast are the train passengers in Figure 2 moving? There are many correct answers because their motion is relative. This means it depends on the frame of reference you choose to measure their motion. Relative motion is movement in relation to a frame of reference. For example, as the train moves past a platform, people standing on the platform will see those on the train speeding by. But when the people on the train look at one another, they don’t seem to be moving at all.

Which Frame Should You Choose? When you sit on a train and look out a window, a treetop may help you see how fast you are moving relative to the ground. But suppose you get up and walk toward the rear of the train. Looking at a seat or the floor may tell you how fast you are walking relative to the train. However, it doesn’t tell you how fast you are moving relative to the ground outside. Choosing a meaningful frame of reference allows you to describe motion in a clear and relevant manner.

Measuring Distance

Distance is the length of a path between two points. When an object moves in a straight line, the distance is the length of the line connecting the object’s starting point and its ending point.

It is helpful to express distances in units that are best suited to the motion you are studying. The SI unit for measuring distance is the meter (m). For very large distances, it is more common to make measurements in kilometers (km). One kilometer equals 1000 meters. For instance, it’s easier to say that the Mississippi River has a length of 3780 kilometers than 3,780,000 meters. Distances that are smaller than a meter are measured in centimeters (cm). One centimeter is one hundredth of a meter. You might describe the distance a marble rolls, for example, as 6 centimeters rather than 0.06 meter.
### Measuring Displacements

**Combining Displacements**

**Procedure**
1. Draw a dot at the intersection of two lines near the bottom edge of a sheet of graph paper. Label this dot "Start."
2. Draw a second, similar dot near the top of the paper. Label this dot "End."
3. Draw a path from the Start dot to the End dot. Choose any path that stays on the grid lines.
4. Use a ruler to determine the distance of your path.
5. Use a ruler to determine the displacement from start to end.

**Analyse and Conclude**
1. **Observing** Which is shorter, the distance or the displacement?
2. **Evaluating and Revising** How could you have made the distance shorter?
3. **Inferring** If you keep the Start and End points the same, is it possible to make the displacement shorter? Explain your answer.

**Measuring Displacements**

To describe an object’s position relative to a given point, you need to know how far away and in what direction the object is from that point. Displacement provides this information. **Distance** is the length of the path between two points. Displacement is the direction from the starting point and the length of a straight line from the starting point to the ending point.

Displacements are sometimes used when giving directions. Telling someone to "Walk 5 blocks" does not ensure they’ll end up in the right place. However, saying "Walk 5 blocks north from the bus stop" will get the person to the right place. Accurate directions give the direction from a starting point as well as the distance.

Think about the motion of a roller coaster car. If you measure the path along which the car has traveled, you are describing distance. The direction from the starting point to the car and the length of the straight line from the starting point to the car describe displacement. After completing one trip around the track, the roller coaster car’s displacement is zero.

**Combining Displacements**

Displacement is an example of a vector. A vector is a quantity that has magnitude and direction. The magnitude can be size, length, or amount. Arrows on a graph or map are used to represent vectors. The length of the arrow shows the magnitude of the vector. Vector addition is the combining of vector magnitudes and directions.

**Displacement Along a Straight Line** When two displacements, represented by two vectors, have the same direction, you can add their magnitudes. In Figure 3A, the magnitudes of the car’s displacements are 4 kilometers and 2 kilometers. The total magnitude of the displacement is 6 kilometers. If two displacements are in opposite directions, the magnitudes subtract from each other, as shown in Figure 3B. Because the car’s displacements (4 kilometers and 2 kilometers) are in opposite directions, the magnitude of the total displacement is 2 kilometers.

![Figure 3](image-url)

**Figure 3** When motion is in a straight line, vectors add and subtract easily.

- **A** Add the magnitudes of two displacement vectors that have the same direction.
- **B** Two displacement vectors with opposite directions are subtracted from each other.
**Displacement That Isn’t Along a Straight Path**

When two or more displacement vectors have different directions, they may be combined by graphing. Figure 4 shows vectors representing the movement of a boy walking from his home to school. He starts by walking 1 block east. Then he turns a corner and walks 1 block north. He turns once again and walks 2 blocks east. For the last part of his trip to school, he walks 3 blocks north. The lengths of the vectors representing this path are 1 block, 1 block, 2 blocks, and 3 blocks. The boy walked a total distance of 7 blocks. You can determine this distance by adding the magnitudes of each vector along his path. The vector in red is called the resultant vector, which is the vector sum of two or more vectors. In this case, it shows the displacement. The resultant vector points directly from the starting point to the ending point. If you place a sheet of paper on the figure and mark the length of the resultant vector, you see that it equals the length of 5 blocks. Vector addition, then, shows that the boy’s displacement is 5 blocks approximately northeast, while the distance he walked is 7 blocks.

**Figure 4 Measuring the resultant vector** (the diagonal red line) shows that the displacement from the boy’s home to his school is two blocks less than the distance he actually traveled.

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**Section 11.1 Assessment**

**Reviewing Concepts**

1. **What is a frame of reference?** How is it used to measure motion?
2. **How are distance and displacement similar and different?**
3. **How are displacements combined?**
4. **A girl is watching a plane fly tells her friend that the plane isn’t moving at all. Describe a frame of reference in which the girl’s description would be true.**

**Critical Thinking**

5. **Using Analogies** Is displacement more like the length of a rope that is pulled tight or the length of a coiled rope? Explain.
6. **Making Judgments** Would you measure the height of a building in meters? Give reasons for your answer.

**7. Problem Solving** Should your directions to a friend for traveling from one city to another include displacements or distances? Explain.

**8. Inferring** The resultant vector of two particular displacement vectors does not equal the sum of the magnitudes of the individual vectors. Describe the directions of the two vectors.

**Writing in Science**

**Compare-Contrast Paragraph** Write a paragraph describing how the distance you travel from home to school is different from your displacement from home to school. (Hint: Make a simple sketch similar to Figure 4 and refer to it as you write.)

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**Building Science Skills**

**Measuring** Have students use a map of the city or area to measure the straight-line distance from their homes to the school. They will have to use the scale information on the map to convert from distances on the map to actual distances. Then, have them determine the distances they travel from their home to school by observing the odometer of a car or bus. To get the distances traveled, they should subtract the odometer readings at their start points from the odometer readings when they arrive at the school. Have them compare the distances. In almost every case, the distance traveled should be greater than the straight-line distance on the map. **Logical**

**3 Assess**

**Evaluate Understanding**

Ask students to write a paragraph describing a situation in which the same motion appears differently from different frames of reference.

**Reteach**

Use Figure 4 to reteach the difference between displacement and distance traveled.

Students’ paragraphs should generally describe distances and directions they travel on the way to school. They should understand that displacement is determined by a straight-line distance from home to school. The total distance they travel will almost always be greater than the magnitude of the displacement, unless they travel in a single direction the whole time. If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 11.1.
11.2 Speed and Velocity

**Reading Focus**

**Objectives**

11.2.1 Identify appropriate SI units for measuring speed.
11.2.2 Compare and contrast average speed and instantaneous speed.
11.2.3 Interpret distance-time graphs.
11.2.4 Calculate the speed of an object using slopes.
11.2.5 Describe how velocities combine.

**Build Vocabulary**

**Venn Diagram** Have students draw a Venn diagram to show how the key terms of the section are related to each other. Student diagrams should show circles labeled Speed and Direction. The area in which the circles overlap should be labeled Velocity.

**Reading Strategy**

Answers may vary. Sample answers are shown below.

a. Average speed is distance divided by time. 
   b. I could use this to calculate various speeds, like the average speed at which I travel getting to school.
   c. Instantaneous speed is different from average speed.
   d. You can’t use a single speedometer reading to determine how long a trip will take.
   e. Velocity is not the same as speed.
   f. This could be useful in giving directions or in describing the path that you take on a walk.

**Instruct**

**Speed**

**Build Science Skills**

**Forming Operational Definitions** An operational definition limits the meaning of a term to what is observed or measured in a particular situation. Ask, What is an operational definition of speed for a skater on a circular track? (Sample answer: The amount of time it takes to circle the track one time, the number of times the skater could circle the track one time) What is an operational definition for a person walking down a street? (Sample answer: The number of meters traveled each second) Verbal, Logical

**Focus**

**Reading Strategy**

Monitor Your Understanding After you have finished reading this section, copy the table below. Identify several things you have learned that are relevant to your life. Explain why they are relevant to you.

<table>
<thead>
<tr>
<th>What Is Relevant</th>
<th>Why It Is Relevant</th>
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</tbody>
</table>

Look out a window for a few minutes, and you will see things in motion. Some things are moving slowly. Perhaps you see a leaf floating through the air. Other things, such as a car or a bird, are moving fast. The growth rate of trees and grass is so slow that their motion cannot be detected with the unaided eye. The differences among these types of motion can be described in terms of speed.

**Vocabulary**

◆ speed◆ average speed◆ instantaneous speed◆ velocity

**Key Concepts**

- How are instantaneous speed and average speed different?
- How can you find the speed from a distance-time graph?
- How are speed and velocity different?
- How do velocities add?
- How do velocities add?
- Instantaneous speed is the speed at a particular instant.
- Average speed is the total distance traveled divided by the total time taken.

**Speed**

To describe the speed of a car, you might say it is moving at 45 kilometers per hour. Speed is the ratio of the distance an object moves to the amount of time the object moves. The SI unit of speed is meters per second (m/s). However, just as with distances, you need to choose units that make the most sense for the motion you are describing. The in-line skater in Figure 5 may travel 2 meters in one second. The speed would be expressed as 2 m/s. A car might travel 80 kilometers in one hour. Its speed would be expressed as 80 km/h.

Two ways to express the speed of an object are average speed and instantaneous speed. Average speed is computed for the entire duration of a trip, and instantaneous speed is measured at a particular instant. In different situations, either one or both of these measurements may be a useful way to describe speed.

**Section Resources**

- **Print**
  - *Laboratory Manual*, Investigation 11B
  - *Reading and Study Workbook With Math Support*, Section 11.2 and Math Skill: Interpreting a Distance-Time Graph
  - *Math Skills and Problem Solving Workbook*, Section 11.2
  - *Transparencies*, Section 11.2

- **Technology**
  - Interactive Textbook, Section 11.2
  - Presentation Pro CD-ROM, Section 11.2
  - Go Online, NSTA SciLinks, Motion; PHSchool.com, Data sharing
Average Speed  Describing the speed of a hiker isn’t as easy as describing constant speed along a straight line. A hiker may travel slowly along rocky areas but then travel quickly when going downhill. Sometimes it is useful to know how fast something moves for an entire trip. Average speed, $v$, is the total distance traveled, $d$, divided by the time, $t$, it takes to travel that distance. This can be written as an equation:

$$v = \frac{d}{t}$$

During the time an object is moving, its speed may change, but this equation tells you the average speed over the entire trip.

Math Skills

Calculating Average Speed

While traveling on vacation, you measure the times and distances traveled. You travel 35 kilometers in 0.4 hour, followed by 53 kilometers in 0.6 hour. What is your average speed?

1. Read and Understand
   - What information are you given?
     - Total Distance ($d$) = 35 km + 53 km = 88 km
     - Total Time ($t$) = 0.4 h + 0.6 h = 1.0 h

2. Plan and Solve
   - What unknown are you trying to calculate?
     - Average Speed ($v$) = ?
   - What formula contains the given quantities and the unknown?
     - $v = \frac{d}{t}$
   - Replace each variable with its known value.
     - $v = \frac{88 \text{ km}}{1 \text{ h}} = 88 \text{ km/h}$

3. Look Back and Check
   - Is your answer reasonable?
     - Yes, 88 km/h is a typical highway speed.

Math Practice

1. A person jogs 4.0 kilometers in 32 minutes, then 2.0 kilometers in 22 minutes, and finally 1.0 kilometer in 16 minutes. What is the jogger’s average speed in kilometers per minute?
2. A train travels 190 kilometers in 3.0 hours, and then 120 kilometers in 2.0 hours. What is its average speed?

Motion

Customize for English Language Learners

Create a Word Wall

Students can relate the concepts in this section to the vocabulary words by creating a word wall. Write the words speed, average speed, instantaneous speed, and velocity on the board. Then, as students work through the section, ask them to define each word in their own terms. Discuss their definitions and write acceptable definitions on the board next to each word. Students may also draw a graph or paste a magazine picture next to the corresponding word.
Instantaneous Speed  Average speed is useful because it lets you know how long a trip will take. Sometimes however, such as when driving on the highway, you need to know how fast you are going at a particular moment. The car’s speedometer gives your instantaneous speed. Instantaneous speed, \( v \), is the rate at which an object is moving at a given moment in time. For example, you could describe the instantaneous speed of the car in Figure 6 as 55 km/h.

Graphing Motion

A distance-time graph is a good way to describe motion. Figure 7 shows distance-time graphs for the motion of three cars. Recall that slope is the change in the vertical axis value divided by the change in the horizontal axis value. On these graphs, the slope is the change in the distance divided by the change in time.

The speed of a line on a distance-time graph is speed. In Figure 7A, the car travels 500.0 meters in 20.0 seconds, or 25.0 meters per second. In Figure 7B, another car travels 250.0 meters in 20.0 seconds at a constant speed. The slope of the line is 250.0 meters divided by 20.0 seconds, or 12.5 meters per second. Notice that the line for the car traveling at a higher speed is steeper. A steeper slope on a distance-time graph indicates a higher speed.

Figure 7C shows the motion of a car that is not traveling at a constant speed. This car travels 200.0 meters in the first 8.0 seconds. It then stops for 4.0 seconds, as indicated by the horizontal part of the line. Next the car travels 300.0 meters in 8.0 seconds. The times when the car is gradually increasing or decreasing its speed are shown by the curved parts of the line. The slope of the straight portions of the line represent periods of constant speed. Note that the car’s speed is 25 meters per second during the first part of its trip and 38 meters per second during the last part of its trip.

Facts and Figures

Speed Records  According to the Guinness World Records, the fastest human sprinter is Tim Montgomery, who set a record of 100 m in 9.78 s in 2002. Fred Rompelberg set a record for the fastest speed on a bicycle when he rode 268.831 km/h (167.043 mph) in 1995. In 1972, the fastest recorded wind speed was clocked at 333 km/h (207 mph) in Thule, Greenland. The fastest speed in the universe is the speed of light. Light travels in a vacuum at \( 3.00 \times 10^8 \) m/s (186,000 miles/second).
Measuring Distance and Speed

Every car has a speedometer, which measures the car's speed, and an odometer, which measures the distance it has traveled. These devices work by counting the number of times the car's wheels turn (to give distance) and their rate of turning (speed).

**Interpreting Diagrams** What is the purpose of the worm gears?

- **Pointer** The pointer is attached to the drag cup. The faster the magnet spins, the greater the angle the drag cup turns. The higher speed is shown by the pointer.
- **Coil spring** This spring holds the pointer at zero when the car and the magnet are at rest.
- **Digital Odometer** Some cars have a magnetic sensor that detects turns of the transmission shaft. The signal is transmitted to a computer, which calculates and displays the car's distance traveled.
- **Cable** A cable linked to the transmission rotates at a rate directly proportional to the road speed.
- **Worm gears** The worm gears reduce the cable's rotational speed and move the odometer dials.
- **Drag cup** The drag cup turns from its resting position through an angle that increases with the magnet's spin rate.
- **Magnet** The magnet is attached to the shaft. As the shaft spins, the magnet, a magnetic field exerts force on the drag cup.

Some cars have a magnetic sensor that calculates and displays the car's distance traveled. This sensor is transmitted to a computer, which is connected to an electronic dial, indicating that the car has traveled one tenth of a mile.

For Enrichment

Have students use a library or the Internet to research how speeds are measured on ships, airplanes, or spacecraft. Have them write a paragraph explaining their findings.

**Verbal, Portfolio**

**Answer to . . .**

**Figure 7** The slope of the line would increase.
Figure 8 A cheetah's speed may be as fast as 90 km/h. To describe the cheetah's velocity, you must also know the direction in which it is moving.

**Velocity**

The cheetah is the fastest land animal in the world. Suppose a cheetah, running at 90 kilometers per hour, is 30 meters from an antelope that is standing still. How long will it be before the cheetah reaches the antelope? Do you have enough information to answer the question? The answer is no. Sometimes knowing only the speed of an object isn't enough. You also need to know the direction of the object's motion. Together, the speed and direction in which an object is moving are called **velocity**. To determine how long it will be before the cheetah reaches the antelope, you need to know the cheetah's velocity, not just its speed.

**Velocity is a description of both speed and direction of motion. Velocity is a vector.**

Figure 8 shows a cheetah in motion. If you have ever seen a video of a cheetah chasing its prey, you know that a cheetah can change speed and direction very quickly. To represent the cheetah's motion, you could use velocity vectors. You would need vectors of varying lengths, each vector corresponding to the cheetah's velocity at a particular instant. A longer vector would represent a faster speed, and a shorter one would show a slower speed. The vectors would also point in different directions to represent the cheetah's direction at any moment.

A change in velocity can be the result of a change in speed, a change in direction, or both. The sailboat in Figure 9 moves in a straight line (constant direction) at a constant speed. The sailboat can be described as moving with uniform motion, which is another way of saying it has constant velocity. The sailboat may change its velocity simply by speeding up or slowing down. However, the sailboat's velocity also changes if it changes its direction. It may continue to move at a constant speed, but the change of direction is a change in velocity.

**Figure 9** As the sailboat's direction changes, its velocity also changes, even if its speed stays the same. **Inferring** If the sailboat slows down at the same time that it changes direction, how will its velocity be changed?
Combining Velocities

Sometimes the motion of an object involves more than one velocity.

Two or more velocities add by vector addition. The velocity of the river relative to the riverbank (X) and the velocity of the boat relative to the river (Y) in Figure 10A combine. They yield the velocity of the boat relative to the riverbank (Z). This velocity is 17 kilometers per hour downstream.

In Figure 10B, the relative velocities of the current (X) and the boat (Y) are at right angles to each other. Adding these velocity vectors yields a resultant velocity of the boat relative to the riverbank of 13 km/h (Z).

Note that this velocity is at an angle to the riverbank.

### Section 11.2 Assessment

**Reviewing Concepts**

1. What does velocity describe?
2. What shows the speed on a distance-time graph?
3. What is the difference between average speed and instantaneous speed?
4. How can two or more velocities be combined?

**Critical Thinking**

5. Applying Concepts Does a car’s speedometer show instantaneous speed, average speed, or velocity? Explain.
6. Designing Experiments Describe an experiment you could perform to determine the average speed of a toy car rolling down an incline.

7. **Applying Concepts** Explain why the slope on a distance-time graph is speed. (Hint: Use the definition of speed on page 332 and the graphs in Figure 7.)

8. An Olympic swimmer swims 50.0 meters in 23.1 seconds. What is his average speed?
9. A plane’s average speed between two cities is 600 km/h. If the trip takes 2.5 hours, how far does the plane fly? (Hint: Use the average speed formula in the form \(d = vt\).)

**Combining Velocities**

**Use Visuals**

**Figure 10** Figure 10B shows two velocity vectors at right angles combining to form a single vector. You can use this opportunity to show students how to find the magnitude of resultant vectors.

Start by reminding students of the Pythagorean theorem:

\[a^2 + b^2 = c^2\]

for right triangles in which \(a\) and \(b\) are the legs and \(c\) is the hypotenuse. In this case, \(a\) is the speed of the boat, \(b\) is the speed of the river, and \(c\) is the resulting combined speed.

Do the following calculation on the board:

\[c = \sqrt{a^2 + b^2}
= \sqrt{(12 \text{ km/h})^2 + (5 \text{ km/h})^2}
= \sqrt{144 \text{ km}^2/\text{h}^2 + 25 \text{ km}^2/\text{h}^2}
= \sqrt{169 \text{ km}^2/\text{h}^2}
= 13 \text{ km/h}\]

When you have finished the calculation, point out that the result agrees with the speed shown in Figure 10B.

**Visual, Logical**

**Evaluate Understanding**

Ask students to write a paragraph describing how they could measure the average speed of a racecar on a racetrack. Also have them draw the velocity vectors at several locations for a racecar traveling at a constant speed around a circular track.

**Reteach**

Use the graphs in Figure 7 to reteach the concepts in the section.

**Math Practice**

Solutions

8. \(v = (50.0 \text{ m/s})(23.1 \text{ s}) = 1.16 \text{ m/s}\)
9. \(d = (600 \text{ km/h})(2.5 \text{ h}) = 1500 \text{ km}\)

**Answer to . . .**

**Figure 9** Both the magnitude and direction of the velocity will change.
Navigation at Sea

For centuries, crossing the oceans was extremely perilous. There are few landmarks at sea to guide the sailor, and methods of measuring direction, speed, and distance were crude and often inaccurate.

The invention of the magnetic compass brought major advancement in navigation in the early 1100s. Although the compass allowed a sailor to maintain an accurate course, it did nothing to tell him where he actually was. For this, a frame of reference was needed, and the one adopted was the system of latitude and longitude. This system measures location in degrees north or south of the equator, and degrees east or west of Greenwich, England.

Using a device called a sextant, latitude in the northern hemisphere was relatively easy to determine. Finding longitude was more difficult. The solution was to combine celestial observation and the use of a highly accurate sea-going clock that kept track of the time at a fixed location on Earth.
Finding location
Regular calculations of latitude and longitude have been the cornerstone of ocean navigation for about 300 years. A sextant and an accurate sea-going clock were needed to calculate both.

Determining latitude
To determine latitude is to find out how far north or south you are from the equator. In the northern hemisphere, latitude is measured with reference to Polaris. Using a sextant, you measure the angle of Polaris above the horizon, and this gives you your latitude, expressed in degrees. If Polaris is directly overhead, you must be at the North Pole (90° north latitude); if it is on the horizon, you must be at the equator (0°).

Determining longitude
To determine longitude is to find out how far east or west you are from Greenwich, England. To do this, while you are still in your home port, you set your sea-going clock for noon when the sun is at its highest point. Then, while you are at sea, you check the clock again when the sun is at its highest point. If the clock says 3 P.M., then you must have traveled 3 hours west of the port. Since the sun moves 15° per hour, 3 hours corresponds to 45° west.

Build Science Skills
Observing Have students go out on a clear night and locate Polaris, the pole star. Students may do this on their own, or you may have a class field trip. If you go as a group, also take a few pairs of binoculars and a telescope, if available. With a basic pair of binoculars, students can see many more stars, as well as many interesting celestial sights such as star clusters, the moons of Jupiter, and craters on Earth’s moon. Teach students how to use the two stars at the end of the Big Dipper to locate Polaris. Then, follow the line from these two stars “up” away from the dipper (in the direction of the opening in the dipper; the actual direction will depend on the position of the dipper). The first bright star in the line is Polaris.

Have students use a protractor and a ruler or other straight object to estimate Polaris’ angle of elevation above the horizon. This angle should be equal to the latitude at which you are observing. Have students compare their estimates to the actual latitude.

Visual, Group, Portfolio
**Build Science Skills**

**Measuring**

**Purpose** After doing this activity, students will be able to use a handheld GPS receiver to find coordinates, mark waypoints, and navigate to a location.

**Materials** handheld GPS receivers, 1 per group

**Advance Prep** Clear data from all the GPS receivers. Set all receivers so they are using the same units for coordinates. If you are unfamiliar with operating a GPS receiver, review the manual and practice marking a few waypoints (waypoints are locations that you store in the memory of a GPS unit). Find several locations on the school grounds and write down the GPS coordinates for those locations (students will return to these locations in the activity).

**Class Time** 30 minutes

**Procedure**

1. Start by showing the class the basics of operating the GPS receiver. You may do this outdoors, or if you are in the classroom, put the receiver in simulator mode. Show students how to tell how strong the signals are, how to read the coordinates of their location, and how to mark a waypoint.
2. Start all groups at a single point. Have them acquire the coordinates at that location and mark a waypoint. Assign each group a different location and give them the coordinates (but do not tell them where the location is). Then, have them use the receivers to find their assigned locations. You may have them use the navigation feature of the receiver to find the location, or they may just use the coordinates. Have them mark a waypoint when they reach the location.
3. After they have found their location, have the group return and describe the location to you. Verify that it is close to the location that you intended. Check each group's receiver to see if their marked waypoints have the correct coordinates.

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**Modern navigation**

Today's sea navigators are fortunate by comparison with their predecessors. Instead of having to make complex calculations involving times and sextant angles, they can buy a global positioning system receiver. This modern receiver not only provides quick and accurate readings of latitude and longitude, but it also displays the ship's position on a digital chart.

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**GPS satellite**

Each satellite transmits a range of possible positions for the ship (shown here by colored circles). The GPS receiver calculates its distance from a minimum of three satellites by analyzing the different travel times of their signals. The distance from each satellite gives a range of possibilities for the receiver's location. To find its exact position, a microchip in the on-board receiver calculates where the signals intersect.

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**Global Positioning System (GPS)**

A GPS receiver calculates its distance from a minimum of three satellites by analyzing the different travel times of their signals. The distance from each satellite gives a range of possibilities for the receiver's location. To find its exact position, a microchip in the on-board receiver calculates where the signals intersect.

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**Master control**

Located in Colorado, the master control communicates with all the satellites.

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**Satellite network**

The global network consists of 24 satellites in six different circular orbits around Earth.

---

The satellites orbit 20,200 km above Earth's surface.

---

GPS satellite Each satellite emits precisely timed radio signals.
Today, receivers are made in a range of sizes down to handheld models. They usually give a position accurate to 100 meters, but enhanced units are accurate within 10 meters.

**Expected Outcome** Students may have trouble finding the locations at first. The GPS receivers may have varying degrees of accuracy, depending on the receiver and the outside conditions. Also, students may be confused if the axes of the coordinates do not align with the boundaries of the area. However, students should get used to operating the receiver and following the coordinates. Note that due to inaccuracies in GPS data and differences in individual receivers, the locations that students find might not align perfectly with the locations that you found initially.

**Kinesthetic, Group, Logical**

**Going Further**

Students’ paragraphs should describe how early navigators measured the speed of a ship by throwing a log or wooden panel overboard. The log or panel was tied with a rope that had knots tied at regular intervals. The speed of the ship (relative to the water) could be measured by counting the number of knots that passed over the edge of the ship in a certain time interval. Knots are still used as units of speed in navigation, although they are measured with more precise instruments. 1 knot = 1 nautical mile per hour = 6076 feet per hour = 1.15 mph.

**Verbal**

**Discovery Channel Video Field Trip**

After students have viewed the Video Field Trip, ask them the following questions: What was the shape of Earth according to the ancient Greeks? What Earth dimension did they calculate using this shape? (They knew Earth was a sphere, and calculated its circumference.) What does latitude measure? Longitude? (Latitude measures how far north or south a location is. Longitude measures how far east or west a location is.) What did navigators notice about how high the sun rose at noon in northern regions? How could this be used to determine the position of their ships? (Navigators noticed that in northern regions the sun remained low in the sky even in the middle of the summer. The height of the sun at noon told navigators how far north they were. Some students may note that when the sun is low in the sky at noon in the Southern Hemisphere, this would indicate how far south you are.) How did navigators know how far west they were from their homeport in the 1700s? (The ship’s clock would be set at the same time as the clock in the navigator’s homeport. As the ship traveled west, the sun was lower in the sky when the clock read noon.) List two modern technologies that are now used in making maps. (Student answers may include aerial photography, satellites, and computers.)
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

Reading Strategy

Summarizing

Read the section on acceleration. Then copy and complete the concept map below to organize what you know about acceleration.

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

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.

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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.

Build Vocabulary

Word Forms
- linear
  - contains the word line
  - means, “in a straight line,” or more generally, “having to do with lines.”
- nonlinear
  - means not in a straight line or having to do with lines that are not straight.

Reading Strategy

a. Speed (or direction)
b. Direction (or speed)
c. m/s²

What Is Acceleration?

Use Visuals

Figure 11 Use the example of a bouncing basketball to introduce acceleration. Ask, As the ball falls from the girl’s hand, how does its speed change? (Its speed increases.) At what points does the ball have zero velocity? (When it touches the girl’s hand and when it touches the floor) How does the velocity of the ball change when it bounces on the floor? (The speed quickly drops to zero, then quickly increases again. The ball also changes direction.)

INSTRUCT

What is Acceleration?

Use Visuals

Figure 11 Use the example of a bouncing basketball to introduce acceleration. Ask, As the ball falls from the girl’s hand, how does its speed change? (Its speed increases.) At what points does the ball have zero velocity? (When it touches the girl’s hand and when it touches the floor) How does the velocity of the ball change when it bounces on the floor? (The speed quickly drops to zero, then quickly increases again. The ball also changes direction.)

Visual, Logical

Reading Focus

a. Speed (or direction)
b. Direction (or speed)
c. m/s²

Section Resources

Print
- Reading and Study Workbook With Math Support, Section 11.3
- Math Skills and Problem Solving Workbook, Section 11.3
- Transparencies, Section 11.3

Technology
- Interactive Textbook, Section 11.3
- Presentation Pro CD-ROM, Section 11.3
- Go Online, NSTA SciLinks, Acceleration
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/s²). Objects falling near Earth's surface accelerate downward at a rate of 9.8 m/s². 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/s², the acceleration due to gravity.

![Figure 12](image)

**Figure 12** The velocity of an object in free fall increases 9.8 m/s each second.

Build Reading Literacy

**Outline** Refer to page 156D in Chapter 6, which provides the guidelines for an outline.

Have students create an outline of Section 11.3 (pp. 342–348). Outlines should follow the heading structure used in the section. Major headings are shown in green, and subheadings are shown in blue. Ask students, **Based on your outline, what are two types of changes associated with acceleration? (Changes in speed and changes in direction)** Name two types of graphs that can be used to represent acceleration. (Speed-time graphs and distance-time graphs)

**Verbal, Logical**

Students may think that if an object is accelerating then the object is speeding up. Explain to students that this is true in common, everyday usage. But in scientific terms, acceleration refers to any change in velocity. Velocity is a vector including both speed and direction, so acceleration can be speeding up, slowing down, or even just changing direction.

**Use Visuals**

**Figure 12**: Have students examine Figure 12. Ask, **How much time passes between each image of the falling rock? (1 s)** How does the distance traveled change between successive time intervals? (The distance traveled increases.) **How does the average speed change between successive time intervals? (The average speed increases.**)

**Visual, Logical**

Customize for Inclusion Students

**Visually Impaired**

Students who are visually impaired may grasp the concept of acceleration by considering the following scenario. When traveling in a closed car with your eyes closed, it is hard to tell how far you have traveled or how fast you are going. But you can feel accelerations. Ask, **How do you know when you are speeding up or slowing down? (When speeding up, it feels as if you are pressed against the back of the seat. When you are slowing down, it feels as if you are pulled forward against the seat belt.)** **How can you tell if you are changing direction? (You can feel yourself pulled to one side, away from the direction the car is turning.)**
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.

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.

Figure 13 When you ride on a carousel, you accelerate because of the changing direction.
### 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 can calculate acceleration for straight-line motion by dividing the change in velocity by the total time.**

$$a = \frac{\Delta v}{\Delta t}$$

where $a$ is the acceleration, $\Delta v$ is the change in velocity, and $\Delta t$ is the change in time.

**What is constant acceleration?**

**Calculating Acceleration**

Acceleration is the rate at which velocity changes. You can 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, this equation can be written as follows.

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

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 change even if the velocity 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.

**Figure 14** The roller coaster is accelerating; its speed is increasing (because it is falling) and its direction is changing (because the track is curved).
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** = ?

   What formula contains the given quantities and the unknown?
   
   \[ a = \frac{(v_f - v_i)}{t} \]

   Replace each variable with its known value.
   
   \[ \text{Acceleration} = \frac{(6 \text{ m/s} - 0 \text{ m/s})}{2 \text{ s}} \]
   
   \[ = 3 \text{ m/s}^2 \]

   down the ramp

3. **Look Back and Check**

   Is your answer reasonable?

   - Objects in free fall accelerate at a rate of 9.8 m/s\(^2\).
   - The ramp is not very steep. An acceleration of 3 m/s\(^2\) 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/s\(^2\). 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.
**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.

**Figure 17** The horizontal part of the graph shows a biker’s constant speed. The part of the graph with negative slope shows negative acceleration as the mountain biker slows to a stop.

**Graphs of Accelerated Motion**

**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 to also include the units in their calculation. (4 m/s²) Now have them calculate the slope of the line between 10 and 20 seconds on the graph in Figure 17. (0.5 m/s²)

**Logical**

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

**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/s²) 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**
Section 11.3 (continued)

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

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

Section 11.3 Assessment

Reviewing Concepts

1. Describe three types of changes in velocity.
2. What is the equation for acceleration?
3. Show what acceleration is on a speed-time graph?
4. Define instantaneous acceleration.
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 16.0 m/s. Train B travels at 8.0 m/s but accelerates constantly at 1.0 m/s\(^2\). 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 10.0 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?

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.

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.

Section 11.3 Assessment

1. 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).
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. Train B \((v = v_i + at = 8.0 \text{ m/s} + (1.0 \text{ m/s}^2)(10.0 \text{ s}) = 8.0 \text{ m/s} + 10.0 \text{ m/s} = 18.0 \text{ m/s})\)
7. The graph indicates that the object is accelerating.