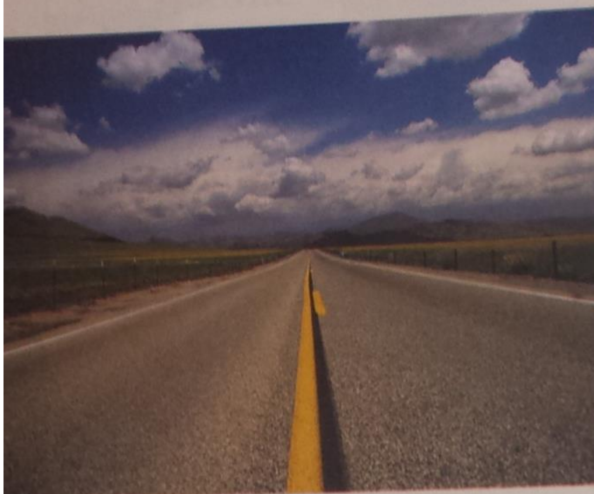
Chapter 2

Linear Motion



We experience the concepts of speed, velocity, and acceleration when riding in automobiles.

Motion occurs all around us. We see it in the everyday activity of people, of cars on the highway, in trees that sway in the wind, and with patience, we see it in the nighttime stars. There is motion at the microscopic level that we cannot see directly: jostling atoms make heat and sound, flowing electrons make electricity, and vibrating electrons produce radio and television. Even the light that lets us see motion is caused by the motion of electrons in atoms. Truly, motion is everywhere.

Motion is easy to recognize, but it is hard to describe. Even the Greek scientists of more than 2000 years ago, who had a very good understanding of many of the ideas of physics we study today, had great difficulty describing motion. They failed because they did not understand the idea of *rate*. A quantity divided by *time* is a **rate.** It tells how fast something happens, or how much something changes in a certain amount of time. In this chapter we will describe motion by the rates known as *speed, velocity,* and *acceleration*. It would be very nice if this chapter helped you to master these concepts, but it will be enough for you to become familiar with them and to be able to distinguish among them. So we'll consider only the simplest form of motion, motion along a straight-line path—*linear motion*. In Chapter 3 we'll extend these concepts to include motion along curved paths. The following chapters will sharpen your understanding of the concepts of motion.

2.1 Motion Is Relative

Everything moves. Even things that appear to be at rest move. They move with respect to, or **relative** to, the sun and stars. A book that is at rest, relative to the table it lies on, is moving at about 30 kilometers per second relative to the sun. The book moves even faster relative to the center of our galaxy. When we discuss the motion of something, we describe its motion relative to something else. When we say that a space shuttle moves at 8 kilometers per second, we mean its movement relative to Earth below. When we say a racing car in the Indy 500 reaches a speed of 300 kilometers per hour, of course we mean relative to the track. Unless stated otherwise, when we discuss the speeds of things in our environment, we mean speed with respect to the surface of Earth. Motion is relative.

2.2 Speed

A moving object travels a certain distance in a given time. A car, for example, travels so many kilometers in an hour. **Speed** is a measure of how fast something is moving. It is the rate at which distance is covered. Remember, the word *rate* is a clue that something is being *divided by time.* Speed is always measured in terms of a unit of distance divided by a unit of time. Speed is defined as the distance covered *per* unit of time. The word *per* means "divided by."

Figure 2.1
A cheetah is the fastest land animal over distances less than 500 meters and can achieve peak speeds of 100 km/h.

Any combination of units for distance and time that are useful and convenient are legitimate for describing speed. Miles per hour (mi/h), kilometers per hour (km/h), centimeters per day (the speed of a sick snail?), or light-years per century are all legitimate units for speed. The slash symbol (/) is read as "per." Throughout this book

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Table 2.1 Approximate Speeds in Different Units
20 km/h = 12 mi/h = 6 m/s
40 km/h = 25 mi/h = 11 m/s
60 km/h = 37 mi/h = 17 m/s
80 km/h = 50 mi/h = 22 m/s
100 km/h = 62 mi/h = 28 m/s
120 km/h = 75 mi/h = 33 m/s

we'll primarily use the units *meters per second* (m/s) for speed. Table 2.1 shows some comparative speeds in different units.

Figure 2.2 ▲
The speedometer for a North American car gives readings of instantaneous speed in both mi/h and km/h. Odometers for the U.S. market give readings in miles; those for the Canadian market give readings in kilometers.

Instantaneous Speed

A car does not always move at the same speed. A car may travel down a street at 50 km/h, slow to 0 km/h at a red light, and speed up to only 30 km/h because of traffic. You can tell the speed of the car at any instant by looking at the car's speedometer. The speed at any instant is called the **instantaneous speed.** A car traveling at 50 km/h may go at that speed for only one minute. If the car continued at that speed for a full hour, it would cover 50 km. If it continued at that speed for only half an hour, it would cover only half that distance, or 25 km. In one minute the car would cover less than 1 km.

Average Speed

In planning a trip by car, the driver often wants to know how long it will take to cover a certain distance. The car will certainly not travel at the same speed all during the trip. The driver cares only about the **average speed** for the trip as a whole. The average speed is defined as follows:

$$\text{average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

Average speed can be calculated rather easily. For example, if we drive a distance of 60 kilometers during a time of 1 hour, we say our average speed is 60 kilometers per hour (60 km/h). Or, if we travel 240 kilometers in 4 hours,

$$\text{average speed} = \frac{\text{total distance covered}}{\text{time interval}} = \frac{240\text{ km}}{4\text{ h}} = 60\text{ km/h}$$

Note that when a distance in kilometers (km) is divided by a time in hours (h), the answer is in kilometers per hour (km/h).

Since average speed is the distance covered divided by the time of travel, it does not indicate variations in the speed that may take place during the trip. In practice, we experience a variety of speeds on most trips, so the average speed is often quite different from the instantaneous speed. Whether we talk about average speed or instantaneous speed, we are talking about the rates at which distance is traveled.

Questions

1. The speedometer in every car also has an odometer that records the distance traveled.
   a. If the odometer reads zero at the beginning of a trip and 35 km a half hour later, what is the average speed?
   b. Would it be possible to attain this average speed and never exceed a reading of 70 km/h on the speedometer?
2. If a cheetah can maintain a constant speed of 25 m/s, it will cover 25 meters every second. At this rate, how far will it travel in 10 seconds? In 1 minute?

2.3 Velocity

In everyday language, we can use the words *speed* and *velocity* interchangeably. In physics, we make a distinction between the two. Very simply, the difference is that **velocity** is speed in a given direction. When we say a car travels at 60 km/h, we are specifying its speed. But if we say a car moves at 60 km/h to the north, we are specifying its velocity. Speed is a description of how fast an object moves; velocity is how fast and in what direction it moves. We will see in the next section that there are good reasons for the distinction between speed and velocity.

Answers

(Are you reading this before you have formulated a reasoned answer in your mind? If so, do you also exercise your body by watching others do push-ups? Exercise your thinking! When you encounter the many questions throughout this book, *think* before you read the footnoted answers. You'll not only learn more, you'll enjoy learning more.)

1. a. $\text{average speed} = \dfrac{\text{total distance covered}}{\text{time interval}} = \dfrac{35 \text{ km}}{0.5 \text{ h}} = 70 \text{ km/h}$

   b. No, not if the trip started from rest and ended at rest, because any intervals with an instantaneous speed less than 70 km/h would have to be compensated with instantaneous speeds greater than 70 km/h to yield an average of 70 km/h. In practice, average speeds are usually appreciably less than peak instantaneous speeds.

2. In 10 s the cheetah will cover 250 m, and in 1 minute (or 60 s) it will cover 1500 m, more than 15 football fields! If we know the average speed and the time of travel, then the distance covered is

$$\text{distance} = \text{average speed} \times \text{time interval}$$

$$\text{distance} = (25 \text{ m/s}) \times (10 \text{ s}) = 250 \text{ m}$$

$$\text{distance} = (25 \text{ m/s}) \times (60 \text{ s}) = 1500 \text{ m}$$

A little thought will show that this relationship is simply a rearrangement of

■ Question

The speedometer of a car moving northward reads 60 km/h. It passes another car that travels southward at 60 km/h. Do both cars have the same speed? Do they have the same velocity?

Constant Velocity

From the definition of velocity, it follows that to have a constant velocity requires both constant speed *and* constant direction. Constant speed means that the motion remains at the same speed—the object does not move faster or slower. Constant direction means that the motion is in a straight line—the object's path does not curve at all. Motion at constant velocity is motion in a straight line at constant speed.

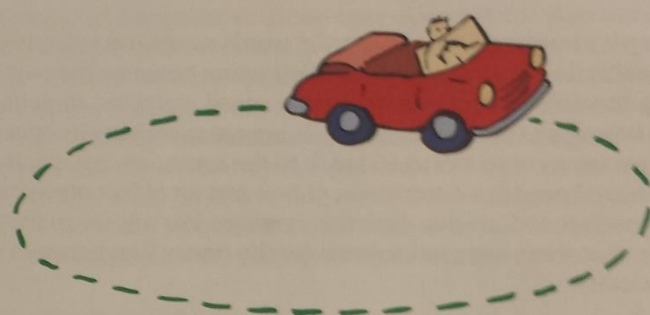

Figure 2.3 ▶
The car on the circular track may have a constant speed but not a constant velocity, because its direction of motion is changing every instant.

Changing Velocity

If *either* the speed *or* the direction (or both) is changing, then the velocity is changing. Constant speed and constant velocity are not the same. A body may move at constant speed along a curved path, for example, but it does not move with constant velocity, because its direction is changing every instant.

In a car there are three controls that are used to change the velocity. One is the gas pedal, which is used to maintain or increase the speed. The second is the brake, which is used to decrease the speed. The third is the steering wheel, which is used to change the direction.

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■ Answer

Both cars have the same speed, but they have opposite velocities because they are moving in opposite directions.

2.4 Acceleration

We can change the state of motion of an object by changing its speed, its direction of motion, or both. Any of these changes is a change in velocity. Sometimes we are interested in how fast the velocity is changing. A driver on a two-lane road who wants to pass another car would like to be able to speed up and pass in the shortest possible time. The rate at which the velocity is changing is called **acceleration.** Because acceleration is a rate, it is a measure of how the velocity is changing with respect to time.

$$\text{acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

We are familiar with acceleration in an automobile. The driver depresses the gas pedal, which is appropriately called the accelerator. The passengers then experience acceleration, or "pickup" as it is sometimes called, as they are pressed into their seats. The key idea that defines acceleration is *change*. Whenever we change our state of motion, we are accelerating. A car that can accelerate well has the ability to change its velocity rapidly. A car that can go from zero to 60 km/h in 5 seconds has a greater acceleration than another car that can go from zero to 80 km/h in 10 seconds. So having good acceleration means being able to change velocity quickly and does not necessarily refer to how fast something is moving.

In physics, the term *acceleration* applies to decreases as well as increases in speed. The brakes of a car can produce large retarding accelerations, that is, they can produce a large decrease per second in the speed. This is often called *deceleration*, or *negative acceleration*. We experience deceleration when the driver of a bus or car slams on the brakes and we tend to hurtle forward.

Figure 2.4 ▲
A car is accelerating whenever there is a *change* in its state of motion.

Acceleration applies to changes in *direction* as well as changes in speed. If you ride around a curve at a constant speed of 50 km/h, you feel the effects of acceleration as your body tends to move outward toward the outside of the curve. You may round the curve at constant speed, but your velocity is not constant, because your direction is changing every instant. Your state of motion is changing:

you are accelerating. Now you can see why it is important to distinguish between speed and velocity and why acceleration is defined as the rate of change in *velocity*, rather than *speed*. Acceleration, like velocity, is directional. If we change either speed or direction, or both, we change velocity and we accelerate.

In much of this book we will be concerned only with motion along a straight line. When straight-line motion is considered, it is common to use speed and velocity interchangeably. When the direction is not changing, acceleration may be expressed as the rate at which *speed* changes.

$$\text{acceleration (along a straight line)} = \frac{\text{change in speed}}{\text{time interval}}$$

Speed and velocity are measured in units of distance per time. The units of acceleration are a bit more complicated. Since acceleration is the change in velocity or speed per time interval, its units are those of speed per time. If we speed up, without changing direction, from zero to 10 km/h in 1 second, our change in speed is 10 km/h in a time interval of 1 s. Our acceleration along a straight line is

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time interval}} = \frac{10\ \text{km/h}}{1\ \text{s}} = 10\ \text{km/h·s}$$

The acceleration is 10 km/h·s, which is read as "10 kilometers per hour-second." Note that a unit for time enters twice: once for the unit of speed and again for the interval of time in which the speed is changing. If you understand this, you can answer the following questions. If you don't, maybe the answers to the questions will help.

Questions

1. Suppose a car moving in a straight line steadily increases its speed each second, first from 35 to 40 km/h, then from 40 to 45 km/h, then from 45 to 50 km/h. What is its acceleration?
2. In 5 seconds a car moving in a straight line increases its speed from 50 km/h to 65 km/h, while a truck goes from rest to 15 km/h in a straight line. Which undergoes greater acceleration? What is the acceleration of each vehicle?

Answers

Apply

1. We see that the speed increases by 5 km/h during each 1-s interval. The acceleration is therefore 5 km/h·s during each interval.
2. The car and truck both increase their speed by 15 km/h during the same time interval, so their acceleration is the same. If you realized this without first calculating the accelerations, you're thinking conceptually. The acceleration of each vehicle is

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time interval}} = \frac{15\ \text{km/h}}{5\ \text{s}} = 3\ \text{km/h·s}$$

2.5 Free Fall: How Fast

An apple falls from a tree. Does it accelerate while falling? We know it starts from a rest position and gains speed as it falls. We know this because it would be safe to catch if it fell a meter or two, but not if it fell from a high-flying balloon. Thus, the apple must gain more speed during the time it drops from a great height than during the shorter time it takes to drop a meter. This gain in speed indicates that the apple does accelerate as it falls.

Gravity causes the apple to accelerate downward once it begins falling. In real life, air resistance affects the acceleration of a falling object. Let's imagine there is no air resistance and that gravity is the only thing affecting a falling object. Such an object would then be in **free fall.** Freely falling objects are affected only by gravity. Table 2.2 shows the instantaneous speed at the end of each second of fall of a freely falling object dropped from rest. The **elapsed time** is the time that has elapsed, or passed, since the beginning of the fall.

Figure 2.5 ▲
If a falling rock were somehow equipped with a speedometer, in each succeeding second of fall its reading would increase by almost 10 m/s. Table 2.2 shows the speed we would read at various seconds of fall.

Table 2.2
Free Fall Speeds of Objects Dropped from Rest

Elapsed Time (seconds)	Instantaneous Speed (meters/second)
0	0
1	10
2	20
3	30
4	40
5	50
•	•
•	•
•	•
t	$10t$

Note in Table 2.2 the way the speed changes. During each second of fall the instantaneous speed of the object increases by an additional 10 meters per second. This gain in speed per second is the acceleration.

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time interval}} = \frac{10 \text{ m/s}}{1 \text{ s}} = 10 \text{ m/s}^2$$

Note that when the change in speed is in m/s and the time interval is in s, the acceleration is in m/s^2, which is read as "meters per second squared." The unit of time, the second, occurs twice—once for the unit of speed and again for the time interval during which the speed changes.

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The acceleration of an object falling under conditions where air resistance is negligible is about 10 meters per second squared (10 m/s²). For free fall, it is customary to use the letter *g* to represent the acceleration because the acceleration is due to gravity. Although *g* varies slightly in different parts of the world, its average value is nearly 10 m/s². More accurately, *g* is 9.8 m/s², but it is easier to see the ideas involved when it is rounded off to 10 m/s². Where accuracy is important, the value of 9.8 m/s² should be used for the acceleration during free fall. Note in Table 2.2 that the instantaneous speed of an object falling from rest is equal to the acceleration multiplied by the amount of time it falls, the elapsed time.

$$\text{instantaneous speed} = \text{acceleration} \times \text{elapsed time}$$

The instantaneous speed v of an object falling from rest after an elapsed time t can be expressed in equation form*

$$v = gt$$

The letter v symbolizes both speed and velocity. Take a moment to check this equation with Table 2.2. You will see that whenever the acceleration $g = 10$ m/s² is multiplied by the elapsed time in seconds, the result is the instantaneous speed in meters per second.

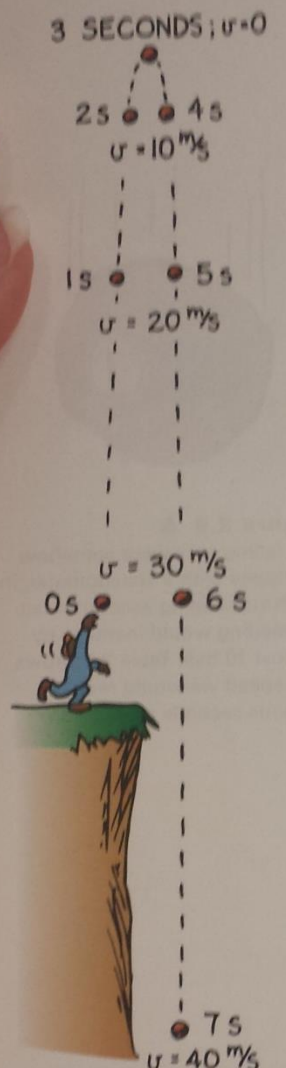


Figure 2.6 ▲
The change in speed each second is the same whether the ball is going upward or downward.

■ Question

What would the speedometer reading on the falling rock shown in Figure 2.5 be 4.5 seconds after it drops from rest? How about 8 seconds after it is dropped? 15 seconds?

So far, we have been looking at objects moving straight downward due to gravity. Now consider an object thrown straight up. It continues to move upward for a while, then it comes back down. At the highest point, when the object is changing its direction of motion from upward to downward, its instantaneous speed is zero. It then starts downward just as if it had been dropped from rest at that height.

During the upward part of this motion, the object slows from its initial upward velocity to zero velocity. We know the object is accelerating because its velocity is changing. How much does its speed decrease each second? It should come as no surprise that the speed decreases at the same rate it increases when moving downward—at 10 meters per second each second. So as Figure 2.6 shows, the

■ Answer

The speedometer readings would be 45 m/s, 80 m/s, and 150 m/s, respectively. You can reason this from Table 2.2 or use the equation $v = gt$, where g is replaced by 10 m/s².

* This relationship follows from the definition of acceleration when the acceleration is g and the initial speed is zero. If the object is initially moving downward at speed v_0, the speed v after any elapsed time t is $v = v_0 + gt$. This book will not focus on such added complications. You can learn a lot from even the simplest cases!

instantaneous speed at points of equal elevation in the path is the same whether the object is moving upward or downward. The *velocities* are different of course, because they are in opposite directions. During each second, the speed or the velocity changes by 10 m/s. The acceleration is 10 m/s^2 the entire time, whether the object is moving upward or downward.

2.6 Free Fall: How Far

How *fast* something moves is entirely different from how *far* it moves—speed and distance are not the same thing. To understand the difference, return to Table 2.2. At the end of the first second, the falling object has an instantaneous speed of 10 m/s. Does this mean it falls a distance of 10 meters during this first second? No. Here's where the difference between instantaneous speed and average speed comes in. If the object falls 10 meters the first second, its *average* speed is 10 m/s. But we know the speed began at zero and took a full second to get to 10 m/s. So the average speed is between zero and 10 m/s. For any object moving in a straight line with constant acceleration, we find the average speed the way we find the average of any two numbers: add them and divide by 2. So adding the initial speed of zero and the final speed of 10 m/s and then dividing by 2, we get 5 m/s. During the first second, the object has an average speed of 5 m/s. So it falls a distance of 5 meters. To check your understanding of this, carefully consider the following question before going further.

Question

During the span of the second time interval in Table 2.2, the object begins at 10 m/s and ends at 20 m/s. What is the average speed of the object during this 1-second interval? What is its acceleration?

Table 2.3 shows the total distance moved by a freely falling object dropped from rest. At the end of one second, it has fallen 5 meters. At the end of 2 seconds, it has dropped a total distance of 20 meters. At the end of 3 seconds, it has dropped 45 meters altogether. These distances form a mathematical pattern: at the

Answer

The average speed will be

$$\frac{\text{beginning speed + final speed}}{2} = \frac{10\text{ m/s} + 20\text{ m/s}}{2} = \frac{30\text{ m/s}}{2} = 15\text{ m/s}$$

The acceleration will be

$$\frac{\text{change in speed}}{\text{time interval}} = \frac{20\text{ m/s} - 10\text{ m/s}}{1\text{ s}} = \frac{10\text{ m/s}}{1\text{ s}} = 10\text{ m/s}^2$$

Table 2.3 Free Fall Distances of an Object Dropped from Rest	
Elapsed Time (seconds)	**Distances Fallen (meters)**
0	0
1	5
2	20
3	45
4	80
5	125
•	•
•	•
•	•
t	$\frac{1}{2}gt^2$

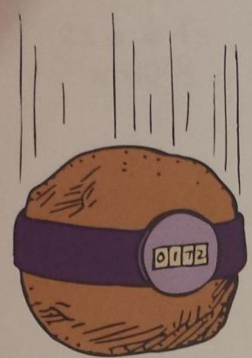


Figure 2.7 ▲
Pretend that a falling rock is somehow equipped with an *odometer*. The readings of distance fallen increase with time and are shown in Table 2.3.

end of time t, the object has fallen a distance d of $\frac{1}{2}gt^2$.* Try using $g = 10\ m/s^2$ to calculate the distance fallen for some of the times shown in Table 2.3.

■ Question

An apple drops from a tree and hits the ground in one second. What is its speed upon striking the ground? What is its average speed during the one second? How high above ground was the apple when it first dropped?

■ Answer

Using 10 m/s^2 for g we find

speed $v = gt = (10\ m/s^2)(1\ s) = 10\ m/s$

average speed $\bar{v} = \dfrac{\text{beginning } v + \text{final } v}{2} = \dfrac{0\ m/s + 10\ m/s}{2} = 5\ m/s$

(The bar over the symbol v denotes average speed $\bar{v}$.)

distance d = average speed × time interval = $(5\ m/s)(1\ s) = 5\ m$ or equivalently,

distance $d = \frac{1}{2}gt^2 = (\frac{1}{2})(10\ m/s^2)(1\ s)^2 = 5\ m$

Notice that the distance can be found by either of these equivalent relationships.

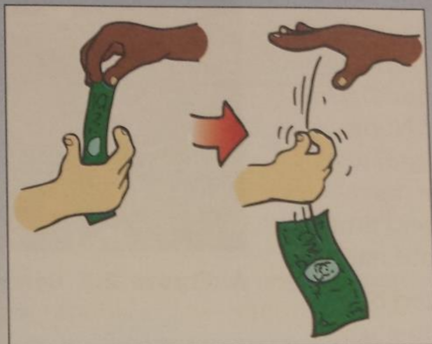
$$\begin{aligned} ^{*}\ \text{distance} &= \text{average speed} \times \text{time interval} \\ &= \frac{\text{beginning speed} + \text{final speed}}{2} \times \text{time} \\ &= \frac{0 + gt}{2} \times t \\ &= \frac{1}{2}gt^2 \end{aligned}$$

DOING PHYSICS

Reaction Time

Try this with your friends. Hold a dollar bill so that the midpoint hangs between a friend's fingers. Challenge your friend to catch it by snapping his or her fingers shut when you release it. The bill won't be caught!

Explanation: It takes at least 1/7 second for nerve impulses to travel from the eye to the brain to the fingers. But, according to the equation $d = (1/2)gt^2$, in only 1/8 second the bill falls 8 centimeters—half the length of the bill.



Activity

We used freely falling objects to describe the relationship between distance traveled, acceleration, and velocity acquired. In our examples, we used the acceleration of gravity, $g = 10\ \text{m/s}^2$. But accelerating objects need not be freely falling objects. A car accelerates when we step on the gas or the brake pedal. Whenever an object's initial speed is zero and the acceleration a is constant, that is, steady and "nonjerky," the equations* for the velocity and distance traveled are

$$v = at \text{ and } d = \frac{1}{2}at^2$$

2.7 Graphs of Motion

Equations and tables are not the only way to describe relationships such as velocity and acceleration. Another way is to use graphs that visually describe relationships. Since you'll develop basic graphing skills in the laboratory, we won't make a big deal of graphs. Here we'll simply show the graphs for Tables 2.2 and 2.3.

Figure 2.9 is a graph of the speed-versus-time data in Table 2.2. Note that speed v is plotted on the vertical axis and time t is plotted on the horizontal axis. In this case, the "curve" that best fits the points forms a straight line. The straightness of the curve indicates a "linear"

* If the object has an initial speed v_o, some thought will show that the equations for velocity and distance traveled become $v = v_o + at$ and $d = v_ot + \frac{1}{2}at^2$.

PHYSICS OF SPORTS

Hang Time

Some people, such as basketball players and ballet dancers, are gifted with great jumping ability. Leaping straight up, they seem to hang in the air in defiance of gravity. Ask your friends to estimate the "hang time" of the great jumpers—the amount of time a jumper is airborne (feet off the ground). One or two seconds? Several seconds? Nope. Surprisingly, the hang time of the greatest jumpers is almost always less than 1 second! Our perception of a longer hang time is one of many illusions we have about nature.

Jumping ability is best measured by a standing vertical jump. Stand facing a wall, and with feet flat on the floor and arms extended upward, make a mark on the wall at the top of your reach. Then make your jump, and at the peak, make another mark. The distance between these two marks measures your vertical leap. If it's more than 2 feet (0.6 meters), you're exceptional.

Here's the physics. When you leap upward, jumping force is applied only as long as your feet are still in contact with the ground. The greater the force, the greater your launch speed and the higher the jump is. It is important to note that as soon as your feet leave the ground, whatever upward speed you attain immediately decreases at the steady rate of g, 10 m/s^2. Maximum height is attained when your upward speed decreases to zero. You then begin falling, gaining speed at exactly the same rate, g. If you land as you took off, upright with legs extended, then time rising equals time falling. Hang time is the sum of rising and falling times. While airborne, no amount of leg or arm pumping or other bodily motions will change your hang time.

The relationship between rising or falling time and vertical height is given by

$$d = \frac{1}{2}gt^2$$

▲ **Figure 2.8** How high can you jump?

If we know the vertical height, we can rearrange this expression to read

$$t = \sqrt{\frac{2d}{g}}$$

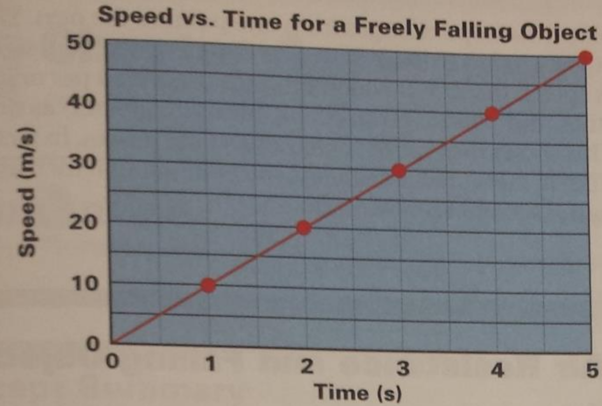
Basketball player Spud Webb's record jumping height is 1.25 meters (4 feet). Setting d* equal to 1.25 m, and using the more precise 9.8 m/s^2 for g, we find that t, half the hang time, is

$$t = \sqrt{\frac{2d}{g}} = \sqrt{\frac{2(1.25\text{ m})}{9.8\text{ m/s}^2}} = 0.51\text{ s}$$

Doubling this, we see Spud's record hang time is slightly greater than 1 second!

We've only been talking about vertical motion. How about running jumps? We'll learn in Chapter 3 that hang time depends only on the jumper's vertical speed at launch; it does not depend on horizontal speed. While airborne, the jumper's horizontal speed remains constant but the vertical speed undergoes acceleration. Interesting physics!

* The value of 1.25 m for d represents the maximum height of the jumper's center of gravity. The height gained by the jumper's center of gravity is what's important in determining jumping ability. You will learn about center of gravity in Chapter 10.



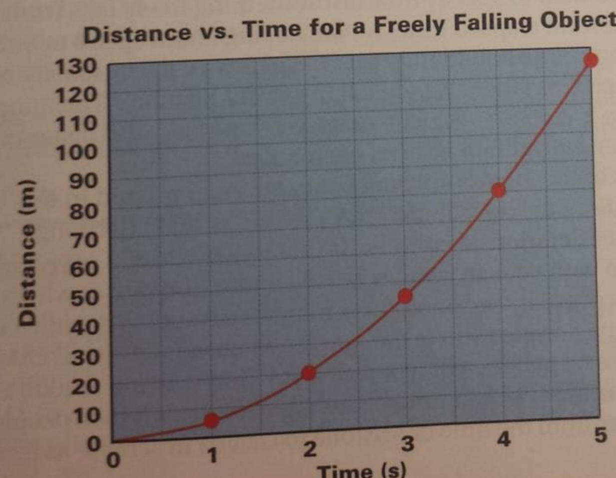
◀ **Figure 2.9**
A speed-versus-time graph of the data from Table 2.2.

relationship between speed and time. For every increase of 1 s, there is the same 10 m/s increase in speed. Mathematicians call this *linearity,* and the graph shows why—the curve is a straight line. Since the object is dropped from rest, the line starts at the origin, where both v and t are zero. If we double t, we double v; if we triple t, we triple v; and so on. This particular linearity is called a *direct proportion.*

The curve is a straight line, so its slope is constant—like a flight of stairs. *Slope* is the vertical change divided by the horizontal change for any part of the line. On this graph the slope measures speed per time, or acceleration. Note that for each 10 m/s of vertical change there is a corresponding horizontal change of 1 s. We see the slope is 10 m/s divided by 1 s, or 10 m/s^2. The straight line shows the acceleration is constant. If the acceleration were greater, the slope of the graph would be steeper. For more information about slope, see Appendix C.

Figure 2.10 is a graph of the distance-versus-time data in Table 2.3. Distance d is plotted on the vertical axis, and time t is on the horizontal axis. The result is a curved line. The curve shows that the relationship between distance traveled and time is not linear. The relationship shown here is *parabolic*—when we double t, we do not double d; we quadruple it. Distance depends on time *squared!*

A curved line also has a slope. If you look at the graph in Figure 2.10 you can see that the curve has a certain slant or "steepness" at



◀ **Figure 2.10**
A distance-versus-time graph of the data from Table 2.3.

every point. This slope changes from one point to the next. The slope of the curve on a distance-versus-time graph is very significant. It is speed, the *rate* at which distance is covered per unit of time. In this graph the slope steepens (becomes greater) as time passes. This shows that speed increases as time passes. In fact, if the slope could be measured accurately, you would find it increases by 10 meters per second each second.

2.8 Air Resistance and Falling Objects

gure 2.11
feather and a coin accelerate ually when there is no air ound them.

Drop a feather and a coin and we notice the coin reaches the floor far ahead of the feather. Air resistance is responsible for these different accelerations. This fact can be shown quite nicely with a closed glass tube connected to a vacuum pump. The feather and coin are placed inside. When the tube is inverted with air inside, the coin falls much more rapidly than the feather. The feather flutters through the air. But if the air is removed with a vacuum pump and the tube is quickly inverted, the feather and coin fall side by side with the same acceleration, *g*, as shown in Figure 2.11.

Air resistance noticeably alters the motion of things like falling feathers or pieces of paper. But air resistance less noticeably affects the motion of more compact objects like stones and baseballs. In many cases the effect of air resistance is small enough to be neglected. With negligible air resistance, falling objects can be considered to be falling freely. Air resistance will be covered in more detail in Chapter 5.

2.9 How Fast, How Far, How Quickly How Fast Changes

Much of the confusion that occurs in analyzing the motion of falling objects comes about from mixing up "how fast" with "how far." When we wish to specify how fast something freely falls from rest after a certain elapsed time, we are talking about speed or velocity. The appropriate equation is $v = gt$. When we wish to specify how far that object has fallen, we are talking about distance. The appropriate equation is $d = \frac{1}{2}gt^2$. Velocity or speed (how fast) and distance (how far) are entirely different from each other.

One of the most confusing concepts encountered in this book is acceleration, or "how quickly does speed or velocity change." What makes acceleration so complex is that it is *a rate of a rate*. It is often confused with velocity, which is itself a rate (the rate at which distance is covered). Acceleration is not velocity, nor is it even a change in velocity; acceleration is the rate at which velocity itself changes.

Please be patient with yourself if you find that you require a few hours to achieve a clear understanding of motion. It took people nearly 2000 years from the time of Aristotle to Galileo to achieve as much!

2 Chapter Assessment

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Concept Summary

Motion is described relative to something.

Speed is a measure of how fast something is moving.

- Speed is the rate at which distance is covered, and it is measured in units of distance divided by time.
- Instantaneous speed is the speed at any instant.
- Average speed is the total distance covered divided by the time interval.

Velocity is speed together with direction.

- Velocity is constant only when speed and direction are both constant.

Acceleration is the rate at which velocity is changing with respect to time.

- An object accelerates when its speed is increasing, when its speed is decreasing, and/or when its direction is changing.
- Acceleration is measured in units of speed divided by time.

An object in free fall is falling under the influence of gravity alone when air resistance does not affect its motion.

- An object in free fall has a constant acceleration of about 10 m/s^2.

Key Terms

acceleration (2.4)
average speed (2.2)
elapsed time (2.5)
free fall (2.5)
instantaneous speed (2.2)
rate (2.0)
relative (2.1)
speed (2.2)
velocity (2.3)

Review Questions *Check Concepts*

1. What do we mean when we say that motion is relative? What is everyday motion usually relative to? (2.1)
2. Speed is the rate at which what happens? (2.2)
3. You walk across the room at 2 kilometers per hour. Express this speed using abbreviated units. (2.2)
4. What is the difference between instantaneous speed and average speed? (2.2)
5. Does the speedometer of a car read instantaneous speed or average speed? (2.2)
6. What is the difference between speed and velocity? (2.3)
7. If the speedometer of a car reads a constant speed of 40 km/h, can you say that the car has a constant velocity? Why or why not? (2.3)
8. What two controls on a car cause a change in speed? What control causes only a change in velocity? (2.3)
9. What quantity describes how quickly you change how fast you're traveling, or how quickly you change your direction? (2.4)
10. Acceleration is the rate at which what happens? (2.4)
11. What is the acceleration of a car that travels in a straight line at a constant speed of 100 km/h? (2.4)
12. What is the acceleration of a car moving along a straight-line path that increases its speed from zero to 100 km/h in 10 s? (2.4)
13. By how much does the speed of a vehicle moving in a straight line change each second when it is accelerating at 2 km/h·s? At 4 km/h·s? At 10 km/h·s? (2.4)
14. Why does the unit of time enter twice in the unit of acceleration? (2.4)
15. What is the meaning of *free fall?* (2.5)

16. For a freely falling object dropped from rest, what is the instantaneous speed at the end of the fifth second of fall? The sixth second? (2.5)

17. For a freely falling object dropped from rest, what is the *acceleration* at the end of the fifth second of fall? The sixth second? At the end of any elapsed time t? (2.5)

18. Toss a ball upward. What is the change in speed each second on the way up? On the way down? (2.5)

19. How far will a freely falling object fall from rest in five seconds? Six seconds? (2.6)

20. How far will an object move in one second if its average speed is 5 m/s? (2.6)

21. How far will a freely falling object have fallen from a position of rest when its instantaneous speed is 10 m/s? (2.6)

22. What does the slope of the curve on a distance-versus-time graph represent? (2.7)

23. What does the slope of the curve on a velocity-versus-time graph represent? (2.7)

24. Does air resistance increase or decrease the acceleration of a falling object? (2.8)

25. What is the appropriate equation for how fast an object freely falls from a position of rest? For how far that object falls? (2.9)

Plug and Chug *Use Equations*

26. Calculate the average speed (in m/s) of a cheetah that runs 140 meters in 5 seconds.

27. a. Calculate the average speed (in km/h) of Charlie, who runs to the store 4 kilometers away in 30 minutes.

    b. Calculate the distance (in km) that Charlie runs if he maintains this average speed for 1 hour.

28. Calculate the acceleration of a car (in km/h·s) that can go from rest to 100 km/h in 10 s.

29. Calculate the instantaneous speed (in m/s) at the 10-second mark for a car that accelerates at 2 m/s^2 from a position of rest.

30. Calculate the speed (in m/s) of a skateboarder who accelerates from rest for 3 seconds down a ramp at an acceleration of 5 m/s^2.

31. Calculate the instantaneous speed of an apple that falls freely from a rest position and accelerates at 10 m/s^2 for 1.5 seconds.

32. An object is dropped from rest and falls freely. After 6 seconds, calculate its instantaneous speed, average speed, and distance fallen.

33. Calculate the instantaneous speed and distance fallen for an object that falls freely from rest for 8 seconds.

Think and Explain *Think Critically*

34. Why is it that an object can accelerate while traveling at constant speed, but not at constant velocity?

35. Light travels in a straight line at a constant speed of 300 000 km/s. What is the light's acceleration?

36. Which has more acceleration when moving in a straight line—a car increasing its speed from 50 to 60 km/h, or a bicycle that goes from zero to 10 km/h in the same time? Defend your answer.

37. a. If a freely falling rock were equipped with a speedometer, by how much would its speed readings increase with each second of fall?

    b. Suppose the freely falling rock were dropped near the surface of a planet where $g = 20\ m/s^2$. By how much would its speed readings change each second?

38. If a freely falling rock were equipped with an odometer, would the readings for distance fallen each second stay the same, increase with time, or decrease with time?

39. a. When a ball is thrown straight up, by how much does the speed decrease each second? Neglect air resistance.

    b. After the ball reaches the top and begins its return back down, by how much does its speed increase each second?

    c. Compare the times going up and coming down.

40. Table 2.2 shows that the instantaneous speed of an object dropped from rest is 10 m/s after 1 second of fall. Table 2.3 shows that the object has fallen only 5 meters during this time. Your friend says this is incorrect, because distance traveled equals speed times time, so the object should fall 10 meters. What do you say?

41. A ball is thrown straight up. What will be the instantaneous velocity at the top of its path? What will be its acceleration at the top? Why are your answers different?

Think and Solve

Develop Problem-Solving Skills

42. If humans originated in Africa and migrated to other parts of the world, some time would be required for this to occur. At the modest rate of a mere one kilometer per year, how many centuries would it take for humans originating in Africa to migrate to China, some 10 000 kilometers away?

43. A dragster going at 15 m/s north increases its velocity to 25 m/s north in 4 seconds. What is its acceleration during this time interval?

44. A car going at 30 m/s undergoes an acceleration of 2 m/s^2 for 4 seconds. What is its final speed? How far did it travel while it was accelerating?

45. We drive for 1 hour at 20 km/h. Then we drive for 1 hour at 30 km/h. What is our average speed?

46. We drive a distance of 1 kilometer at 20 km/h. Then we drive an additional distance of 1 kilometer at 30 km/h. What is our average speed?

47. If you throw a ball straight upward at a speed of 10 m/s, how long will it take to reach zero speed? How long will it take to return to its starting point? How fast will it be going when it returns to its starting point?

48. **a.** Find the speed required to throw a ball straight up and have it return 6 seconds later. Neglect air resistance.

b. How high does the ball go?

49. Calculate the hang time of an athlete who jumps a vertical distance of 0.75 meter.

50. If a salmon swims straight upward in the water fast enough to break through the surface at a speed of 5 meters per second, how high can it jump above water?

Activities *Performance Assessment*

51. By any method you choose, determine your average speed of walking. How do your results compare with those of your classmates?

52. You can compare your reaction time with that of a friend by catching a ruler that is dropped between your fingers. Let your friend hold the ruler as shown in the figure.

Snap your fingers shut as soon as you see the ruler released. On what does the number of centimeters that pass through your fingers depend? You can find your reaction time in seconds by solving $d = \frac{1}{2}gt^2$; for time, $t = \sqrt{2d/g}$. If you express d in meters (likely a fraction of a meter), then $t = 0.45\sqrt{d}$; if you express d in centimeters, then $t = 0.045\sqrt{d}$. Compare your reaction time with those of your classmates.

53. Calculate your personal "hang time," the tim[e] your feet are off the ground during a vertical jump.

More Problem-Solving Practice
Appendix F