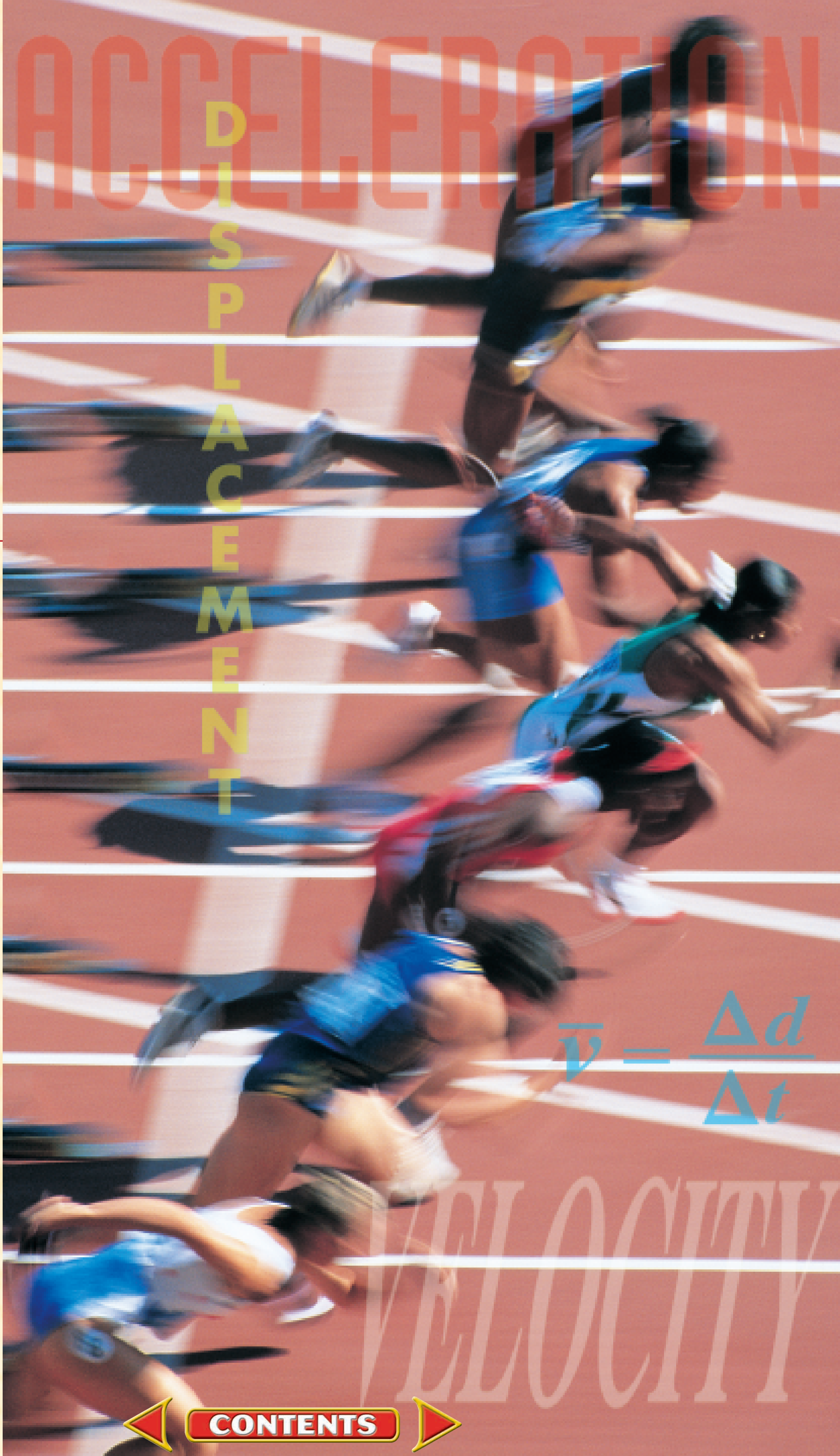
# Burst of Motion

**Sprinters, tensed at the starting block, explode into motion at the sound of the starting gun. That instant burst of motion is a key to winning the event. How would you describe the motion of a sprinter as she leaves the starting block?**

*Look at the text on page 57 for the answer.*

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CHAPTER

# 3 Describing Motion


In the fabled race between the tortoise and the hare, the moral of the tale was "slow and steady wins the race." That may be good advice for a long-distance race between hare and tortoise, but it is not the best way to win every race. For example, the short length of the 100-m dash means that a runner must reach top speed as soon as possible. What's more, a runner must maintain that top speed until she crosses the finish line. Florence Griffith-Joyner needed only 10.49 s to run the 100-m course at the 1988 Olympics. She won an Olympic gold medal for her record-breaking performance. Florence Griffith-Joyner could move!

And so does almost everything else. Movement is all around you—fast trains and slow breezes; speedy skiers and lazy clouds. The movement is in many directions—the straight-line path of a bowling ball in a lane's gutter and the curved path of a tether ball; the spiral of a falling kite and the swirls of water circling a drain. Do you ever think about motion and how things move? Do you wonder what's happening as a basketball swishes through the basket, or a football sails between the goal posts?

In the previous chapter, you learned about several mathematical tools that will be useful in your study of physics. In this chapter, you'll begin to use these tools to analyze motion in terms of displacement, velocity, and acceleration. When you understand these concepts, you can apply them in later chapters to all kinds of movement, using sketches, motion diagrams, graphs, and equations. These concepts will help you to determine how fast and how far an object will move, whether the object is speeding up or slowing down, and whether it is standing still or moving at a constant speed.

## WHAT YOU'LL LEARN

- You will describe motion by means of motion diagrams incorporating coordinate systems.
- You will develop descriptions of motion using vector and scalar quantities.
- You will demonstrate the first step, *Sketch the Problem*, in the strategy for solving physics problems.

## WHY IT'S IMPORTANT

- Without a knowledge of velocity, time intervals, and displacement, travel by plane, train, or bus would be chaotic at best, and the landing of a space vehicle on Mars an impossibility.

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# 3.1 Picturing Motion

## OBJECTIVES

- **Draw** and **use** motion diagrams to describe motion.
- **Use** a particle model to represent a moving object.

What comes to your mind when you hear the word *motion?* A speeding automobile? A spinning ride at an amusement park? A football kicked over the crossbar of the goalpost? Or trapeze artists swinging back and forth in a regular rhythm? As you can see in **Figure 3–1,** when an object is in motion, its position changes, and that its position can change along the path of a straight line, a circle, a graceful arc, or a back-and-forth vibration.

Picture not available on CD

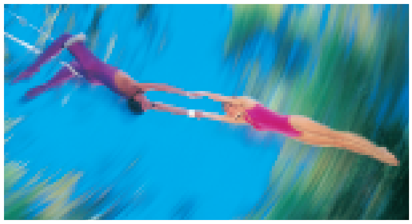

**FIGURE 3–1** An object in motion changes its position as it moves. You will learn about motion along a straight line, around a circle, along a curved arc, and along a back-and-forth path.

## Motion Diagrams

A motion diagram is a powerful tool for the study of motion. You can get a good idea of what a motion diagram is by thinking about the following procedure for making a video of a student athlete training for a race. Point the camcorder in a single direction, perpendicular to the direction of the motion, and hold it still while the motion is occurring, as shown in **Figure 3–2.** The camcorder will record an image 30 times per second. Each image is called a *frame.*

**FIGURE 3–2** When the race begins, the camcorder will record the position of the sprinter 30 times each second.



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FIGURE 3–3 If you relate the position of the runner to the background in each frame, you will conclude that the sprinter is in motion.

**Figure 3–3** shows what a series of consecutive frames might look like. Notice that the runner is in a different position in each frame, but everything in the background remains in the same position. These facts indicate that relative to the ground, only the runner is in motion.

Now imagine that you stacked the frames on top of one another as shown in **Figure 3–4.** You see more than one image of each moving object, but only a single image of all motionless objects. A series of images of a moving object that records its position after equal time intervals is called a **motion diagram.** Successive images recorded by a camcorder are at time intervals of one-thirtieth of a second. Those in **Figure 3–4** have a larger time interval.

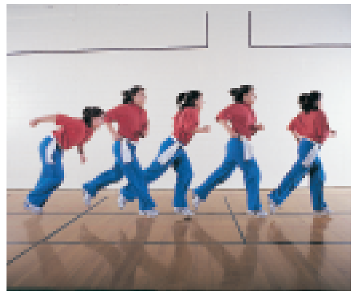

FIGURE 3–4 This series of images, taken at regular intervals, creates a motion diagram for the student's practice run.

Some examples of motion diagrams are shown in **Figure 3–5.** In one diagram, a jogger is motionless, or at rest. In another, she is moving at a constant speed. In a third, she is speeding up, and in a fourth, she is slowing down. How can you distinguish the four situations?

In **Figure 3–3,** you saw that motionless objects in the background did not change positions. Therefore, you can associate the jogger in **Figure 3–5a** with an object at rest. Now look at the way the distance between successive positions changes in the three remaining diagrams. If the change in position gets larger, as it does in **Figure 3–5c,** the jogger is speeding up. If the change in position gets smaller, as in **Figure 3–5d,** she is slowing down. In **Figure 3–5b,** the distance between images is the same, so the jogger is moving at a constant speed.

You have just defined four concepts in the study of motion: at rest, speeding up, slowing down, and constant speed. You defined them in terms of the procedure or operation you used to identify them. For that reason, each definition is called an **operational definition.** You will find this method of defining a concept to be useful in this course.

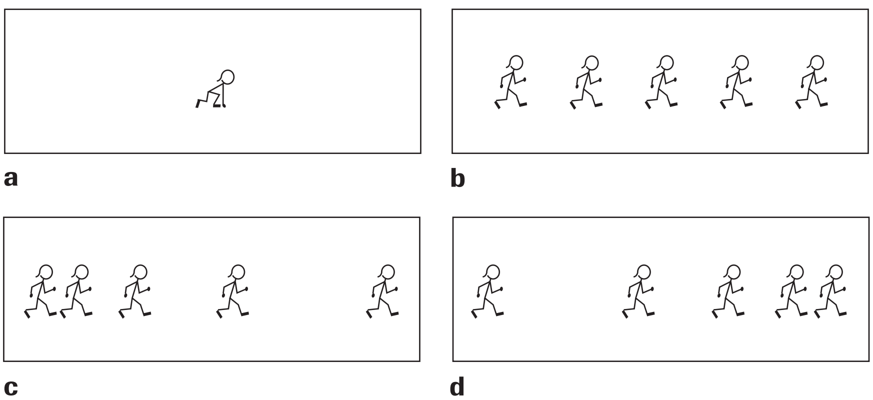


FIGURE 3–5 By noting the distance the jogger moves in equal time intervals, you can determine that the jogger in **a** is standing still, in **b** she is moving at a constant speed, in **c** she is speeding up, and in **d** she is slowing down.

**HELP WANTED**

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## The Particle Model

Keeping track of the motion of the runner is easier if you disregard moving arms and legs and concentrate on a single point at the center of her body. In effect, you can consider all of her mass to be concentrated at that point. Replacing an object by a single point is called the **particle model.** But to use the particle model, you must make sure that the size of the object is much less than the distance it moves, and you must ignore internal motions such as the waving of the runner's arms. In a camcorder motion diagram, you could identify one central point on the runner, for example, the knot on her belt, and make measurements of distance with relation to the knot. In **Figure 3–6,** you can see that the particle model provides simplified versions of the motion diagrams in **Figure 3–5.** In the next section, you'll learn how to create and use a motion diagram that shows how much distance was covered and the time interval in which it occurred.

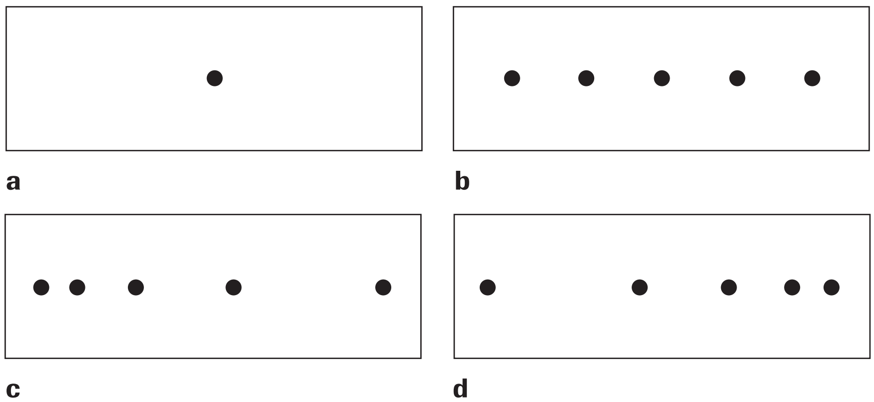


**FIGURE 3–6** Using the particle model, you can draw simplified motion diagrams such as these for the jogger in **Figure 3–5.**

## 3.1 Section Review

1. Use the particle model to draw a motion diagram for a runner moving at a constant speed.
2. Use the particle model to draw a motion diagram for a runner starting at rest and speeding up.
3. Use the particle model to draw a motion diagram for a car that starts from rest, speeds up to a constant speed, and then slows to a stop.
4. **Critical Thinking** Use the particle model to draw a motion diagram for a wheel of an auto turning at a constant speed. Assume that the wheel is touching the ground and does not slip. Place the dot at the hub of the wheel. Would it make any difference if the dot were placed on the rim of the wheel? Explain.




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# Where and When? 3.2

Would it be possible to make measurements of distance and time from a motion diagram such as that shown in **Figure 3–7?** Before turning on the camcorder, you could place a meterstick or a measuring tape on the ground along the path of the runner. The measuring tape would tell you where the runner was in each frame. A clock within the view of the camera could tell the time. But where should you place the measuring tape? When should you start the stopwatch?

### OBJECTIVES

- **Choose** coordinate systems for motion problems.
- **Differentiate** between scalar and vector quantities.
- **Define** a displacement vector and **determine** a time interval.
- **Recognize** how the chosen coordinate system affects the signs of vector quantities.

## Coordinate Systems

When you decide where to put the measuring tape and when to start the stopwatch, you are defining a **coordinate system.** A coordinate system tells you where the zero point of the variable you are studying is located and the direction in which the values of the variable increase. The **origin** is the point at which the variables have the value zero. In the example of the runner, the origin, that is, the zero end of the measuring tape, can be placed at the starting line. The motion is in a straight line, thus your measuring tape should lie along that straight line. The straight line is an axis of the coordinate system. You probably would place the tape so that the meter scale increases to the right of the zero, but putting it in the opposite direction is equally correct. In **Figure 3–8,** the origin of the coordinate system is on the left.

To measure motion in two dimensions, for example, the motion of a high jumper, you need to know both the direction parallel to the ground and the height above the ground. That is, you need two axes. Normally, the horizontal direction is called the *x*-axis, and the vertical direction, perpendicular to the *x*-axis, is called the *y*-axis.

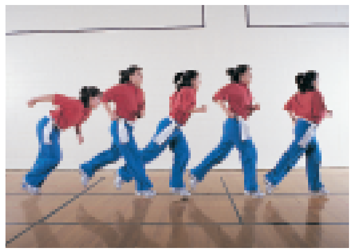


**FIGURE 3–7** To determine time and distance, a coordinate system must be specified.

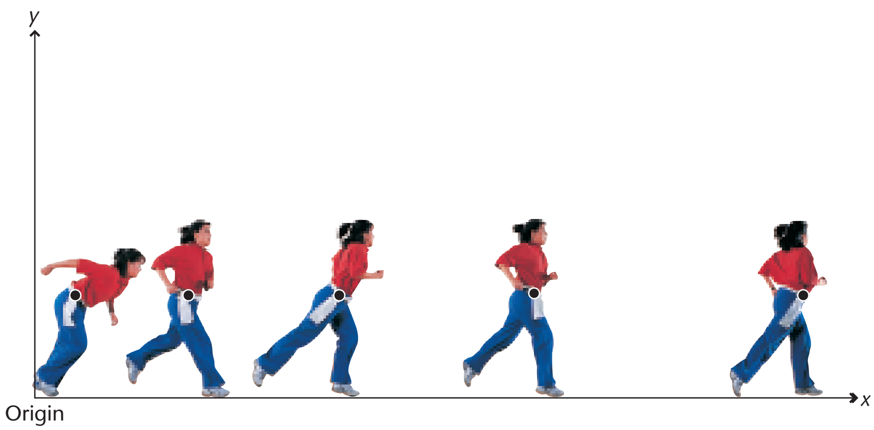


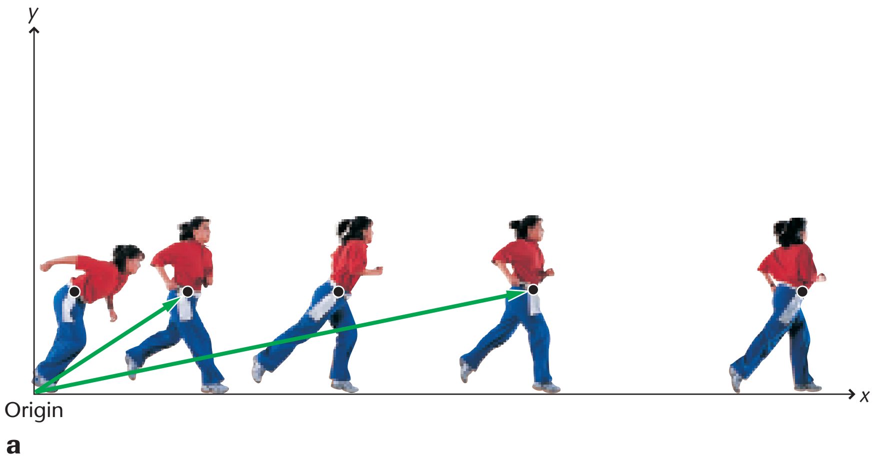

**FIGURE 3–8** When the origin is at the left, the positive values of *x* extend horizontally to the right, and the positive values of *y* extend vertically upward.

F.Y.I.

The gold medal for the men's 4 × 100 m relay in the 1996 Olympics was won by Canada with a time of 37.69 s. Donovan Bailey set the pace with a time of 8.96 s in his split.

You can locate the position of a sprinter at a particular time on a motion diagram by drawing an arrow from the origin to the belt of the sprinter, as shown in **Figure 3–9a.** The arrow is called a **position vector.** The length of the position vector is proportional to the distance of the object from the origin and points from the origin to the location of the moving object at a particular time.

Is there such a thing as a negative position? If there is, what does it mean? Suppose you chose the coordinate system just described, that is, the *x*-axis extending in a positive direction to the right. A negative position would be a position to the left of the origin, as shown in **Figure 3–9b.** In the same way, a negative time would occur before the clock or stopwatch was started. Thus, both negative positions and times are possible and acceptable.



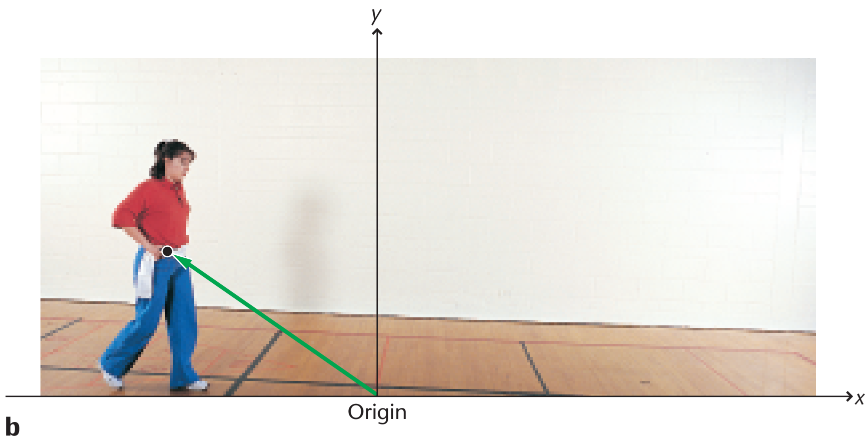
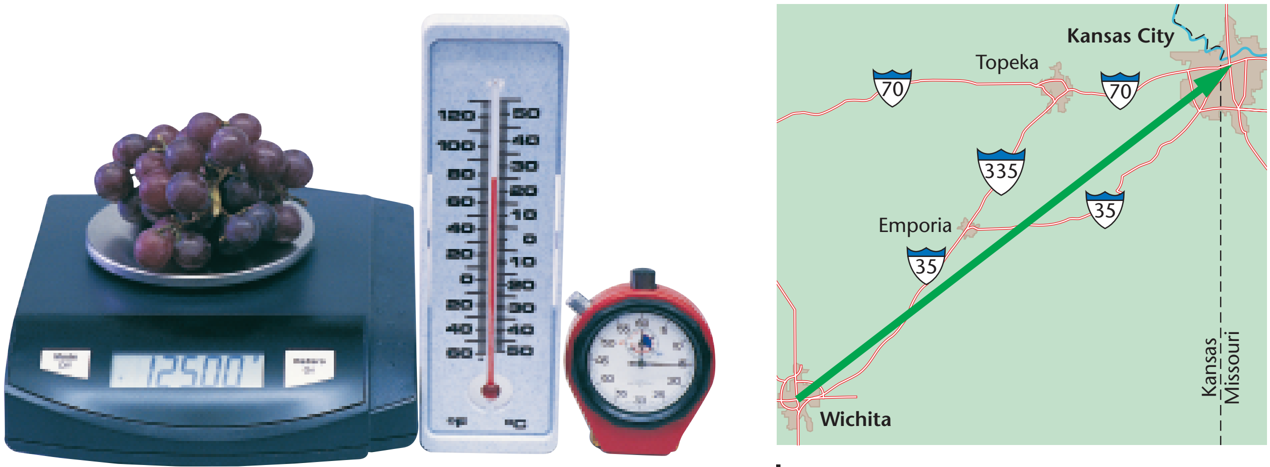




**FIGURE 3–9** Two position vectors in **a**, drawn from the origin to the knot on the sprinter's belt, locate her position at two different times. The position of the sprinter in **b**, as she walks toward the starting block, is negative in this coordinate system.

## Vectors and Scalars

What is the difference between the information you can obtain from the devices in **Figure 3–10a** and what you can learn from **Figure 3–10b?** In **Figure 3–10a,** you learn that 15 s have elapsed, the temperature is 25°C, and the mass of the grapes on the balance is 125.00 g. Each of these is a definite quantity easily recorded as a




**a** **b**

**FIGURE 3–10** Time, temperature, and mass are scalar quantities, expressed as numbers with units. The arrow in **b** represents a vector quantity. It indicates the direction of Kansas City relative to Wichita and its length is proportional to the distance between the two cities.

number with its units. A quantity such as these that tells you only the magnitude of something is called a **scalar quantity.**

Other quantities, such as the location of one city with respect to another, require both a direction and a number with units. In **Figure 3–10b,** the length of the arrow between Wichita, Kansas, and Kansas City, Missouri, is proportional to the distance between the two cities. You can calculate the distance using the scale of miles for the map. The distance between the two cities, 192 miles, is a scalar quantity. In addition, the arrow tells you the direction of Kansas City in relation to Wichita. Kansas City is 192 miles northeast of Wichita. This information, represented by the arrow on the map, is called a **vector quantity.** A vector quantity tells you not only the magnitude of the quantity, but also its direction.

Symbols often are used to represent quantities. Scalar quantities are represented by simple letters such as $m$, $t$, and $T$ for mass, time, and temperature, respectively. Vector quantities are often represented by a letter with an arrow above it, for example, $\vec{v}$ for velocity and $\vec{a}$ for acceleration. In this book, vectors are represented by boldface letters, for example, $\boldsymbol{v}$ represents velocity and $\boldsymbol{a}$ represents acceleration.

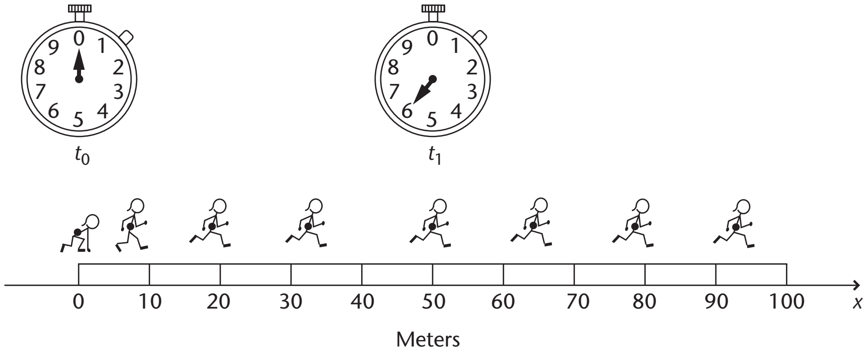
## Color Convention

- Displacement vectors are **green.**

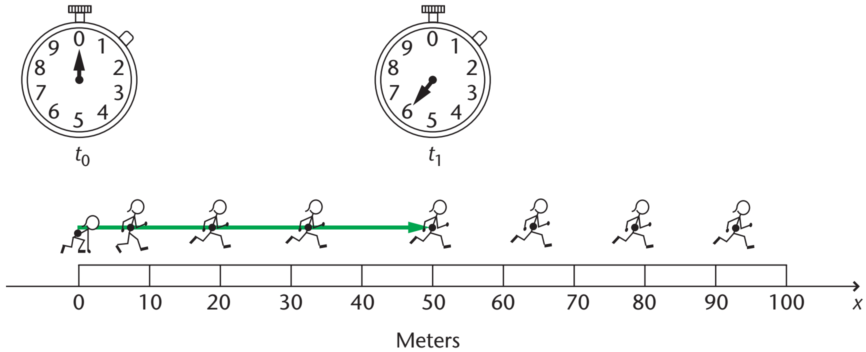
## Time Intervals and Displacements

The motion of the runner depends upon both the scalar quantity time and the vector quantity displacement. **Displacement** defines the distance and direction between two positions. The sprinter begins at the starting line and a short time later crosses the finish line. How long did it take her to move this far? That is, what was the change in time displayed on the clock? You would find this by subtracting the time shown when she started from the time shown when she finished the race. Assign the symbol $t_0$ to her starting time and the symbol $t_1$ to her time at the finish line. The difference between $t_0$ and $t_1$ is the **time interval.** A common symbol for the time interval is $\Delta t$, where the Greek letter *delta*, $\Delta$, is used to mean a change in a quantity. The time interval is defined mathematically as $\Delta t = t_1 - t_0$.

**FIGURE 3–11** In **a,** you can see that the sprinter ran 50 m in the time interval $t_1 - t_0$, which is 6 s. In **b,** the initial position of the sprinter is used as a reference point. The displacement vector indicates both the magnitude and direction of the sprinter's change in position during the 6-s interval.




**a**




**b**

## Pocket Lab

### Rolling Along

Tape a 2.5- to 3-m strip of paper to the floor or other smooth, level surface. Gently roll a smooth rubber or steel ball along the paper so that it takes about 4 or 5 s to cover the distance. Now roll the ball while a recorder makes beeps every 1.0 s. Mark the paper at the position of the rolling ball every 1.0 s.

**Analyze and Conclude** Are the marks on the paper evenly spaced? Make a data table of position and time and use the data to plot a graph. In a few sentences, describe the graph.

**Figure 3–11a** shows that the time interval for the 100-m sprinter from the start to the time when she is halfway through the course is 6.0 s. What was the change in position of the sprinter as she moved from the starting block to midway in the race? The position of an object is the separation between that object and a reference point. The symbol $\boldsymbol{d}$ may be used to represent position. **Figure 3–11b** shows an arrow drawn from the runner's initial position, $\boldsymbol{d}_0$, to her position 50 m along the track, $\boldsymbol{d}_1$. This arrow is called a displacement vector and is represented by the symbol $\Delta\boldsymbol{d}$. The change in position of an object is called its displacement.

The length, or size, of the displacement vector is called the **distance** between the two positions. That is, the distance the runner moved from $\boldsymbol{d}_0$ to $\boldsymbol{d}_1$ was 50 m. Distance is a scalar quantity.

What would happen if you chose a different coordinate system, that is, if you measured the position of the runner from another location? While both position vectors would change, the displacement vector would not. You will frequently use displacement when studying the motion of an object because displacement is the same in any coordinate system. The displacement of an object that moves from position $\boldsymbol{d}_0$ to $\boldsymbol{d}_1$ is given by $\Delta\boldsymbol{d} = \boldsymbol{d}_1 - \boldsymbol{d}_0$. The displacement vector is drawn with its tail at the earlier position and its head at the later position. Note in



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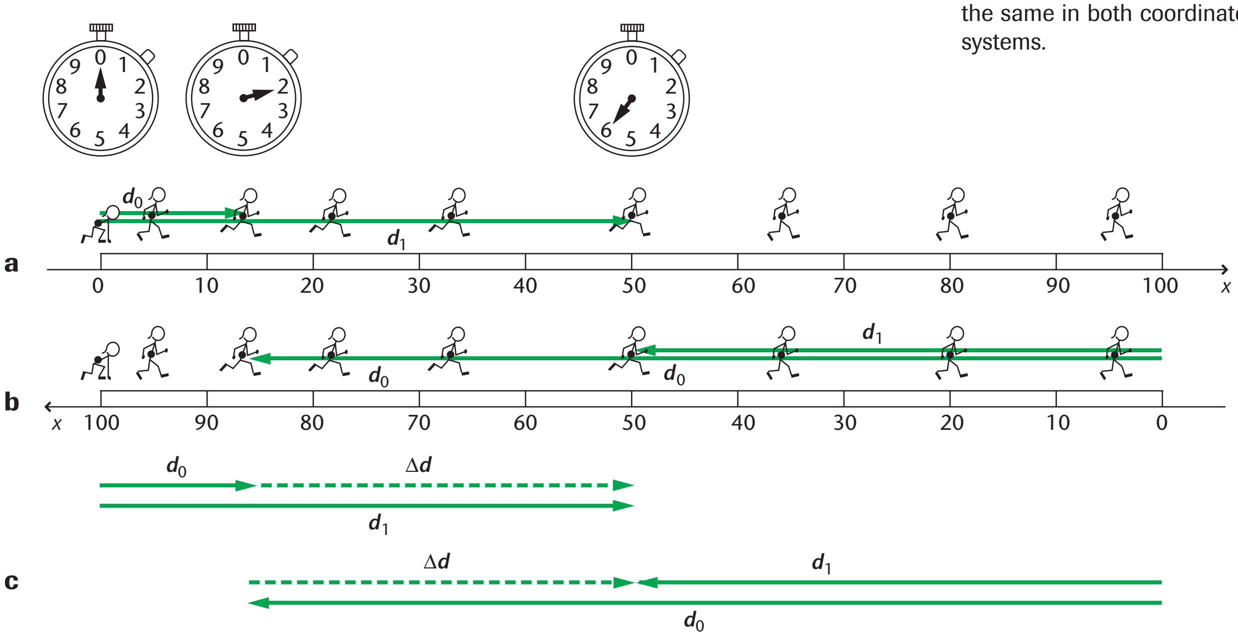
**Figure 3–12a** and **Figure 3–12b** the two different placements of the origin of the *x*-axis. The displacement, $\Delta \boldsymbol{d}$, in the time interval from 2 s to 6 s does not change, as shown in **Figure 3-12c.**

**FIGURE 3–12** The displacement of the sprinter during the 4-s time interval is found by subtracting $d_0$ from $d_1$. $\Delta d$ is the same in both coordinate systems.




# 3.2 Section Review

1. The dots below are a motion diagram for a car speeding up. The starting point is shown. Make a copy of the motion diagram, and draw displacement vectors between each pair of dots using a green pencil.

   Begin End

   • • • • • •

2. The dots below are a motion diagram for a runner slowing to a stop at the end of a race. On a copy of the motion diagram, draw displacement vectors between each pair of dots.

   Begin End

   • • • • • •

3. The dots below are a motion diagram for a bus that first speeds up, then moves at a constant speed, then brakes to a halt. On a copy of the diagram, draw the displacement vectors and explain where the bus was speeding up, where it was going at a constant speed, and where it was slowing down.

   Begin End

   • • • • • • • • • •

4. **Critical Thinking** Two students compared the position vectors they each had drawn on a motion diagram to show the position of a moving object at the same time. They found that the directions of their vectors were not the same. Explain.

# How It Works

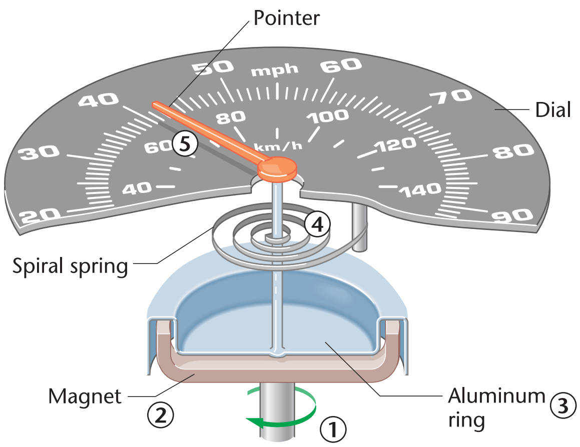
## Speedometers

A speedometer is a device for measuring the speed or rate of change of position of an object. Automobiles have relied on magnetic speedometers for decades. In these cars, the speedometer is dependent on the rotation of a gear on the transmission of the car. Recently however, an increasing number of automobiles rely on electronics for many of the automobile's systems, including the speedometer. In these cars, the speedometer is dependent upon a signal produced by a sensor within the transmission.

1. In cars with a magnetic speedometer, the pathway from the transmission to the speedometer dial on the dashboard consists of four parts: a cable, a magnet, an aluminum ring, and a pointer. When the automobile moves, a gear at the rear end of the transmission causes a cable to spin. The cable moves faster when the car moves faster, slower when the car moves slower.

2. The cable is attached to a magnet that spins at the same rate as the cable. Next to the magnet is an aluminum ring.

3. Because aluminum is nonmagnetic, it is unaffected by a stationary magnet. However, in Chapter 25, you will learn that a moving magnet will produce an electrical current in metals. Thus, the spinning magnet produces an electrical current in the aluminum ring and causes the ring to act like a magnet. This produces a twisting force, called torque.




4. The torque causes the aluminum ring to rotate. A spiral spring is set to maintain an opposite push against the torque from the spinning magnet. The faster the magnet spins, the greater the torque, and the greater the spring push.

5. The spring is connected to a pointer that rotates in front of a dial. The dial is usually graduated in both miles per hour and kilometers per hour.

6. In automobiles with an electronic speedometer, the path from the transmission to a speed reading is more direct. The electronic transmission includes a vehicle speed sensor (VSS). The VSS produces electrical pulses that are in direct proportion to the output of the gearbox. The electrical pulses are sent to a microprocessor. Based on the information it receives, the microprocessor turns on segments of a digital display that form numbers indicating the speed of the automobile.

### Thinking Critically

1. When a car moves in reverse, does the pointer move? Why or why not?
2. Would the speedometer reading be accurate if larger tires were placed on the car? Explain.

# Velocity and Acceleration 3.3

You've learned how to use a motion diagram to show objects moving at different speeds. How could you measure how fast they are moving? With devices such as a meterstick and a clock, you can measure position and time. Can these two quantities be combined in some way to create a quantity that tells you the rate of motion?

## Velocity

Suppose you recorded a speedy jogger and a slow walker on one motion diagram, as shown in **Figure 3–13.** From one frame to the next, you can see that the position of the jogger changes more than that of the walker. In other words, for a fixed time interval, the displacement, $\Delta \boldsymbol{d}$, is larger for the jogger because she is moving faster. The jogger covers a larger distance than the walker does in the same amount of time. Now, suppose that the walker and the jogger each travel 100 m. Each would need a different amount of time to go that distance. How would these time intervals compare? Certainly the time interval, $\Delta t$, would be smaller for the jogger than for the walker.

**Average velocity** From these examples, you can see that both displacement, $\Delta \boldsymbol{d}$, and time interval, $\Delta t$, might reasonably be needed to create the quantity that tells how fast an object is moving. How could you combine them?

The ratio $\Delta \boldsymbol{d}/\Delta t$ has the correct properties. It is the change in position divided by the time interval during which that change took place, or $(\boldsymbol{d}_1 - \boldsymbol{d}_0)/(t_1 - t_0)$. This ratio increases when $\Delta \boldsymbol{d}$ increases, and it also increases when $\Delta t$ gets smaller, so it agrees with the interpretation you made of the movements of the walker and runner. It is a vector in the same direction as the displacement. The ratio $\Delta \boldsymbol{d}/\Delta t$ is called the **average velocity, $\bar{\boldsymbol{v}}$.**

**Average Velocity** $$\bar{\boldsymbol{v}} \equiv \frac{\Delta \boldsymbol{d}}{\Delta t} = \frac{\boldsymbol{d}_1 - \boldsymbol{d}_0}{t_1 - t_0}$$

The symbol $\equiv$ means that the left-hand side of the equation is defined by the right-hand side.

### OBJECTIVES

- **Define** *velocity* and *acceleration* operationally.
- **Relate** the direction and magnitude of velocity and acceleration vectors to the motion of objects.
- **Create** pictorial and physical models for solving motion problems.

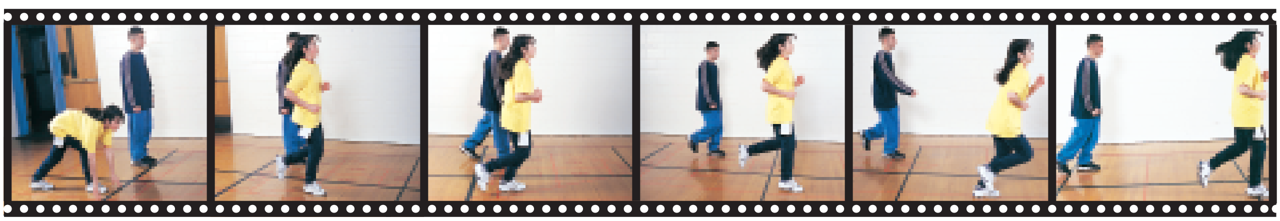


**FIGURE 3–13** Because the jogger is moving faster than the walker, the jogger's displacement is greater than the displacement of the walker in each time interval.

# F.Y.I.

The first person to reach the speed of sound, Mach I, was Major Charles E. "Chuck" Yeager of the U.S. Air Force. He attained Mach 1.06 at 43 000 feet in 1947 while flying the Bell X-1 rocket research plane.

The **average speed** is the ratio of the total distance traveled to the time interval. Automobile speeds are measured in miles per hour (mph) or kilometers per hour (km/h), but in this course, the usual unit will be meters per second (m/s).

**Instantaneous velocity** Why *average* velocity? A motion diagram tells you the position of a moving object at the beginning and end of a time interval. It doesn't tell you what happened within the time interval. Within a time interval, the speed of the object could have remained the same, increased, or decreased. The object may have stopped or even changed directions. All that can be determined from the motion diagram is an average velocity, which is found by dividing the total displacement by the time interval in which it took place.

What if you want to know the speed and direction of an object at a particular instant in time? The quantity you are looking for is **instantaneous velocity**. In this text, the term *velocity* will refer to instantaneous velocity, represented by the symbol $\boldsymbol{v}$.

**Color Conventions**

- Displacement vectors are **green.**
- Velocity vectors are **red.**

**Average velocity motion diagrams** How can you show average velocity on a motion diagram? Although the average velocity vector is in the same direction as displacement, the two vectors are not measured in the same units. Nevertheless, they are proportional; when displacement is larger over a given time interval, so is average velocity. A motion diagram isn't a precise graph of average velocity, but you can indicate the direction and magnitude of the average velocity vectors on it. Use a red pencil to draw arrows proportional in length to the displacement vectors. Label them, as shown in **Figure 3–14.**

The definition of average velocity, $\bar{\boldsymbol{v}} = \Delta \boldsymbol{d}/\Delta t$, shows that you could calculate velocity from the displacement of an object, but look at the equation in a different way. Rearrange the equation $\bar{\boldsymbol{v}} = \Delta \boldsymbol{d}/\Delta t$ by multiplying both sides by $\Delta t$.

**Displacement from Average Velocity and Time** $\Delta \boldsymbol{d} = \bar{\boldsymbol{v}}\Delta t$

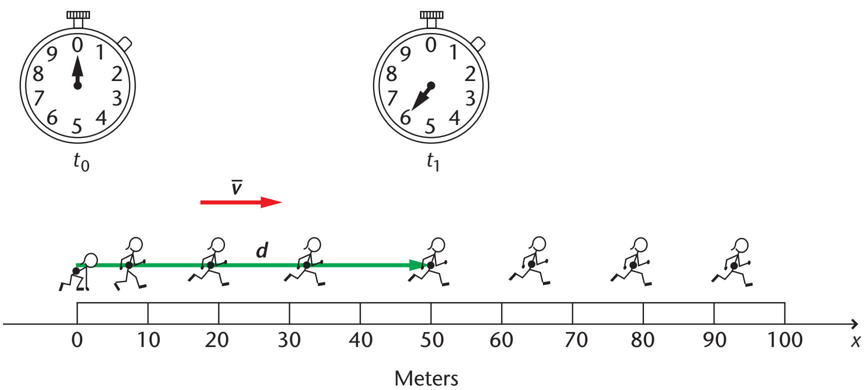



**FIGURE 3–14** Average velocity vectors have the same direction as their corresponding displacement vectors. Their magnitudes are different but proportional and they have different units.

Now, write the displacement, $\Delta\boldsymbol{d}$, in terms of the two positions $\boldsymbol{d}_0$ and $\boldsymbol{d}_1$.

$$\Delta\boldsymbol{d} = \boldsymbol{d}_1 - \boldsymbol{d}_0$$

Substitute $\boldsymbol{d}_1 - \boldsymbol{d}_0$ for $\Delta\boldsymbol{d}$ in the first equation.

$$\boldsymbol{d}_1 - \boldsymbol{d}_0 = \bar{\boldsymbol{v}}\Delta t$$

Add $\boldsymbol{d}_0$ to both sides of the equation.

$$\boldsymbol{d}_1 = \boldsymbol{d}_0 + \bar{\boldsymbol{v}}\Delta t$$

This equation tells you that over the time interval $\Delta t$, the average velocity of a moving object results in a change in position equal to $\bar{\boldsymbol{v}}\Delta t$. If there were no average velocity, there would be no change in position.

The motion diagrams in **Figure 3–15** describe a long golf putt that comes to a stop at the rim of the hole. Study the diagrams to answer these questions. When is the average velocity within a time interval greatest? When is it smallest? You can see that the average velocity vector is the longest in the first time interval. There was the greatest displacement of the ball in that time interval because the average velocity was greatest. The average velocity was the least in the last time interval in which the length of the average velocity vector is shortest.

What is the direction of the average velocity vectors in **Figure 3–15?** Before answering, you must define a coordinate system. If the origin is the point at which the ball was tapped by the golf club, then the ball was moving in a positive direction and the direction of the average velocity vector is positive, as shown in **Figure 3–15a.** But suppose you chose the hole as the origin. Then the direction of the average velocity vector is negative, as shown in **Figure 3–15b.** Either choice is correct.

## Pocket Lab

### Swinging

Use a video recorder to capture an object swinging like a pendulum. Then attach a piece of tracing paper or other see-through material over the TV screen as you play back the video frame by frame. Use a felt marker to show the position of the center of the swinging object at every frame as it moves from one side of the screen to the opposite side.

**Analyze and Conclude** Does the object have a steady speed? Describe how the speed changes. Where is the object moving the fastest? Do you think that your results are true for other swinging objects? Why?

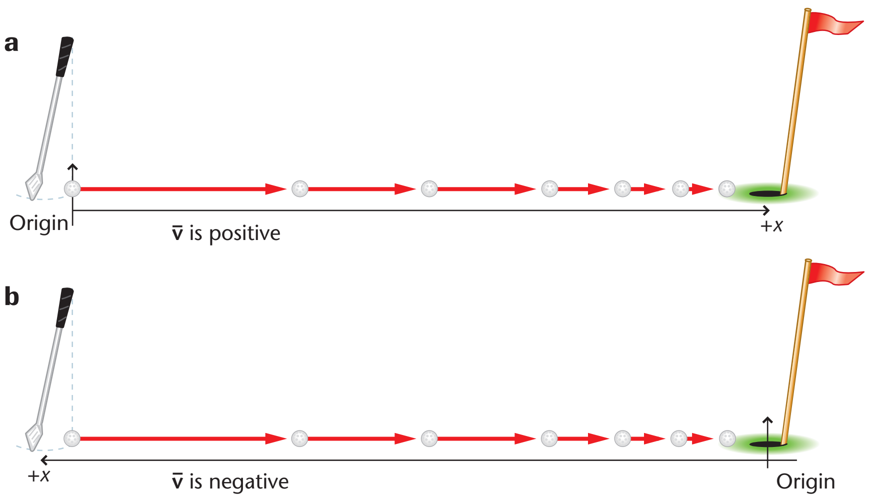



**FIGURE 3–15** The sign of the average velocity depends upon the chosen coordinate system. The coordinate systems in **a** and **b** are equally correct.

## Acceleration

The average velocity of the golf ball in **Figure 3–15** was changing from one time interval to the next. You can tell because the average velocity vectors in each time interval have different magnitudes. At the same time, the instantaneous velocity, or velocity, must also be changing. An object in

**EARTH SCIENCE CONNECTION**

**Wind Speed** The Beaufort Scale is used by meteorologists to indicate wind speeds. A wind comparable to the fastest speed run by a person is classed as 5, a strong breeze. A wind as fast as a running cheetah is classified as 11, a storm. Winds of up to 371 km/h (beyond the scale) have been registered on Mount Washington, New Hampshire.

motion whose velocity is changing is said to be accelerating. Recall that an object's velocity changes when either the magnitude or direction of the motion changes.

How can you relate the change in velocity to the time interval over which it occurs to describe acceleration? When the change in velocity is increasing or the change in velocity occurs over a shorter time interval, the acceleration is larger. The ratio $\Delta \boldsymbol{v}/\Delta t$ has the properties needed to describe acceleration.

Let $\bar{\boldsymbol{a}}$ be the **average acceleration** over the time interval $\Delta t$.

**Average Acceleration** $$\bar{\boldsymbol{a}} \equiv \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{\boldsymbol{v}_1 - \boldsymbol{v}_0}{t_1 - t_0}$$

What is the unit of average acceleration? Both velocity and change in velocity are measured in meters per second, m/s, so because average acceleration is change in velocity divided by time, the unit of average acceleration is meters per second per second. The unit is abbreviated $m/s^2$.

**Color Conventions**

- Displacement vectors are **green.**
- Velocity vectors are **red.**
- Acceleration vectors are **violet.**

**Using motion diagrams to obtain average acceleration** How can you find the change in average velocity using motion diagrams? Motion diagrams indicate position and time. From position and time, you can determine average velocity. You can get a rough idea, or qualitative description, of acceleration by looking at how the average velocity changes.

In a motion diagram, the average acceleration vector, $\bar{\boldsymbol{a}}$ is proportional to the change in the average velocity vector, $\Delta\bar{\boldsymbol{v}}$. You can draw the average acceleration and change in average velocity vectors the same length, but use the color violet to represent acceleration vectors.

**Figure 3–16** shows a motion diagram describing a car that speeds up, then travels at a constant speed, and then slows down. The origin is at the left, so the car is moving in the positive direction. You can see that when the car is speeding up, the average velocity and average acceleration vectors are in the same direction, and they are both positive. When the car is slowing down, the average velocity vector and the average acceleration vector are in opposite directions. The average velocity is positive, but the average acceleration is negative. When the velocity is constant, the average velocity vectors are of equal length. There is no change in average velocity; therefore, the average acceleration is zero.

When average velocity is increasing, as in the first four time intervals of **Figure 3–16,** the acceleration is in the same direction as the average

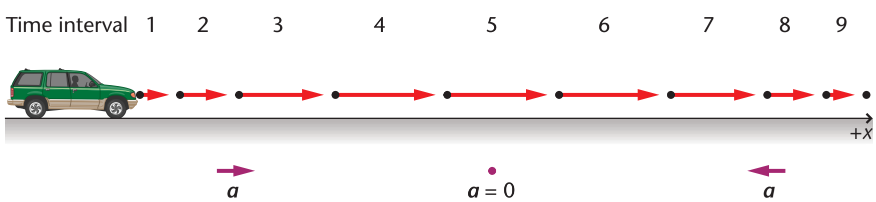



**FIGURE 3–16** In this diagram, the origin is on the left. As a result, all the average velocity vectors are positive. The sign of the acceleration is determined by whether the car is speeding up or slowing down.



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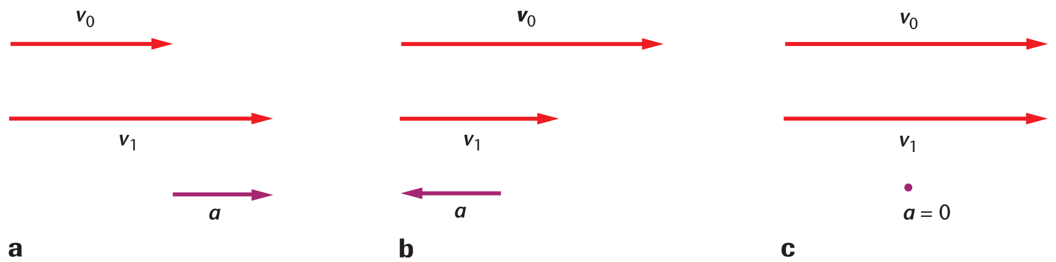



**FIGURE 3–17** The direction of the acceleration is determined by whether the car is speeding up, slowing down, or traveling at constant speed.

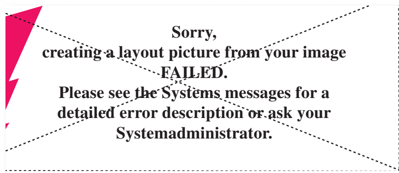
velocity. Similarly, the vector diagram in **Figure 3–17a** represents motion that is speeding up from $\boldsymbol{v}_0$ to $\boldsymbol{v}_1$. When motion is slowing down, as in time intervals 6–9 in **Figure 3–16** and in **Figure 3–17b,** the average acceleration is in a direction opposite that of the average velocity**.** When average velocity is constant, as in time intervals 4–6, $\boldsymbol{v}_0$ is equal to $\boldsymbol{v}_1$ and **Figure 3–17c** shows that the acceleration is zero.

You can now describe the motion of the sprinter as she leaves the starting block in a 100-m race. Her average velocity is increasing to the right, so with the origin at the starting block, both her average velocity and average acceleration are positive. What happens to these quantities just after the sprinter crosses the finish line? The average velocity decreases but is still in a positive direction as the sprinter slows down, but slowing down means that the average acceleration is negative.

In the remainder of this chapter, you'll learn how to sketch a problem and link it with the motion diagrams you've learned to draw. In many cases throughout this book, you'll be asked to solve problems in three steps. In this chapter, however, the focus will be on the first step.

## Burst of Motion

Answers question from page 42.




## Problem Solving Strategies

### Solving Problems

1. **Sketch the Problem** Carefully read the problem statement and make a mental picture of the problem situation. Decide whether the problem has more than one part. Then, sketch the situation. Establish a coordinate system and add it to your sketch. Next, reread the problem and make a list of unique symbols to represent each of the variables that are given or known. Finally, decide which quantity or quantities are unknown and give them symbols. This is called building a pictorial model. Next, create a physical model. When solving motion problems, the physical model is a motion diagram.
2. **Calculate Your Answer** Now use the physical model as a guide to the equations and graphs you will need. Use them to solve for the unknown quantity.
3. **Check Your Answer** Did you answer the question? Is the answer reasonable? This step is as important as the others, but it may be the hardest.

# Notion of Motion

## Problem

You are to construct motion diagrams based on a steady walk and a simulated sprint.

## Hypothesis

Devise a procedure for creating motion diagrams for a steady walk and a sprint.

## Possible Materials

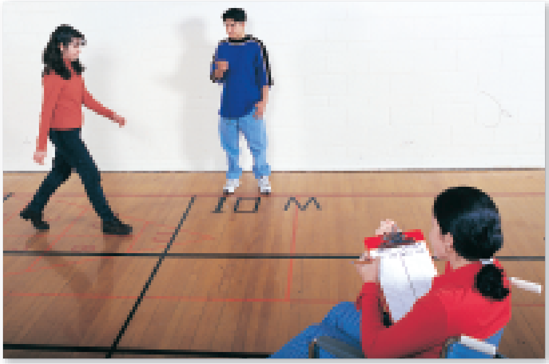
stopwatch
metersticks
10-m length of string, cord, or tape

## Plan the Experiment

1. Decide on the variables to be measured and how you will measure them.
2. Decide how you will measure the distance over the course of the walk.
3. Create a data table.

| Data and Observations | | | | | | | |
|---|---|---|---|---|---|---|---|
| Steady Walk | | | | | | | |
| distance | | | | | | | |
| time | | | | | | | |
| velocity | | | | | | | |

4. Organize team members to perform the individual tasks of walker, sprinter, time-keeper, and recorder.
5. **Check the Plan** Make sure your teacher approves your final plan before you proceed.
6. Think about how the procedures you use for the fast sprint may differ from those you used for the steady walk, then follow steps 1–5.
7. Dispose of, recycle, or put away materials as appropriate.




## Analyze and Conclude

1. **Organizing Data** Use your data to write a word description of each event.
2. **Comparing Results** Describe the data in the velocity portion of the WALK portion of the experiment. Then describe the data in the velocity portion of the SPRINT portion of the experiment.
3. **Comparing Data** Make a motion diagram for each event. Label the diagrams *Begin* and *End* to indicate the beginning and the end of the motion.
4. **Organizing Data** Draw the acceleration vectors on your motion diagram for the two events.
5. **Comparing Results** Compare the pattern of average velocity vectors for the two events. How are they different? Explain.
6. **Inferring Conclusions** Compare the acceleration vectors from the steady walk and the sprint. What can you conclude?

## Apply

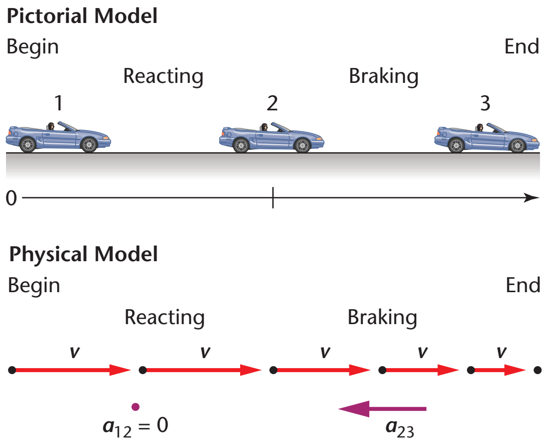
1. Imagine that you have a first-row seat for the 100-m world championship sprint. Write a description of the race in terms of velocity and acceleration. Include a motion diagram that would represent the race run by the winner.

## Sketch the Problem

Here is a typical motion problem: *A driver, going at a constant speed of 25 m/s, sees a child suddenly run into the road. It takes the driver 0.40 s to hit the brakes. The car then slows at a rate of 8.5 m/s$^2$. What is the total distance the car moves before it stops?*

Follow **Figure 3–18** as you set up this problem. What information is given? First, the speed is constant, then the brakes are applied, so this is a two-step problem. For the first step, the constant velocity is 25 m/s, and the time interval is 0.40 s. In the second step, the initial velocity is 25 m/s; the final velocity is 0.0 m/s. The acceleration is −8.5 m/s$^2$. There are three positions in this problem—the beginning, middle, and end—$\boldsymbol{d}_1$, $\boldsymbol{d}_2$, and $\boldsymbol{d}_3$. The unknown is position $\boldsymbol{d}_3$. Use $\boldsymbol{a}_{12}$ for the acceleration between $\boldsymbol{d}_1$ and $\boldsymbol{d}_2$, and $\boldsymbol{a}_{23}$ for the acceleration between $\boldsymbol{d}_2$ and $\boldsymbol{d}_3$.

The motion diagram shows that in the first part, the acceleration is zero. In the second part, the acceleration is in the direction opposite to the velocity. In this coordinate system, the acceleration is negative.




**Known:**
$d_1 = 0.0$ m
$v_1 = 25$ m/s
$a_{12} = 0.0$ m/s$^2$
$t_2 = 0.40$ s
$v_2 = 25$ m/s
$v_3 = 0.0$ m/s
$a_{23} = -8.5$ m/s$^2$

**Unknown:**
$d_3$

**FIGURE 3–18** Symbols for time and velocity are subscripted to identify the position at which they are valid. The subscripts on the symbol ***a*** indicate the two positions between which each acceleration is valid.

## 3.3 Section Review

*For the following questions, build the pictorial and physical models as shown in the preceding example. Do not solve the problems.*

1. A dragster starting from rest accelerates at 49 m/s$^2$. How fast is it going when it has traveled 325 m?
2. A speeding car is traveling at a constant speed of 30 m/s when it passes a stopped police car. The police car accelerates at 7 m/s$^2$. How fast will it be going when it catches up with the speeding car?
3. **Critical Thinking** In solving a physics problem, why is it important to make a table of the given quantities and the unknown quantity, and to assign a symbol for each?

# CHAPTER 3 REVIEW

## Key Terms

**3.1**
- motion diagram
- operational definition
- particle model

**3.2**
- coordinate system
- origin
- position vector
- scalar quantity
- vector quantity
- displacement
- time interval
- distance

**3.3**
- average velocity
- average speed
- instantaneous velocity
- average acceleration

## *Summary*

### 3.1 Picturing Motion
- A motion diagram shows the position of an object at successive times.
- In the particle model, the object in the motion diagram is replaced by a series of single points.
- An operational definition defines a concept in terms of the process or operation used.

### 3.2 Where and When?
- You can define any coordinate system you wish in describing motion, but some are more useful than others.
- While a scalar quantity has only magnitude, or size, a vector quantity has both magnitude and a direction.
- A position vector is drawn from the origin of the coordinate system to the object. A displacement vector is drawn from the position of the moving object at an earlier time to its position at a later time.
- The distance is the length or magnitude of the displacement vector.

### 3.3 Velocity and Acceleration
- Velocity and acceleration are defined in terms of the processes used to find them. Both are vector quantities with magnitude and direction.
- Average speed is the ratio of the total distance traveled to the time interval.
- The most important part of solving a physics problem is translating words into pictures and symbols.
- To build a pictorial model, analyze the problem, draw a sketch, choose a coordinate system, assign symbols to the known and unknown quantities, and tabulate the symbols.
- Use a motion diagram as a physical model to find the direction of the acceleration in each part of the problem.

## Key Equations

**3.3**

$$\bar{\boldsymbol{v}} \equiv \frac{\Delta \boldsymbol{d}}{\Delta t} = \frac{\boldsymbol{d}_1 - \boldsymbol{d}_0}{t_1 - t_0} \qquad \Delta \boldsymbol{d} = \bar{\boldsymbol{v}}\Delta t \qquad \bar{\boldsymbol{a}} \equiv \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{\boldsymbol{v}_1 - \boldsymbol{v}_0}{t_1 - t_0}$$

## *Reviewing Concepts*

### Section 3.1
1. What is the purpose of drawing a motion diagram?
2. Under what circumstances is it legitimate to treat an object as a point particle?

### Section 3.2
3. How does a vector quantity differ from a scalar quantity?
4. The following quantities describe location or its change: position, distance, and displacement. Which are vectors?
5. How can you use a clock to find a time interval?

### Section 3.3
6. What is the difference between average velocity and average speed?
7. How are velocity and acceleration related?
8. What are the three parts of the problem solving strategy used in this book?



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9. In which part of the problem solving strategy do you sketch the situation?
10. In which part of the problem solving strategy do you draw a motion diagram?

## Applying Concepts

11. Test the following combinations and explain why each does not have the properties needed to describe the concept of velocity: $\Delta \mathbf{d} + \Delta t$, $\Delta \mathbf{d} - \Delta t$, $\Delta \mathbf{d} \times \Delta t$, $\Delta t / \Delta \mathbf{d}$.
12. When can a football be considered a point particle?
13. When can a football player be treated as a point particle?
14. When you enter a toll road, your toll ticket is stamped 1:00 P.M. When you leave, after traveling 55 miles, your ticket is stamped 2:00 P.M. What was your average speed in miles per hour? Could you ever have gone faster than that average speed? Explain.
15. Does a car that's slowing down always have a negative acceleration? Explain.
16. A croquet ball, after being hit by a mallet, slows down and stops. Do the velocity and acceleration of the ball have the same signs?

## Problems

*Create pictorial and physical models for the following problems. Do not solve the problems.*

### Section 3.3

17. A bike travels at a constant speed of 4.0 m/s for 5 s. How far does it go?
18. A bike accelerates from 0.0 m/s to 4.0 m/s in 4 s. What distance does it travel?
19. A student drops a ball from a window 3.5 m above the sidewalk. The ball accelerates at 9.80 $m/s^2$. How fast is it moving when it hits the sidewalk?
20. A bike first accelerates from 0.0 m/s to 5.0 m/s in 4.5 s, then continues at this constant speed for another 4.5 s. What is the total distance traveled by the bike?
21. A car is traveling 20 m/s when the driver sees a child standing in the road. He takes 0.8 s to react, then steps on the brakes and slows at 7.0 $m/s^2$. How far does the car go before it stops?
22. You throw a ball downward from a window at a speed of 2.0 m/s. The ball accelerates at 9.8 $m/s^2$. How fast is it moving when it hits the sidewalk 2.5 m below?
23. If you throw the ball in problem 22 up instead of down, how fast is it moving when it hits the sidewalk? **Hint:** Its acceleration is the same whether it is moving up or down.

**Extra Practice** **For more practice solving problems, go to Extra Practice Problems, Appendix B.**

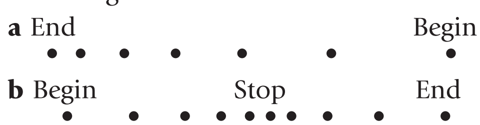
## Critical Thinking Problems

*Each of the following problems involves two objects. Draw the pictorial and physical models for each. Use different symbols to represent the position, velocity, and acceleration of each object. Do not solve the problem.*

24. A truck is stopped at a stoplight. When the light turns green, it accelerates at 2.5 $m/s^2$. At the same instant, a car passes the truck going 15 m/s. Where and when does the truck catch up with the car?
25. A truck is traveling at 18 m/s to the north. The driver of a car, 500 m to the north and traveling south at 24 m/s, puts on the brakes and slows at 3.5 $m/s^2$. Where do they meet?

## Going Further

**Using What You Know** Write a problem and make a pictorial model for each of the following motion diagrams. Be creative!

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