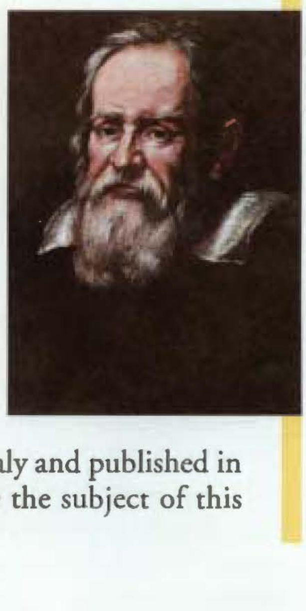
3 Linear Motion

1 Joan Lucas moves with increasing speed when the distance her horse travels each second increases. **2** Likewise for Sue Johnson and her crew who win medals for high speed in their racing shell. **3** Chelcie Liu asks his students to check their thinking with neighbors and predict which ball will first reach the end of the equal-length tracks.

In this chapter we continue with the ideas of a man who was subjected to house arrest because of his ideas, the Italian scientist Galileo Galilei, who died in the same year that Newton was born. These ideas were to be a foundation for Isaac Newton, who, when asked about his success in science, replied that he stood on the shoulders of giants. Most notable of these was Galileo.

Galileo developed an early interest in motion and was soon at odds with his contemporaries, who held to Aristotelian ideas on falling bodies and generally believed that the Sun goes around Earth. He left Pisa to teach at the University of Padua and became an advocate of the new Copernican theory of the solar system. He was the first man to discover mountains on the moon and to find the moons of Jupiter. Because he published his findings in Italian, the language of the people, instead of in Latin, the language of scholars, and because of the recent invention of the printing press, his ideas reached a wide readership. He soon ran afoul of the Church, and he was warned not to teach or hold to Copernican views. He restrained himself publicly for nearly 15 years and then defiantly published his observations and conclusions, which were counter to Church doctrine. The outcome was a trial in which he was found guilty, and he was forced to renounce his discovery that Earth moves. As he walked out of the court, it is said that he whispered, "But it moves." By then an old man, broken in health and spirit, he was sentenced to perpetual house arrest. Nevertheless, he completed his studies on motion, and his writings were smuggled from Italy and published in Holland. His ideas on motion are the subject of this chapter.



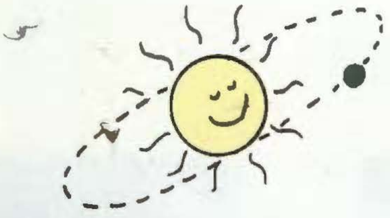


FIGURE 3.1
When you sit on a chair, your speed is zero relative to Earth but 30 km/s relative to the Sun.

Motion Is Relative

Everything moves—even things that appear to be at rest. They move relative to the Sun and stars. As you're reading this, you're moving at about 107,000 kilometers per hour relative to the Sun, and you're moving even faster relative to the center of our galaxy. When we discuss the motion of something, we describe the motion relative to something else. If you walk down the aisle of a moving bus, your speed relative to the floor of the bus is likely quite different from your speed relative to the road. When we say a racing car reaches a speed of 300 kilometers per hour, we mean relative to the track. Unless stated otherwise, when we discuss the speeds of things in our environment, we mean relative to the surface of Earth. Motion is relative.

CHECK POINT

A hungry mosquito sees you resting in a hammock in a 3-m/s breeze. How fast and in what direction should the mosquito fly in order to hover above you for lunch?

Check Your Answer

The mosquito should fly toward you into the breeze. When just above you, it should fly at 3 m/s in order to hover at rest. Unless its grip on your skin is strong enough after landing, it must continue flying at 3 m/s to keep from being blown off. That's why a breeze is an effective deterrent to mosquito bites.

If you look out an airplane window and view another plane flying at the same speed in the opposite direction, you'll see it flying twice as fast—nicely illustrating relative motion.

Speed

Before the time of Galileo, people described moving things as simply "slow" or "fast." Such descriptions were vague. Galileo is credited with being the first to measure speed by considering the distance covered and the time it takes. He defined **speed** as the distance covered per unit of time. Interestingly, Galileo could easily measure distance, but in his day measuring short times was no easy matter. He sometimes used his own pulse and sometimes the dripping of drops from a "water clock" he devised.

$$\boxed{\text{Speed} = \frac{\text{distance}}{\text{time}}}$$

A cyclist who covers 16 meters in a time of 2 seconds, for example, has a speed of 8 meters per second.

Any combination of distance and time units is legitimate for measuring speed; for motor vehicles (or long distances), the units kilometers per hour (km/h) or miles per hour (mi/h or mph) are commonly used. For shorter distances, meters per second (m/s) is more useful. The slash symbol (/) is read as *per* and means "divided by." Throughout this book, we'll primarily use meters per second (m/s). Table 3.1 shows some comparative speeds in different units.[1]

INSTANTANEOUS SPEED

Things in motion often have variations in speed. A car, for example, may travel along 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 its

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Definition of Speed
Average Speed

TABLE 3.1
Approximate Speeds in Different Units

12 mi/h	= 20 km/h	= 6 m/s
25 mi/h	= 40 km/h	= 11 m/s
37 mi/h	= 60 km/h	= 17 m/s
50 mi/h	= 80 km/h	= 22 m/s
62 mi/h	= 100 km/h	= 28 m/s
75 mi/h	= 120 km/h	= 33 m/s
100 mi/h	= 160 km/h	= 44 m/s

[1]Conversion is based on 1 h = 3600 s, 1 mi = 1609.344 m.

speedometer. The speed at any instant is the **instantaneous speed.** A car traveling at 50 km/h usually goes at that speed for less than 1 hour. If it did go at that speed for a full hour, it would cover 50 km. If it continued at that speed for half an hour, it would cover half that distance: 25 km. If it continued for only 1 minute, it would cover less than 1 km.

FIGURE 3.2
A speedometer gives readings in both miles per hour and kilometers per hour.

AVERAGE SPEED

In planning a trip by car, the driver often wants to know the time of travel. The driver is concerned with the **average speed** for the trip. Average speed is defined as

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

Average speed can be calculated rather easily. For example, if we drive a distance of 80 kilometers in a time of 1 hour, we say our average speed is 80 kilometers per hour. Likewise, if we travel 320 kilometers in 4 hours,

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}} = \frac{320\text{ km}}{4\text{ h}} = 80\text{ km/h}$$

$A = \frac{80}{1}$ $A = \frac{320}{4}$

We see 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 whole distance covered divided by the total time of travel, it doesn't indicate the different speeds and variations that may have taken place during shorter time intervals. On most trips, we experience a variety of speeds, so the average speed is often quite different from the instantaneous speed.

If you're cited for speeding, which does the police officer write on your ticket, your *instantaneous speed* or your *average speed?*

If we know average speed and time of travel, distance traveled is easy to find. A simple rearrangement of the definition above gives

$$\text{Total distance covered} = \text{average speed} \times \text{time}$$

If your average speed is 80 kilometers per hour on a 4-hour trip, for example, you cover a total distance of 320 kilometers (80 km/h × 4 h).

CHECK POINT

1. What is the average speed of a cheetah that sprints 100 meters in 4 seconds? If it sprints 50 m in 2 s?
2. If a car moves with an average speed of 60 km/h for an hour, it will travel a distance of 60 km.
   a. How far would it travel if it moved at this rate for 4 h?
   b. For 10 h?
3. In addition to the speedometer on the dashboard of every car is an odometer, which records the distance traveled. If the initial reading is set at zero at the beginning of a trip and the reading is 40 km one-half hour later, what has been your average speed?
4. Would it be possible to attain this average speed and never go faster than 80 km/h?

100/25 m/s

Check Your Answers

(Are you reading this before you have reasoned answers in your mind? As mentioned in the previous chapter, when you encounter Check Yourself questions throughout this book, check your ***thinking*** *before you read the answers. You'll not only learn more, you'll enjoy learning more.)*

1. In both cases the answer is 25 m/s:

$$\text{Average speed} = \frac{\text{distance covered}}{\text{time interval}} = \frac{100\text{ meters}}{4\text{ seconds}} = \frac{50\text{ meters}}{2\text{ seconds}} = 25\text{ m/s}$$

2. The distance traveled is the average speed × time of travel, so
   a. Distance = 60 km/h × 4 h = 240 km
   b. Distance = 60 km/h × 10 h = 600 km
3. Average speed $= \frac{\text{total distance covered}}{\text{time interval}} = \frac{40\text{ km}}{0.5\text{ h}} = 80$ km/h
4. No, not if the trip starts from rest and ends at rest. There are times in which the instantaneous speeds are less than 80 km/h, so the driver must drive at speeds of greater than 80 km/h during one or more time intervals in order to average 80 km/h. In practice, average speeds are usually much lower than high instantaneous speeds.

Velocity

When we know both the speed and the direction of an object, we know its **velocity.** For example, if a car travels at 60 km/h, we know its speed. But if we say it moves at 60 km/h to the north, we specify its *velocity.* Speed is a description of how fast; velocity is how fast *and* in what direction. A quantity such as velocity that specifies direction as well as magnitude is called a **vector quantity.** Recall from Chapter 2 that force is a vector quantity, requiring both magnitude and direction for its description. Likewise, velocity is a vector quantity. In contrast, a quantity that requires only magnitude for a description is called a **scalar quantity.** Speed is a scalar quantity.

Velocity is "directed" speed.

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Changing Velocity

CONSTANT VELOCITY

Constant speed means steady speed. Something with constant speed doesn't speed up or slow down. Constant velocity, on the other hand, means both constant speed *and* constant direction. Constant direction is a straight line—the object's path doesn't curve. So constant velocity means motion in a straight line at a constant speed.

CHANGING VELOCITY

If either the speed or the direction changes (or if both change), then the velocity changes. A car on a curved track, for example, may have a constant speed, but, because its direction is changing, its velocity is not constant. We'll see in the next section that it is *accelerating.*

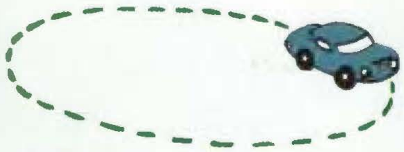

FIGURE 3.3
The car on the circular track may have a constant speed, but its velocity is changing every instant. Why?

CHECK POINT

1. "She moves at a constant speed in a constant direction." Rephrase the same sentence in fewer words.
2. The speedometer of a car moving to the east reads 100 km/h. It passes another car that moves to the west at 100 km/h. Do both cars have the same speed? Do they have the same velocity?
3. During a certain period of time, the speedometer of a car reads a constant 60 km/h. Does this indicate a constant speed? A constant velocity?

Check Your Answers

1. "She moves at a constant velocity."
2. Both cars have the same speed, but they have opposite velocities because they are moving in opposite directions.
3. The constant speedometer reading indicates a constant speed but not a constant velocity, because the car may not be moving along a straight-line path, in which case it is accelerating.

Acceleration

We can change the velocity of something by changing its speed, by changing its direction, or by changing both its speed *and* its direction. How quickly velocity changes is **acceleration:**

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

We are familiar with acceleration in an automobile. When the driver depresses the gas pedal (appropriately called the accelerator), the passengers then experience acceleration (or "pickup," as it is sometimes called) as they are pressed against their seats. The key idea that defines acceleration is *change*. Suppose we are driving and, in 1 second, we steadily increase our velocity from 30 kilometers per hour to 35 kilometers per hour, and then to 40 kilometers per hour in the next second, to 45 in the next second, and so on. We change our velocity by 5 kilometers per hour each second. This change in velocity is what we mean by acceleration.

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{5\text{ km/h}}{1\text{ s}} = 5\text{ km/h·s}$$

In this case, the acceleration is 5 kilometers per hour second (abbreviated as 5 km/h·s). Note that a unit for time enters twice: once for the unit of velocity and again for the interval of time in which the velocity is changing. Also note that acceleration is not just the total change in velocity; it is the *time rate of change,* or *change per second,* in velocity.

FIGURE 3.4
We say that a body undergoes acceleration when there is a *change* in its state of motion.

CHECK POINT

1. A particular car can go from rest to 90 km/h in 10 s. What is its acceleration?
2. In 2.5 s, a car increases its speed from 60 km/h to 65 km/h while a bicycle goes from rest to 5 km/h. Which undergoes the greater acceleration? What is the acceleration of each?

Check Your Answers

1. Its acceleration is 9 km/h·s. Strictly speaking, this would be its average acceleration, for there may have been some variation in its rate of picking up speed.
2. The accelerations of both the car and the bicycle are the same: 2 km/h·s.

$$\text{Acceleration}_{\text{car}} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{65\text{ km/h} - 60\text{ km/h}}{2.5\text{ s}} = \frac{5\text{ km/h}}{2.5\text{ s}} = 2\text{ km/h·s}$$

$$\text{Acceleration}_{\text{bike}} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{5\text{ km/h} - 0\text{ km/h}}{2.5\text{ s}} = \frac{5\text{ km/h}}{2.5\text{ s}} = 2\text{ km/h·s}$$

Although the velocities are quite different, the rates of *change* of velocity are the same. Hence, the accelerations are equal.

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Definition of Acceleration
Numerical Example of Acceleration

The term *acceleration* applies to decreases as well as to increases in velocity. We say the brakes of a car, for example, produce large retarding accelerations; that is, there is a large decrease per second in the velocity of the car. We often call this *deceleration.* We experience deceleration when the driver of a bus or car applies the brakes and we tend to lurch forward.

FIGURE 3.5
Rapid deceleration is sensed by the driver, who lurches forward (in accord with Newton's first law).

Can you see that a car has three controls that change velocity—the gas pedal (accelerator), the brakes, and the steering wheel?

We accelerate whenever we move in a curved path, even if we are moving at constant speed, because our direction is changing—hence, our velocity is changing. We experience this acceleration as we tend to lurch toward the outer part of the curve. We distinguish speed and velocity for this reason and define *acceleration* as the rate at which velocity changes, thereby encompassing changes both in speed and in direction.

Anyone who has stood in a crowded bus has experienced the difference between velocity and acceleration. Except for the effects of a bumpy road, you can stand with no extra effort inside a bus that moves at constant velocity, no matter how fast it is going. You can flip a coin and catch it exactly as if the bus were at rest. It is only when the bus accelerates—speeds up, slows down, or turns—that you experience difficulty standing.

Tested

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

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

CHECK POINT

1. What is the acceleration of a race car that whizzes past you at a constant velocity of 400 km/h?
2. Which has the greater acceleration, an airplane that goes from 1000 km/h to 1005 km/h in 10 seconds or a skateboard that goes from zero to 5 km/h in 1 second?

Check Your Answers

1. Zero, because its velocity doesn't change.
2. Both gain 5 km/h, but the skateboard does so in one-tenth the time. The skateboard therefore has the greater acceleration—in fact, ten times greater. A little figuring will show that the acceleration of the airplane is 0.5 km/h·s, whereas acceleration of the slower-moving skateboard is 5 km/h·s. Velocity and acceleration are very different concepts. Distinguishing between them is very important.

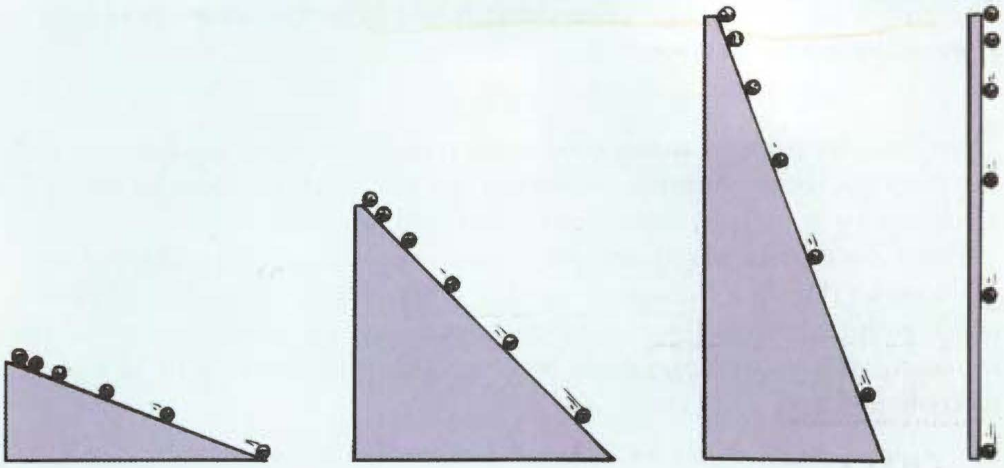
ACCELERATION ON GALILEO'S INCLINED PLANES

Galileo developed the concept of acceleration in his experiments on inclined planes. His main interest was falling objects, and, because he lacked accurate timing devices, he used inclined planes effectively to slow accelerated motion and to investigate it more carefully.

Galileo found that a ball rolling down an inclined plane picks up the same amount of speed in successive seconds; that is, the ball rolls with unchanging acceleration. For example, a ball rolling down a plane inclined at a certain angle might be found to pick up a speed of 2 meters per second for each second it rolls. This gain per second is its acceleration. Its instantaneous velocity at 1-second intervals, at this acceleration, is then 0, 2, 4, 6, 8, 10, and so forth, meters per second. We can see that the instantaneous speed or velocity of the ball at any given time after being released from rest is simply equal to its acceleration multiplied by the time:[2]

$$\text{Velocity acquired} = \text{acceleration} \times \text{time}$$

[2]Note that this relationship follows from the definition of acceleration. From $a = v/t$, simple rearrangement (multiplying both sides of the equation by t) gives $v = at$.



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

FIGURE 3.6

INTERACTIVE FIGURE

The greater the slope of the incline, the greater the acceleration of the ball. What is its acceleration if the ball falls vertically?

If we substitute the acceleration of the ball in this relationship (2 meters per second squared), we can see that, at the end of 1 second, the ball is traveling at 2 meters per second; at the end of 2 seconds, it is traveling at 4 meters per second; at the end of 10 seconds, it is traveling at 20 meters per second; and so on. The instantaneous speed or velocity at any time is simply equal to the acceleration multiplied by the number of seconds it has been accelerating.

Galileo found greater accelerations for steeper inclines. The ball attains its maximum acceleration when the incline is tipped vertically. Then it falls with the acceleration of a falling object (Figure 3.6). Regardless of the weight or size of the object, Galileo discovered that, when air resistance is small enough to be neglected, all objects fall with the same unchanging acceleration.

How nice, the acceleration due to gravity is 10 m/s each second all the way down. Why this is so, for any mass, awaits you in Chapter 4.

Free Fall

HOW FAST

Things fall because of the force of gravity. When a falling object is free of all restraints—no friction, with the air or otherwise—and falls under the influence of gravity alone, the object is in a state of **free fall.** (We'll consider the effects of air resistance on falling objects in Chapter 4.) Table 3.2 shows the instantaneous speed of a freely falling object at 1-second intervals. The important thing to note in these numbers is the way in which the speed changes. *During each second of fall, the object gains a speed of 10 meters per second.* This gain per second is the acceleration. Free-fall acceleration is approximately equal to 10 meters per second each second, or, in shorthand notation, 10 m/s^2 (read as 10 meters per second squared). Note that the unit of time, the second, enters twice—once for the unit of speed and again for the time interval during which the speed changes.

In the case of freely falling objects, it is customary to use the letter *g* to represent the acceleration (because the acceleration is due to *gravity*). The value of *g* is very different on the surface of the Moon and on the surfaces of other planets. Here on Earth, *g* varies slightly in different locations, with an average value equal to 9.8 meters per second each second, or, in shorter notation, 9.8 m/s^2. We round this off to 10 m/s^2 in our present discussion and in Table 3.2 to establish the ideas involved more clearly; multiples of 10 are more obvious than multiples of 9.8. Where accuracy is important, the value of 9.8 m/s^2 should be used.

Note in Table 3.2 that the instantaneous speed or velocity of an object falling from rest is consistent with the equation that Galileo deduced with his inclined planes:

$$\text{Velocity acquired} = \text{acceleration} \times \text{time}$$

TABLE 3.2
Free-Fall from Rest

Time of Fall (seconds)	Velocity Acquired (meters/second)
0	0
1	10
2	20
3	30
4	40
5	50
.	.
.	.
.	.
t	10*t*

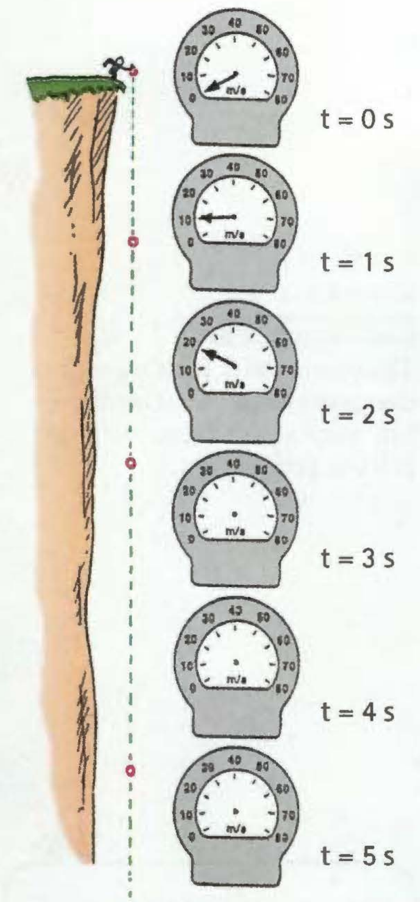


FIGURE 3.7
Pretend that a falling rock is equipped with a speedometer. In each succeeding second of fall, you'd find the rock's speed increasing by the same amount: 10 m/s. Sketch in the missing speedometer needle at t = 3 s, 4 s, and 5 s. (Table 3.2 shows the speeds we would read at various seconds of fall.)

The instantaneous velocity v of an object falling from rest[3] after a time t can be expressed in shorthand notation as

$$v = gt$$

To see that this equation makes good sense, take a moment to check it with Table 3.2. Note that the instantaneous velocity or speed in meters per second is simply the acceleration $g = 10 \text{ m/s}^2$ multiplied by the time t in seconds.

Free-fall acceleration is clearer when we consider a falling object equipped with a speedometer (Figure 3.7). Suppose a rock is dropped from a high cliff and you witness it with a telescope. If you focus the telescope on the speedometer, you'd note increasing speed as time progresses. By how much? The answer is, by 10 m/s each succeeding second.

CHECK POINT

What would the speedometer reading on the falling rock shown in Figure 3.7 be 5 s after it drops from rest? How about 6 s after it is dropped? 6.5 s after it is dropped?

Check Your Answer

The speedometer readings would be 50 m/s, 60 m/s, and 65 m/s, respectively. You can reason this from Table 3.2 or use the equation $v = gt$, where g is 10 m/s^2.

So far, we have been considering objects moving straight downward in the direction of the pull of gravity. How about an object thrown straight upward? Once released, it continues to move upward for a time and then comes back down. At its highest point, when it is changing its direction of motion from upward to downward, its instantaneous speed is zero. Then it starts downward *just as if it had been dropped from rest at that height.*

During the upward part of this motion, the object slows as it rises. It should come as no surprise that it slows at the rate of 10 meters per second each second—the same acceleration it experiences on the way down. So, as Figure 3.8 shows, the instantaneous speed at points of equal elevation in the path is the same whether the object is moving upward or downward. The velocities are opposite, of course, because they are in opposite directions. Note that the downward velocities have a negative sign, indicating the downward direction (it is customary to call *up* positive, and *down* negative.) Whether moving upward or downward, the acceleration is 10 m/s^2 the whole time.

CHECK POINT

A ball is thrown straight upward and leaves your hand at 20 m/s. What predictions can you make about the ball? (Please think about this *before* reading the suggested predictions!)

Check Your Answer

There are several. One prediction is that it will slow to 10 m/s 1 second after it leaves your hand and will come to a momentary stop 2 seconds after leaving your hand, when it reaches the top of its path. This is because it loses 10 m/s each second going up. Another prediction is that 1 second later, 3 seconds total, it will be moving downward at 10 m/s. In another second, it will return to its starting point and be moving at 20 m/s. So the time each way is 2 seconds, and its total time in flight takes 4 seconds. We'll now treat how far it travels up and down.

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Free Fall: How Fast?

$v = gt$

Free Fall: How Far?

[3]If, instead of being dropped from rest, the object is thrown downward at speed v_0, the speed v after any elapsed time t is $v = v_0 + gt$. We will not be concerned with this added complication here; we will instead learn as much as we can from the simplest cases. That will be a lot!

HOW FAR

How *far* an object falls is altogether different from how *fast* it falls. With his inclined planes, Galileo found that the distance a uniformly accelerating object travels is proportional to the *square of the time*. The distance traveled by a uniformly accelerating object starting from rest is

$$\text{Distance traveled} = \frac{1}{2}(\text{acceleration} \times \text{time} \times \text{time})$$

This relationship applies to the distance something falls. We can express it, for the case of a freely falling object, in shorthand notation as

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

in which d is the distance something falls when the time of fall in seconds is substituted for t and squared.[4] If we use 10 m/s^2 for the value of g, the distance fallen for various times will be as shown in Table 3.3.

Note that an object falls a distance of only 5 meters during the first second of fall, although its speed is then 10 meters per second. This may be confusing, for we may think that the object should fall a distance of 10 meters. But for it to fall 10 meters in its first second of fall, it would have to fall at an *average* speed of 10 meters per second for the entire second. It starts its fall at 0 meters per second, and its speed is 10 meters per second only in the last instant of the 1-second interval. Its average speed during this interval is the average of its initial and final speeds, 0 and 10 meters per second. To find the average value of these or any two numbers, we simply add the two numbers and divide by 2. This equals 5 meters per second, which, over a time interval of 1 second, gives a distance of 5 meters. As the object continues to fall in succeeding seconds, it will fall through ever-increasing distances because its speed is continuously increasing.

CHECK POINT

A cat steps off a ledge and drops to the ground in 1/2 second.

a. What is its speed on striking the ground?
b. What is its average speed during the 1/2 second?
c. How high is the ledge from the ground?

Check Your Answers

a. Speed: $v = gt = 10\ m/s^2 \times 1/2\ s = 5\ m/s$

b. Average speed: $\bar{v} = \frac{\text{initial } v + \text{final } v}{2} = \frac{0\ m/s + 5\ m/s}{2} = 2.5\ m/s$

We put a bar over the symbol to denote average speed: $\bar{v}$.

c. Distance: $d = \bar{v}t = 2.5\ m/s \times 1/2\ s = 1.25\ m$

Or equivalently,

$$d = \frac{1}{2}gt^2 = \frac{1}{2} \times 10\ m/s^2 \times (\frac{1}{2}\ s)^2 = 1.25\ m$$

Notice that we can find the distance by either of these equivalent relationships.

[4] Distance fallen from rest: d = average velocity × time

$$d = \frac{\text{initial velocity} + \text{final velocity}}{2} \times \text{time}$$

$$d = \frac{0 + gt}{2} \times t$$

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

(See Appendix B for further explanation.)

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Air Resistance and Falling Objects
Falling Distance

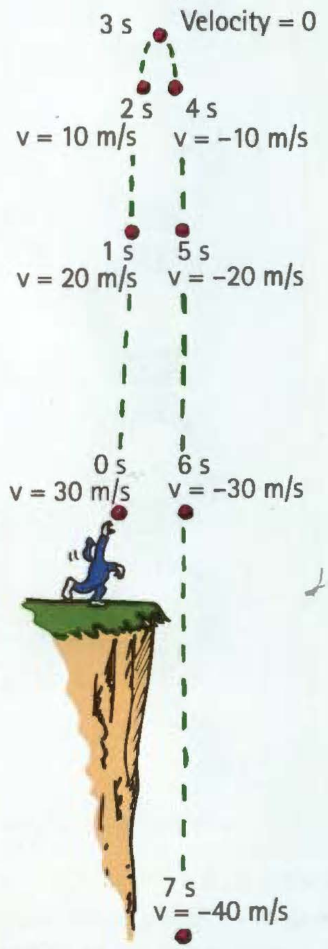


FIGURE 3.8
INTERACTIVE FIGURE
The rate at which the velocity changes each second is the same.

TABLE 3.3
Distance Fallen in Free Fall

Time of Fall (seconds)	Distance Fallen (meters)
0	0
1	5
2	20
3	45
4	80
5	125
.	.
.	.
.	.
t	$\frac{1}{2}10t^2$

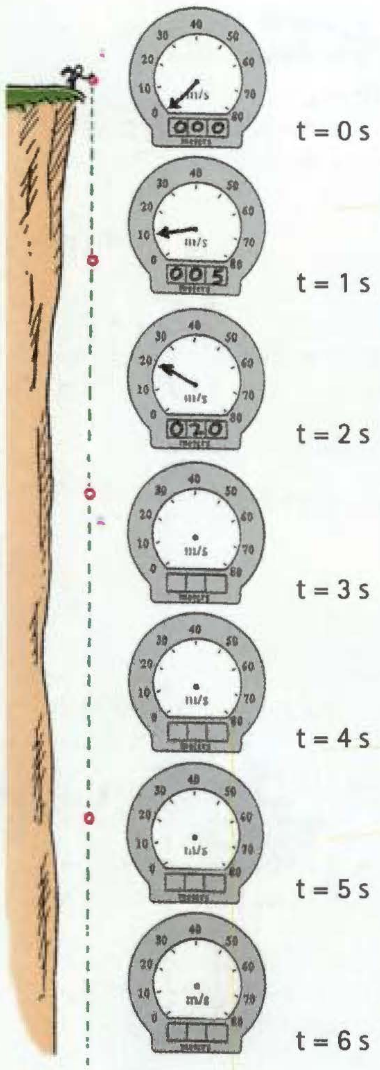


FIGURE 3.9
Pretend that a falling rock is equipped with a speedometer and an odometer. Speed readings increase by 10 m/s and distance readings by $1/2\,gt^2$. Can you complete the speedometer positions and odometer readings?

It is a common observation that many objects fall with unequal accelerations. A leaf, a feather, or a sheet of paper may flutter to the ground slowly. The fact that air resistance is responsible for these different accelerations can be shown very nicely with a closed glass tube containing light and heavy objects—a feather and a coin, for example. In the presence of air, the feather and coin fall with quite different accelerations. But, if the air in the tube is removed by a vacuum pump and the tube is quickly inverted, the feather and coin fall with the same acceleration (Figure 3.10). Although air resistance appreciably alters the motion of things like falling feathers, the motion of heavier objects like stones and baseballs at ordinary low speeds is not appreciably affected by the air. The relationships $v = gt$ and $d = 1/2\,gt^2$ can be used to a very good approximation for most objects falling in air from an initial position of rest.

FIGURE 3.10
A feather and a coin fall at equal accelerations in a vacuum.

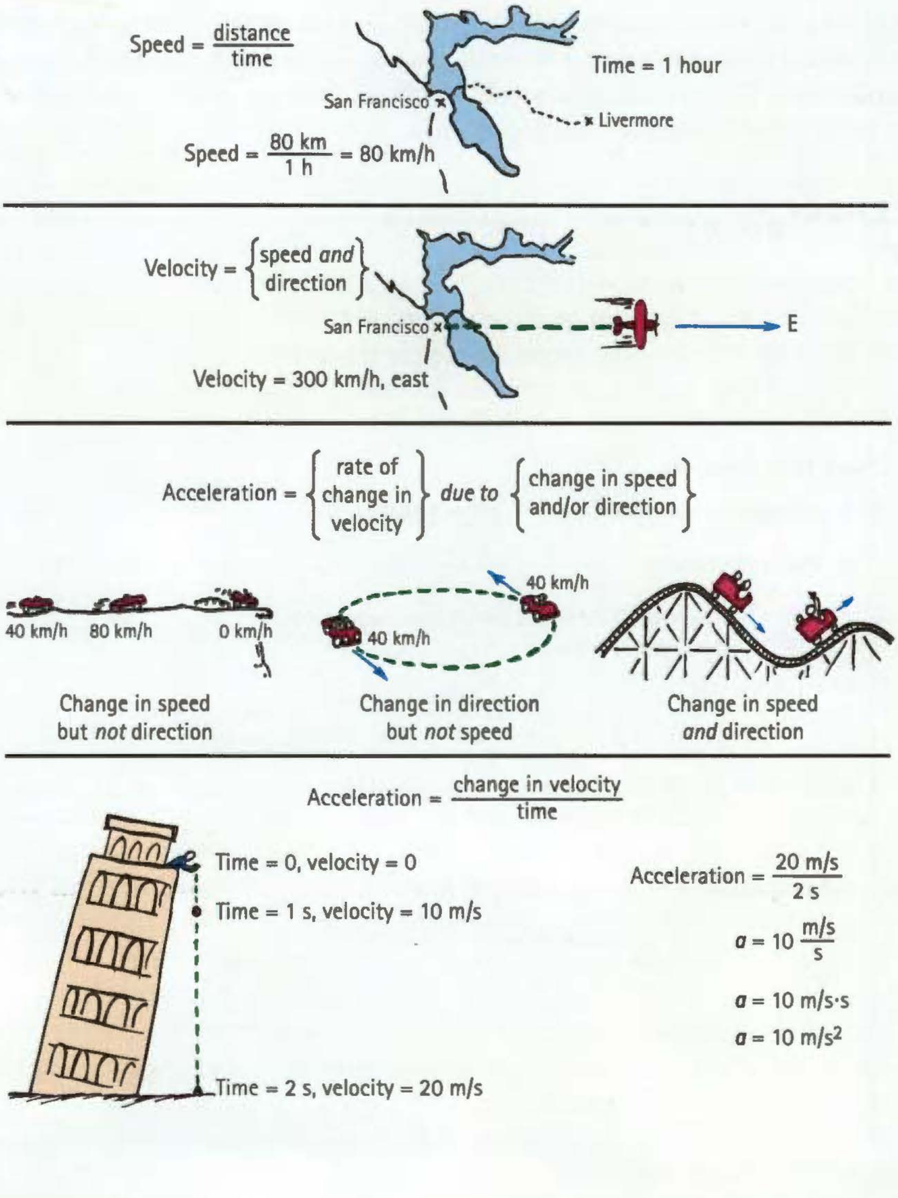
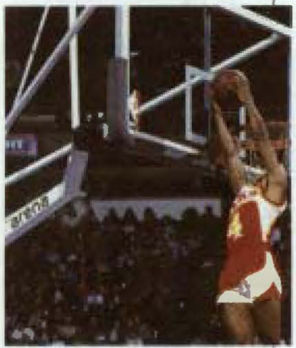


FIGURE 3.11
Motion analysis.

Hang Time



Some athletes and dancers have great jumping ability. Leaping straight up, they seem to "hang in the air," defying gravity. Ask your friends to estimate the "hang time" of the great jumpers—the time a jumper is airborne with feet off the ground. They may say 2 or 3 seconds. But, surprisingly, the hang time of the greatest jumpers is almost always less than 1 second! A longer time is one of many illusions we have about nature.

A related illusion is the vertical height a human can jump. Most of your classmates probably cannot jump higher than 0.5 meter. They can step over a 0.5-meter fence, but, in doing so, their body rises only slightly. The height of the barrier is different than the height a jumper's "center of gravity" rises. Many people can leap over a 1-meter fence, but only rarely does anybody raise the "center of gravity" of their body 1 meter. Even basketball stars Michael Jordan and Kobe Bryant in their prime couldn't raise their body 1.25 meters high, although they could easily reach considerably above the more-than-3-meter-high basket.

Jumping ability is best measured by a standing vertical jump. Stand facing a wall 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 0.6 meter (2 feet), you're exceptional.

Here's the physics. When you leap upward, jumping force is applied only while your feet make contact with the ground. The greater the force, the greater your launch speed and the higher the jump. When your feet leave the ground, your upward speed immediately decreases at the steady rate of g—10 m/s^2. At the top of your jump, your upward speed decreases to zero. Then you begin to fall, 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 time up plus time down. While airborne, no amount of leg or arm pumping or other bodily motions can change your hang time.

The relationship between time up or down and vertical height is given by

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

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

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

The world-record vertical standing jump is 1.25 meters.[5] Let's use this jumping height of 1.25 meters for d, and use the more precise value of 9.8 m/s^2 for g. Solving for t, half the hang time, we get

$$t = \sqrt{\frac{2d}{g}} = \sqrt{\frac{2(1.25\ \text{m})}{9.8\ \text{m/s}^2}} = 0.50\ \text{s}$$

Double this (because this is the time for one way of an up-and-down round-trip) and we see that the record-breaking hang time is 1 second.

We're discussing vertical motion here. How about running jumps? We'll see in Chapter 10 that hang time depends only on the jumper's vertical speed at launch. While airborne, the jumper's horizontal speed remains constant and only the vertical speed undergoes acceleration. Interesting physics!

[5] For a running jump, liftoff speed can be increased and hang time extended as the foot bounds off the floor. We'll discuss this in Chapter 8.

HOW QUICKLY "HOW FAST" CHANGES

Much of the confusion that arises in analyzing the motion of falling objects comes about because it is easy to get "how fast" mixed up with "how far." When we wish to specify how fast something is falling, we are talking about *speed* or *velocity,* which is expressed as $v = gt$. When we wish to specify how far something falls, we are talking about *distance,* which is expressed as $d = 1/2\ gt^2$. Speed or velocity (how fast) and distance (how far) are entirely different from each other.

A most confusing concept, and probably the most difficult encountered in this book, is "how quickly does how fast change"—acceleration. 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 of change of position). Acceleration is not velocity, nor is it even a change in velocity. Acceleration is the rate at which velocity itself changes.

Please remember that it took people nearly 2000 years from the time of Aristotle to reach a clear understanding of motion, so be patient with yourself if you find that you require a few hours to achieve as much!

SUMMARY OF TERMS

Speed How fast something moves; the distance traveled per unit of time.
Instantaneous speed The speed at any instant.
Average speed The total distance traveled divided by the time of travel.
Velocity The speed of an object and a specification of its direction of motion.
Vector quantity Quantity in physics that has both magnitude and direction.
Scalar quantity Quantity that can be described by magnitude without direction.
Acceleration The rate at which velocity changes with time; the change in velocity may be in magnitude, or direction, or both.
Free fall Motion under the influence of gravity only.

SUMMARY OF EQUATIONS

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

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

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

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

Velocity acquired in free fall, from rest: $v = gt$

Distance fallen in free fall, from rest: $d = \frac{1}{2} gt^2$

REVIEW QUESTIONS

Motion Is Relative

1. As you read this, how fast are you moving relative to the chair you are sitting on? Relative to the Sun?

Speed

2. What two units of measurement are necessary for describing speed?

Instantaneous Speed

3. What kind of speed is registered by an automobile speedometer—average speed or instantaneous speed?

Average Speed

4. Distinguish between instantaneous speed and average speed.
5. What is the average speed in kilometers per hour for a horse that gallops a distance of 15 km in a time of 30 min?
6. How far does a horse travel if it gallops at an average speed of 25 km/h for 30 min?

Velocity

7. Distinguish between speed and velocity.

Constant Velocity

8. If a car moves with a constant velocity, does it also move with a constant speed?

Changing Velocity

9. If a car is moving at 90 km/h and it rounds a corner, also at 90 km/h, does it maintain a constant speed? A constant velocity? Defend your answer.

Acceleration

10. Distinguish between velocity and acceleration.
11. What is the acceleration of a car that increases its velocity from 0 to 100 km/h in 10 s?
12. What is the acceleration of a car that maintains a constant velocity of 100 km/h for 10 s? (Why do some of your classmates who correctly answer the previous question get this question wrong?)
13. When are you most aware of motion in a moving vehicle—when it is moving steadily in a straight line or when it is accelerating? If a car moved with absolutely constant velocity (no bumps at all), would you be aware of motion?
14. Acceleration is generally defined as the time rate of change of velocity. When can it be defined as the time rate of change of speed?

Acceleration on Galileo's Inclined Planes

15. What did Galileo discover about the amount of speed a ball gained each second when rolling down an inclined plane? What did this say about the ball's acceleration?
16. What relationship did Galileo discover for the velocity acquired on an incline?

17. What relationship did Galileo discover about a ball's acceleration and the steepness of an incline? What acceleration occurs when the plane is vertical?

Free Fall—How Fast

18. What exactly is meant by a "freely falling" object?
19. What is the gain in speed per second for a freely falling object?
20. What is the velocity acquired by a freely falling object 5 s after being dropped from a rest position? What is the velocity 6 s after?
21. The acceleration of free fall is about 10 m/s^2. Why does the seconds unit appear twice?
22. When an object is thrown upward, how much speed does it lose each second?

How Far

23. What relationship between distance traveled and time did Galileo discover for accelerating objects?
24. What is the distance fallen for a freely falling object 1 s after being dropped from a rest position? What is it 4 s after?
25. What is the effect of air resistance on the acceleration of falling objects? What is the acceleration with no air resistance?

How Quickly "How Fast" Changes

26. Consider these measurements: 10 m, 10 m/s, and 10 m/s^2. Which is a measure of distance, which of speed, and which of acceleration?

PROJECTS

1. Grandma is interested in your educational progress. She perhaps has little science background and may be mathematically challenged. Write a letter to Grandma, without using equations, and explain to her the difference between velocity and acceleration. Tell her why some of your classmates confuse the two, and state some examples that clear up the confusion.
2. Stand flatfooted next to a wall. Make a mark at the highest point you can reach. Then jump vertically and mark this highest point. The distance between the marks is your vertical jumping distance. Use this data to calculate your personal hang time.

PLUG AND CHUG

These are "plug-in-the-number" type activities to familiarize you with the equations that link the concepts of physics. They are mainly one-step substitutions and are less challenging than the Problems.

$$\textbf{Speed} = \frac{\textbf{distance}}{\textbf{time}}$$

1. Calculate your walking speed when you step 1 meter in 0.5 second.
2. Calculate the speed of a bowling ball that travels 4 meters in 2 seconds.

$$\textbf{Average speed} = \frac{\textbf{total distance covered}}{\textbf{time interval}}$$

3. Calculate your average speed if you run 50 meters in 10 seconds.
4. Calculate the average speed of a tennis ball that travels the full length of the court, 24 meters, in 0.5 second.
5. Calculate the average speed of a cheetah that runs 140 meters in 5 seconds.
6. Calculate the average speed (in km/h) of Larry, who runs to the store 4 kilometers away in 30 minutes.

$$\textbf{Distance} = \textbf{average speed} \times \textbf{time}$$

7. Calculate the distance (in km) that Larry runs if he maintains an average speed of 8 km/h for 1 hour.
8. Calculate the distance you will travel if you maintain an average speed of 10 m/s for 40 seconds.
9. Calculate the distance you will travel if you maintain an average speed of 10 km/h for one-half hour.

$$\textbf{Acceleration} = \frac{\textbf{change of velocity}}{\textbf{time interval}}$$

10. Calculate the acceleration of a car (in km/h·s) that can go from rest to 100 km/h in 10 s.
11. Calculate the acceleration of a bus that goes from 10 km/h to a speed of 50 km/h in 10 seconds.
12. Calculate the acceleration of a ball that starts from rest, rolls down a ramp, and gains a speed of 25 m/s in 5 seconds.
13. On a distant planet, a freely falling object gains speed at a steady rate of 20 m/s during each second of fall. Calculate its acceleration.

$$\textbf{Instantaneous speed} = \textbf{acceleration} \times \textbf{time}$$

14. 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.
15. Calculate the speed (in m/s) of a skateboarder who accelerates from rest for 3 s down a ramp at an acceleration of 5 m/s^2.

Velocity acquired in free fall, from rest:

$$v = gt \ (\textbf{where } g = 10 \ \textbf{m/s}^2)$$

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

17. An object is dropped from rest and falls freely. After 7 s, calculate its instantaneous speed.

18. A skydiver steps from a high-flying helicopter. In the absence of air resistance, how fast would she be falling at the end of a 12-s jump?

19. On a distant planet, a freely falling object has an acceleration of 20 m/s^2. Calculate the speed that an object dropped from rest on this planet acquires in 1.5 s.

Distance fallen in free fall, from rest: $d = \frac{1}{2}gt^2$

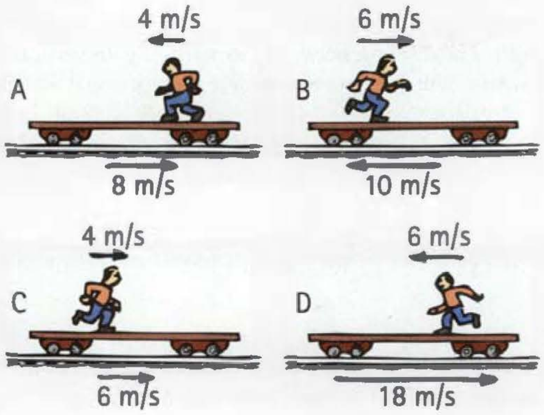
20. An apple drops from a tree and hits the ground in 1.5 s. Calculate how far it falls.

21. Calculate the vertical distance an object dropped from rest covers in 12 s of free fall.

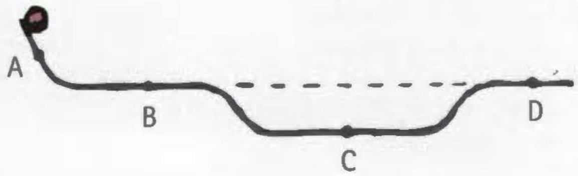
22. On a distant planet a freely falling object has an acceleration of 20 m/s^2. Calculate the vertical distance an object dropped from rest on this planet covers in 1.5 s.

RANKING

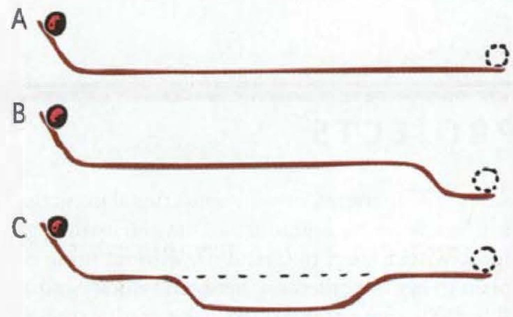
1. Jogging Jake runs along a train flatcar that moves at the velocities shown in positions A–D. From greatest to least, rank the velocity of Jake relative to a stationary observer on the ground. (Call the direction to the right positive.)



2. A track is made of a piece of channel iron bent as shown. A ball released at the left end of the track continues past the various points. Rank the speed of the ball at points A, B, C, and D, from fastest to slowest. (Watch for tie scores.)

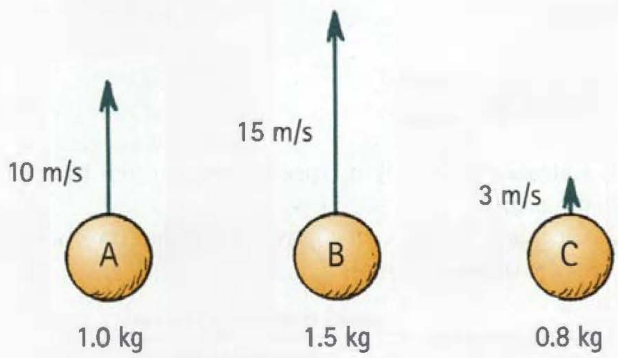


3. A ball is released at the left end of these different tracks. The tracks are bent from equal-length pieces of channel iron.



a. From fastest to slowest, rank the speed of the ball at the right end of the track.
b. From longest to shortest, rank the tracks in terms of the *time* for the ball to reach the end.
c. From greatest to least, rank the tracks in terms of the *average speed* of the ball. Or do all balls have the same average speed on all three tracks?

4. Three balls of different masses are thrown straight upward with initial speeds as indicated.



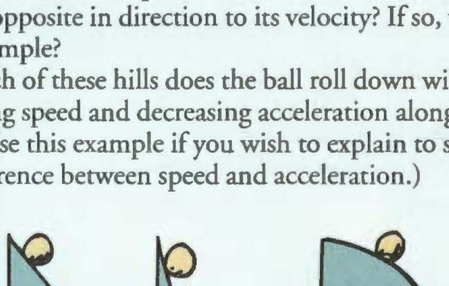
a. From fastest to slowest, rank the speeds of the balls 1 s after being thrown.
b. From greatest to least, rank the accelerations of the balls 1 s after being thrown. (Or are the accelerations the same?)

EXERCISES

1. What is the impact speed when a car moving at 100 km/h bumps into the rear of another car traveling in the same direction at 98 km/h?

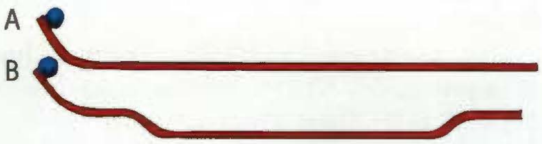
2. Suzie Surefoot can paddle a canoe in still water at 8 km/h. How successful will she be at canoeing upstream in a river that flows at 8 km/h?

3. Is a fine for speeding based on one's average speed or one's instantaneous speed? Explain.
4. One airplane travels due north at 300 km/h while another travels due south at 300 km/h. Are their speeds the same? Are their velocities the same? Explain.
5. Light travels in a straight line at a constant speed of 300,000 km/s. What is the acceleration of light?
6. Can an automobile with a velocity toward the north simultaneously have an acceleration toward the south? Explain.
7. You're in a car traveling at some specified speed limit. You see a car moving at the same speed coming toward you. How fast is the car approaching you, compared with the speed limit?
8. Can an object reverse its direction of travel while maintaining a constant acceleration? If so, give an example. If not, provide an explanation.
9. For straight-line motion, how does a speedometer indicate whether or not acceleration is occurring?
10. Correct your friend who says, "The dragster rounded the curve at a constant velocity of 100 km/h."
11. You are driving north on a highway. Then, without changing speed, you round a curve and drive east. (a) Does your velocity change? (b) Do you accelerate? Explain.
12. Jacob says acceleration is how fast you go. Emily says acceleration is how fast you get fast. They look to you for confirmation. Who's correct?
13. Starting from rest, one car accelerates to a speed of 50 km/h, and another car accelerates to a speed of 60 km/h. Can you say which car underwent the greater acceleration? Why or why not?
14. Cite an example of something with a constant speed that also has a varying velocity. Can you cite an example of something with a constant velocity and a varying speed? Defend your answers.
15. Cite an instance in which your speed could be zero while your acceleration is nonzero.
16. Cite an example of something that undergoes acceleration while moving at constant speed. Can you also give an example of something that accelerates while traveling at constant velocity? Explain.
17. (a) Can an object be moving when its acceleration is zero? If so, give an example. (b) Can an object be accelerating when its speed is zero? If so, give an example.
18. Can you cite an example in which the acceleration of a body is opposite in direction to its velocity? If so, what is your example?
19. On which of these hills does the ball roll down with increasing speed and decreasing acceleration along the path? (Use this example if you wish to explain to someone the difference between speed and acceleration.)



20. Suppose that the three balls shown in Exercise 19 start simultaneously from the tops of the hills. Which one reaches the bottom first? Explain.
21. What is the acceleration of a car that moves at a steady velocity of 100 km/h for 100 s? Explain your answer.
22. Which is greater, an acceleration from 25 km/h to 30 km/h or one from 96 km/h to 100 km/h if both occur during the same time?
23. Galileo experimented with balls rolling on inclined planes of various angles. What is the range of accelerations from angles 0° to 90° (from what acceleration to what)?
24. Be picky and correct your friend who says, "In free fall, air resistance is more effective in slowing a feather than a coin."
25. Suppose that a freely falling object were somehow equipped with a speedometer. By how much would its reading in speed increase with each second of fall?
26. Suppose that the freely falling object in the preceding exercise were also equipped with an odometer. Would the readings of distance fallen each second indicate equal or different falling distances for successive seconds?
27. For a freely falling object dropped from rest, what is the acceleration at the end of the fifth second of fall? At the end of the tenth second of fall? Defend your answers.
28. If air resistance can be neglected, how does the acceleration of a ball that has been tossed straight upward compare with its acceleration if simply dropped?
29. When a ballplayer throws a ball straight up, by how much does the speed of the ball decrease each second while ascending? In the absence of air resistance, by how much does it increase each second while descending? How much time is required for rising compared to falling?
30. Someone standing at the edge of a cliff (as in Figure 3.8) throws a ball nearly straight up at a certain speed and another ball nearly straight down with the same initial speed. If air resistance is negligible, which ball will have the greater speed when it strikes the ground below?
31. Answer the previous question for the case where air resistance is *not* negligible—where air drag affects motion.
32. If you drop an object, its acceleration toward the ground is 10 m/s^2. If you throw it down instead, would its acceleration after throwing be greater than 10 m/s^2? Why or why not?
33. In the preceding exercise, can you think of a reason why the acceleration of the object thrown downward through the air might be appreciably less than 10 m/s^2?
34. While rolling balls down an inclined plane, Galileo observes that the ball rolls 1 cubit (the distance from elbow to fingertip) as he counts to 10. How far will the ball have rolled from its starting point when he has counted to 20?
35. Consider a vertically launched projectile when air drag is negligible. When is the acceleration due to gravity greater? When ascending, at the top, or when descending? Defend your answer.
36. Extend Tables 3.2 and 3.3 to include times of fall of 6 to 10 s, assuming no air resistance.
37. If it were not for air resistance, why would it be dangerous to go outdoors on rainy days?
38. As speed increases for an object in free fall, does acceleration increase also?
39. A ball tossed upward will return to the same point with the same initial speed when air resistance is negligible. When air resistance is not negligible, how does the return speed compare with its initial speed?

40. Two balls are released simultaneously from rest at the left end of equal-length tracks A and B as shown. Which ball reaches the end of its track first?



41. Refer to the pair of tracks in Exercise 40. (a) On which track is the average speed greater? (b) Why is the speed of the ball at the end of the tracks the same?

42. In this chapter, we studied idealized cases of balls rolling down smooth planes and objects falling with no air resistance. Suppose a classmate complains that all this attention focused on idealized cases is worthless because idealized cases simply don't occur in the everyday world. How would you respond to this complaint? How do you suppose the author of this book would respond?

43. A person's hang time would be considerably greater on the Moon. Why?

44. Why does a stream of water get narrower as it falls from a faucet?

45. Make up two multiple-choice questions that would check a classmate's understanding of the distinction between velocity and acceleration.

PROBLEMS

1. You toss a ball straight up with an initial speed of 30 m/s. How high does it go, and how long is it in the air (neglecting air resistance)?

2. A ball is tossed with enough speed straight up so that it is in the air several seconds. (a) What is the velocity of the ball when it reaches its highest point? (b) What is its velocity 1 s before it reaches its highest point? (c) What is the change in its velocity during this 1-s interval? (d) What is its velocity 1 s after it reaches its highest point? (e) What is the change in velocity during this 1-s interval? (f) What is the change in velocity during the 2-s interval? (Careful!) (g) What is the acceleration of the ball during any of these time intervals and at the moment the ball has zero velocity?

3. What is the instantaneous velocity of a freely falling object 10 s after it is released from a position of rest? What is its average velocity during this 10-s interval? How far will it fall during this time?

4. A car takes 10 s to go from $v = 0$ m/s to $v = 25$ m/s at constant acceleration. If you wish to find the distance traveled using the equation $d = 1/2\ at^2$, what value should you use for a?

5. Surprisingly, very few athletes can jump more than 2 feet (0.6 m) straight up. Use $d = 1/2gt^2$ and solve for the time one spends moving upward in a 0.6-m vertical jump. Then double it for the "hang time"—the time one's feet are off the ground.

• 6. A dart leaves the barrel of a blowgun at a speed v. The length of the blowgun barrel is L. Assume that the acceleration of the dart in the barrel is uniform.
   a. Show that the dart moves inside the barrel for a time of $\frac{2L}{v}$.
   b. If the dart's exit speed is 15.0 m/s and the length of the blowgun is 1.4 m, show that the time the dart is in the barrel is 0.19 s.

CHAPTER 3 ONLINE RESOURCES

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Interactive Figures

- 3.6, 3.8

Videos

- Definition of Speed
- Average Speed
- Velocity
- Changing Velocity
- Definition of Acceleration
- Numerical Example of Acceleration
- Free Fall: How Fast?
- $v = gt$
- Free Fall: How Far?
- Air Resistance and Falling Objects
- Falling Distance

Quizzes

Flashcards

Links