Motion happens all around us. Every day, we see objects such as cars, people, and soccer balls move in different directions with different speeds. We are so familiar with the idea of motion that it requires a special effort to analyze motion as a physicist does.

One-dimensional motion is the simplest form of motion. One way to simplify the concept of motion is to consider only the kinds of motion that take place in one direction. An example of this one-dimensional motion is the motion of a commuter train on a straight track, as in Figure 1.1.

In this one-dimensional motion, the train can move either forward or backward along the tracks. It cannot move left and right or up and down. This chapter deals only with one-dimensional motion. In later chapters, you will learn how to describe more complicated motions such as the motion of thrown baseballs and other projectiles.

Motion takes place over time and depends upon the frame of reference.

It seems simple to describe the motion of the train. As the train in Figure 1.1 begins its route, it is at the first station. Later, it will be at another station farther down the tracks. But Earth is spinning on its axis, so the train, stations, and the tracks are also moving around the axis. At the same time, Earth is moving around the sun. The sun and the rest of the solar system are moving through our galaxy. This galaxy is traveling through space as well.

When faced with a complex situation like this, physicists break it down into simpler parts. One key approach is to choose a frame of reference against which you can measure changes in position. In the case of the train, any of the stations along its route could serve as a convenient frame of reference.

Motion and Velocity

Objectives
- Describe motion in terms of frame of reference, displacement, time, and velocity.
- Calculate the displacement of an object travelling at a known velocity for a specific time interval.
- Construct and interpret graphs of position versus time.

Key Terms
- frame of reference
- displacement
- average velocity
- instantaneous velocity

The Language of Physics

Although this chapter discusses displacement, velocity, and acceleration, the concept of vectors is not introduced here. For the purposes of this chapter, it is sufficient to describe the direction of a quantity with a positive or negative sign because the focus is on motion in one dimension. The transition to two-dimensional motion and vectors is made in the chapter “Two-Dimensional Motion and Vectors.”

Misconception Alert!

Many students may have difficulty understanding that the magnitude of a displacement is the length of the straight-line path between two points rather than the distance traveled. Point out that although the odometer on a car shows that it has been driven 5 mi, the displacement may have been 0 mi.

Differentiated Instruction

ENGLISH LEARNERS

The concept of dimensions may not be familiar to students. They may have heard the word dimension used figuratively but not literally. Explain the difference between using the word to mean “magnitude or scope” and using the word to mean “a measure of spatial extent,” as it is used in the text. Engage students in a discussion about the difference between literal and figurative meanings in general.
If an object is at rest (not moving), its position does not change with respect to a fixed frame of reference. For example, the benches on the platform of one subway station never move down the tracks to another station.

In physics, any frame of reference can be chosen as long as it is used consistently. If you are consistent, you will get the same results, no matter which frame of reference you choose. But some frames of reference can make explaining things easier than other frames of reference.

For example, when considering the motion of the gecko in Figure 1.2, it is useful to imagine a stick marked in centimeters placed under the gecko’s feet to define the frame of reference. The measuring stick serves as an x-axis. You can use it to identify the gecko’s initial position and its final position.

Displacement

As any object moves from one position to another, the length of the straight line drawn from its initial position to the object’s final position is called the displacement of the object.

Displacement is a change in position.

The gecko in Figure 1.2 moves from left to right along the x-axis from an initial position, $x_i$, to a final position, $x_f$. The gecko’s displacement is the difference between its final and initial coordinates, or $x_f - x_i$. In this case, the displacement is about 61 cm (85 cm − 24 cm). The Greek letter delta ($\Delta$) before the $x$ denotes a change in the position of an object.

Displacement

$$\Delta x = x_f - x_i$$

displacement = change in position = final position − initial position

Measuring Displacement

A gecko moving along the x-axis from $x_i$ to $x_f$ undergoes a displacement of $\Delta x = x_f - x_i$.

Tips and Tricks

A change in any quantity, indicated by the Greek symbol delta ($\Delta$), is equal to the final value minus the initial value. When calculating displacement, always be sure to subtract the initial position from the final position so that your answer has the correct sign.

The Language of Physics

In this book, $\Delta x$ refers to a change in position along the x-axis of whatever coordinate system is chosen and $\Delta y$ refers to a change in position along the y-axis. In later chapters, these two variables refer to the x and y components of a displacement vector.

Answers

Conceptual Challenge

1. neither (because the displacements are the same)
2. The difference between these two displacements is in their direction—one is positive and the other negative.
Demonstration

**DISPLACEMENT**

**Purpose** Demonstrate the importance of direction in reference to displacement.

**Materials** one meterstick, 3 pieces of modeling clay, one toothpick or paper clip, one toy car

**Procedure** Place the meterstick on edge so that the zero mark is to the students’ left and the students can see the numbers. Put the toothpick in one of the pieces of modeling clay to represent the initial position.

For positive displacement, place the initial position marker and car somewhere between 0 and 10 cm. Roll the car down the meterstick to some point past the 50 cm mark and place the final position marker (the second piece of modeling clay) at the car’s new position. Ask the students to calculate the displacement of the car. It should be a positive number.

For negative displacement, move the initial position marker to the car, and roll the car back toward the zero end of the meterstick. Stop the car and place the third position marker. Ask the students to calculate the displacement for the second leg of the trip. It should be a negative number.

Now have students calculate the total displacement of the car.

Now suppose the gecko runs up a tree, as shown in Figure 1.3. In this case, we place the measuring stick parallel to the tree. The measuring stick can serve as the y-axis of our coordinate system. The gecko’s initial and final positions are indicated by \( y_i \) and \( y_f \), respectively, and the gecko’s displacement is denoted as \( \Delta y \).

**Displacement is not always equal to the distance traveled.**

Displacement does not always tell you the distance an object has moved. For example, what if the gecko in Figure 1.3 runs up the tree from the 20 cm marker (its initial position) to the 80 cm marker. After that, it retreats down the tree to the 50 cm marker (its final position). It has traveled a total distance of 90 cm. However, its displacement is only 30 cm (\( y_f - y_i = 50 \text{ cm} - 20 \text{ cm} = 30 \text{ cm} \)). If the gecko were to return to its starting point, its displacement would be zero because its initial position and final position would be the same.

**Displacement can be positive or negative.**

Displacement also includes a description of the direction of motion. In one-dimensional motion, there are only two directions in which an object can move, and these directions can be described as positive or negative.

In this book, unless otherwise stated, the right (or east) will be considered the positive direction and the left (or west) will be considered the negative direction. Similarly, upward (or north) will be considered positive, and downward (or south) will be considered negative. Figure 1.4 gives examples of determining displacements for a variety of situations.

**Differentiated Instruction**

**INCLUSION**

To help kinesthetic learners reinforce the difference between displacement and distance, have students act out the difference in the classroom. Choose three students to stand in one location in the room. Have them all move to a second location in the room, but with each student taking a different route. Then ask the other students to estimate how far each student moved. Point out that all three students started and ended at the same place, so their displacements are all the same.
Velocity
Where an object started and where it stopped does not completely describe the motion of the object. For example, the ground that you’re standing on may move 8.0 cm to the left. This motion could take several years and be a sign of the normal slow movement of Earth’s tectonic plates. If this motion takes place in just a second, however, you may be experiencing an earthquake or a landslide. Knowing the speed is important when evaluating motion.

Average velocity is displacement divided by the time interval.
Consider the car in Figure 1.5. The car is moving along a highway in a straight line (the x-axis). Suppose that the positions of the car are $x_i$ at time $t_i$ and $x_f$ at time $t_f$. In the time interval $\Delta t = t_f - t_i$, the displacement of the car is $\Delta x = x_f - x_i$. The average velocity, $v_{avg}$, is defined as the displacement divided by the time interval during which the displacement occurred. In SI, the unit of velocity is meters per second, abbreviated as m/s.

\[
v_{avg} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i}
\]

The average velocity of an object can be positive or negative, depending on the sign of the displacement. (The time interval is always positive.) As an example, consider a car trip to a friend’s house 370 km to the west (the negative direction) along a straight highway. If you left your house at 10 a.m. and arrived at your friend’s house at 3 p.m., your average velocity would be as follows:

\[
v_{avg} = \frac{\Delta x}{\Delta t} = \frac{-370 \text{ km}}{5.0 \text{ h}} = -74 \text{ km/h} = 74 \text{ km/h west}
\]

This value is an average. You probably did not travel exactly 74 km/h at every moment. You may have stopped to buy gas or have lunch. At other times, you may have traveled more slowly as a result of heavy traffic. To make up for such delays, when you were traveling slower than 74 km/h, there must also have been other times when you traveled faster than 74 km/h.

The average velocity is equal to the constant velocity needed to cover the given displacement in a given time interval. In the example above, if you left your house and maintained a velocity of 74 km/h to the west at every moment, it would take you 5.0 h to travel 370 km.

PRE-AP
The average velocity of a plane flying across the United States from east to west is different from a plane flying west to east. Have students research plane schedules and calculate the average velocities of a plane flying the same route in opposite directions. Make sure students take time zones into account when determining flight times. Ask students to hypothesize about why there is a difference.

Misconception Alert!
Many students believe that the average speed is always the average of the starting and ending speeds, as discussed in the Tips and Tricks on this student page. (Note that the student Tips and Tricks discusses average velocity rather than average speed because average speed has not yet been introduced.) Use counterexamples to address this misconception.

Example: A car travels from city A to city B (100 km). If the first half of the distance is driven at 50 km/h and the second half is driven at 100 km/h, the average speed is given by the following relation.

\[
\frac{100 \text{ km}}{\frac{50 \text{ km}}{50 \text{ km/h}} + \frac{50 \text{ km}}{100 \text{ km/h}}} = 67 \text{ km/h}
\]

The average speed would be 75 km/h if the car spent equal time at 50 km/h and 100 km/h.
Classroom Practice

AVERAGE VELOCITY AND DISPLACEMENT

A doctor travels to the east from city A to city B (75 km) in 1.0 h. What is the doctor’s average velocity?

Answer: 75 km/h to the east

Problem Solving

REALITY CHECK

When students are calculating average velocity, make sure that they are using a consistent coordinate system. The positive direction should stay the same when determining both the final and the initial positions. Remind students that negative and positive direction depends on the chosen coordinate system. In one problem a negative velocity may mean that the object is moving west, but in another problem it may mean it is moving down.
**Conceptual Challenge**

**Velocity is not the same as speed.**

In everyday language, the terms *speed* and *velocity* are used interchangeably. In physics, however, there is an important distinction between these two terms. As we have seen, velocity describes motion with both a direction and a numerical value (a magnitude) indicating how fast something moves. However, speed has no direction, only magnitude. An object’s average speed is equal to the distance traveled divided by the time interval for the motion.

\[
\text{average speed} = \frac{\text{distance traveled}}{\text{time of travel}}
\]

**Velocity can be interpreted graphically.**

The velocity of an object can be determined if the object’s position is known at specific times along its path. One way to determine this is to make a graph of the motion. Figure 1.6 represents such a graph. Notice that time is plotted on the horizontal axis and position is plotted on the vertical axis.

The object moves 4.0 m in the time interval between \( t = 0 \text{ s} \) and \( t = 4.0 \text{ s} \). Likewise, the object moves an additional 4.0 m in the time interval between \( t = 4.0 \text{ s} \) and \( t = 8.0 \text{ s} \). From these data, we see that the average velocity for each of these time intervals is +1.0 m/s (because \( v_{\text{avg}} = \Delta x / \Delta t = 4.0 \text{ m}/4.0 \text{ s} \)). Because the average velocity does not change, the object is moving with a constant velocity of +1.0 m/s, and its motion is represented by a straight line on the position-time graph.

For any position-time graph, we can also determine the average velocity by drawing a straight line between any two points on the graph. The slope of this line indicates the average velocity between the positions and times represented by these points. To better understand this concept, compare the equation for the slope of the line with the equation for the average velocity.

\[
\text{slope} = \frac{\text{rise}}{\text{run}} = \frac{\text{change in vertical coordinates}}{\text{change in horizontal coordinates}}
\]

\[
v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i}
\]

**Teaching Tip**

Probe your students’ understanding of the concept of slope. Many students may remember the concept from math class. Students will most likely remember slope described by the phrase *rise over run* in algebra class.

**Answers**

**Conceptual Challenge**

1. The book’s displacement is zero, its average velocity is zero, and its average speed is 0.35 m/s.

2. The velocity of car A does not equal the velocity of car B even though their speeds are the same because they are traveling in different directions.
Figure 1.7 represents straight-line graphs of position versus time for three different objects. Object 1 has a constant positive velocity because its position increases uniformly with time. Thus, the slope of this line is positive. Object 2 has zero velocity because its position does not change (the object is at rest). Hence, the slope of this line is zero. Object 3 has a constant negative velocity because its position decreases with time. As a result, the slope of this line is negative.

**Instantaneous velocity may not be the same as average velocity.**

Now consider an object whose position-versus-time graph is not a straight line, but a curve, as in Figure 1.8. The object moves through larger and larger displacements as each second passes. Thus, its velocity increases with time.

For example, between \( t = 0 \) s and \( t = 2.0 \) s, the object moves 8.0 m, and its average velocity in this time interval is 4.0 m/s (because \( v_{\text{avg}} = 8.0 \text{ m/s} / 2.0 \text{ s} \)). However, between \( t = 0 \) s and \( t = 4.0 \) s, it moves 32 m, so its average velocity in this time interval is 8.0 m/s (because \( v_{\text{avg}} = 32 \text{ m} / 4.0 \text{ s} \)). We obtain different average velocities, depending on the time interval we choose. But how can we find the velocity at an instant of time?

To determine the velocity at some instant, such as \( t = 3.0 \) s, we study a small time interval near that instant. As the intervals become smaller and smaller, the average velocity over that interval approaches the exact velocity at \( t = 3.0 \) s. This is called the **instantaneous velocity**. One way to determine the instantaneous velocity is to construct a straight line that is tangent to the position-versus-time graph at that instant. The slope of this tangent line is equal to the value of the instantaneous velocity at that point. For example, the instantaneous velocity of the object in Figure 1.8 at \( t = 3.0 \) s is 12 m/s. The table lists the instantaneous velocities of the object described by the graph in Figure 1.8. You can verify some of these values by measuring the slope of the curve.

### VELOCITY-TIME DATA

<table>
<thead>
<tr>
<th>( t ) (s)</th>
<th>( v ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>2.0</td>
<td>8.0</td>
</tr>
<tr>
<td>3.0</td>
<td>12.0</td>
</tr>
<tr>
<td>4.0</td>
<td>16.0</td>
</tr>
</tbody>
</table>

## Differentiated Instruction

**PRE-AP**

Have students draw their own position-time graphs and choose a specific point on the curve where they would like to find instantaneous velocity. To construct the tangent line at that specific point, students should draw a series of lines that intersect the curve at two points. For the first line, students should choose two points on the curve which are equidistant from their chosen point and connect those two points with a line.

As they construct more lines, the two points connected by the lines should move closer and closer to the chosen point. Eventually, the line will approximate a tangent line to the chosen point. Help students recognize that they are calculating average velocities over shorter and shorter time intervals.
1. What is the shortest possible time in which a bacterium could travel a distance of 8.4 cm across a Petri dish at a constant speed of 3.5 mm/s?
2. A child is pushing a shopping cart at a speed of 1.5 m/s. How long will it take this child to push the cart down an aisle with a length of 9.3 m?
3. An athlete swims from the north end to the south end of a 50.0 m pool in 20.0 s and makes the return trip to the starting position in 22.0 s.
   a. What is the average velocity for the first half of the swim?
   b. What is the average velocity for the second half of the swim?
   c. What is the average velocity for the roundtrip?
4. Two students walk in the same direction along a straight path, at a constant speed—one at 0.90 m/s and the other at 1.90 m/s.
   a. Assuming that they start at the same point and the same time, how much sooner does the faster student arrive at a destination 780 m away?
   b. How far would the students have to walk so that the faster student arrives 5.50 min before the slower student?
5. Does knowing the distance between two objects give you enough information to locate the objects? Explain.

**Critical Thinking**

6. **Interpreting Graphics**

   Figure 1.9 shows position-time graphs of the straight-line movement of two brown bears in a wildlife preserve. Which bear has the greater average velocity over the entire period? Which bear has the greater velocity at \( t = 8.0 \) min? Is the velocity of bear A always positive? Is the velocity of bear B ever negative?

---

**Answers to Section Assessment**

1. 24 s
2. 6.2 s
3. a. 2.50 m/s to the south
   b. 2.27 m/s to the north
   c. 0.0 m/s
4. a. 460 s
   b. 570 m
5. No, because a single distance could correspond to a variety of different positions of the objects.
6. bear B; bear A; no; no