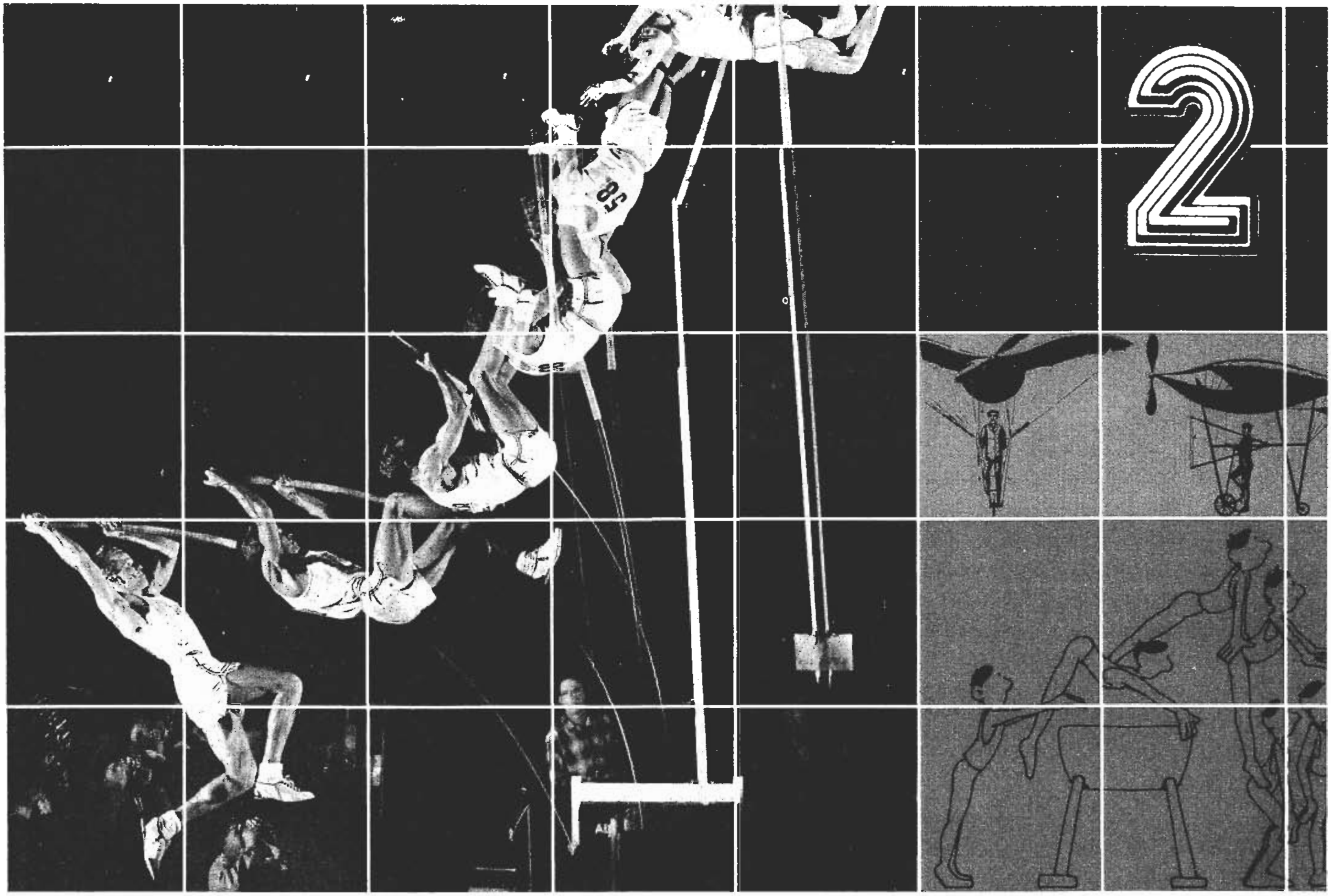


2

Describing Motion

Motion is so much a part of our lives that we can scarcely communicate without using words that refer to it—fast, slow, stop, go, swift, unhurried, hustle, leisurely. This abundant vocabulary reflects the amount and diversity of motion we experience. For survival purposes, many species of animals detect moving rather than stationary objects, a fact every hunter learns. Motion attracts the attention of infants, a fact every parent learns. Because we sense motion directly, many psychologists now suggest that we understand motion before we understand the related concepts of space and time. We experience space by moving about in it. We observe time with the motion of the hands of the clock or the periodic rising and setting of the sun.

Motion permeates all aspects of physics. Atoms and molecules remain in constant motion. The temperature of an object depends on the motion of its molecules. Our model of the internal structure of the atom is based largely on the motion of incredibly small particles. Electrical current arises from the almost imperceptible motion of tiny electrons. Even the apparently fixed stars that fill the night sky are in motion—often at astonishingly high speeds.

In this chapter we introduce the concepts used to describe motion. Motion is defined as a change of position that occurs during a time interval. The concepts of *speed* and *velocity,* used to describe motion, are derived from the concepts of distance and displacement introduced in Chapter 1. The terms

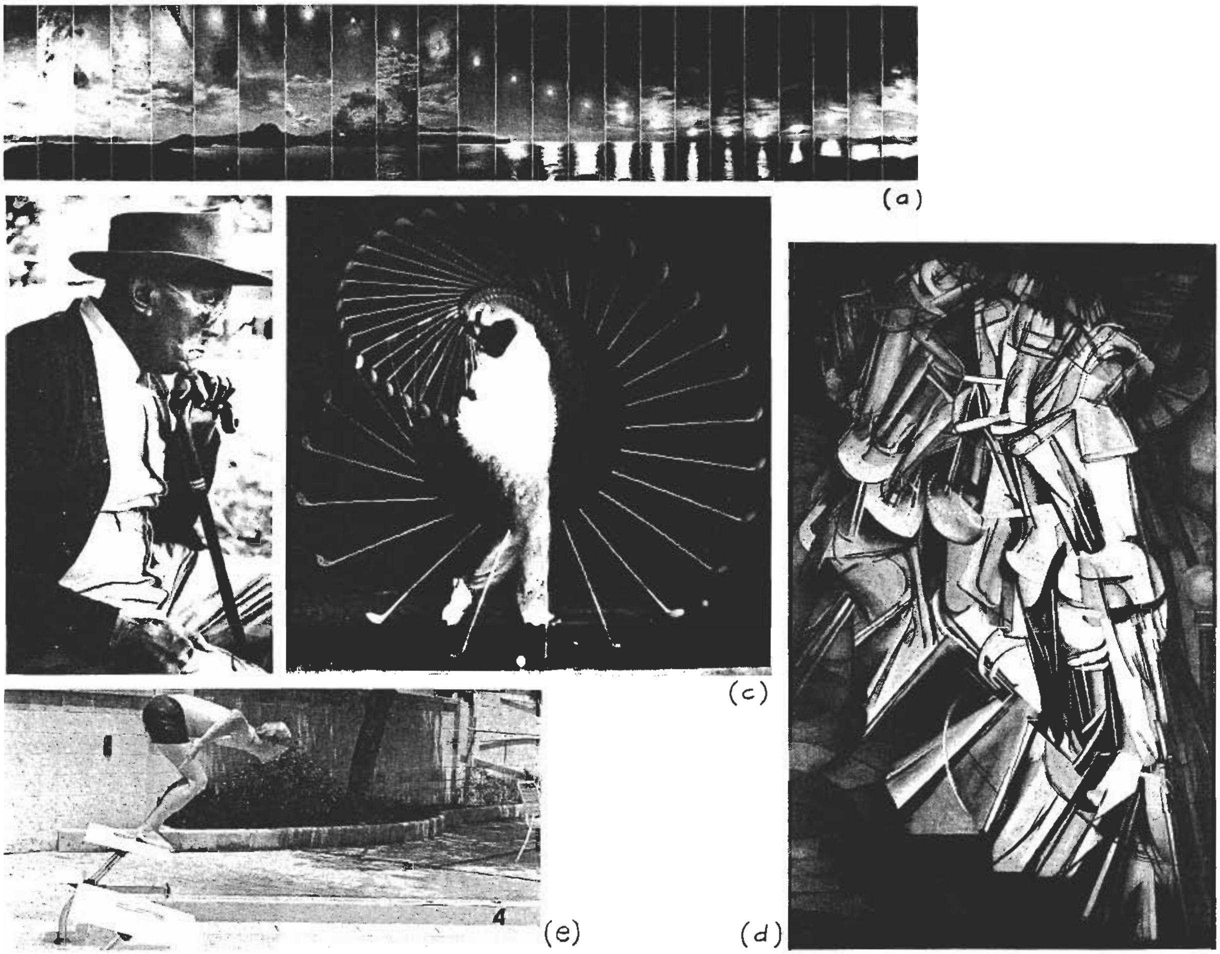


Figure 2-1
Which depict motion?

average and *instantaneous* are added to distinguish speed or velocity over a long time interval from speed or velocity at an instant in time. We use the concept of *acceleration* to describe motion in which the velocity is changing, as when a car starts to move away from a stop sign. Finally, we use the concepts of speed, velocity, and acceleration to analyze several common examples of motion.

IS IT MOVING?

Cars moving along in traffic, children riding bicycles, airplanes flying overhead—you can easily tell that motion occurs. Relative to their surroundings, the cars, children, and airplanes change position. In a textbook we cannot actually watch objects move, but we can capture and analyze motion in photographs, drawings and paintings.

Look at the pictures in Figure 2-1. Which depict motion? What visual clues can you use to support your choice? You probably said that the people or things in A, C, and D were moving, while those in B and E were still. Photographs A and C suggest motion because of the succession of images on the film. Marcel Duchamp used this same idea in his painting, *Nude Descending a Staircase,* shown in D. By contrast, the single image in photographs B and E suggests that the man and the swimmer were stationary, at least during the interval of time in which the photographs were taken. Perhaps they moved before or after the photograph. To know we would have to see another photograph taken at a different time. Only by seeing a *change of position* over *time* can we be certain that motion occurred.

DESCRIBING MOTION

Position and time are both needed to describe motion. When we want to compare the motion of different objects, the simplest strategy is to hold one of them constant and compare results on the second. Take, for example, a traditional race where all runners complete the same route. Distance is held constant and elapsed times are compared. The runner with the shortest elapsed time is the fastest. An alternative approach, used in some auto races, is to race for a fixed time interval (usually 24 hours) and compare distances. The car that traveled the greatest distance at the end of the fixed time interval is the fastest. Either strategy—shortest time with a fixed distance or longest distance over a fixed time interval—is a fair way to determine the winner. Frequently, however, we are faced with comparing two motions when both quantities (distance and elapsed time) are different. The concepts of speed and velocity allow us to make such comparisons. Speed describes the rate of change of position, while velocity describes both the rate and the direction in which position changes.

Speed

Suppose that one runner covers 80 meters (m) in 10 seconds (s) and a second runner completes 108 m in 12 s. Who is faster? To make such a comparison we take the ratio of the distance to the elapsed time, called the **speed** of each runner.

$$\overset{\text{Speed}}{s} = \frac{\overset{\text{Distance}}{\ell}}{\underset{\text{Time}}{t}}$$

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

In our example, the speed of the first runner is 80 m divided by 10 s, which equals 8 meters/second (m/s). The speed of the second runner is 108 m divided by 12 s or 9 m/s. The second runner was faster than the first.

SELF-CHECK 2A

In a speed trial, a bicycle traveled 200 m in 10 s. What was its speed? How did its speed compare to the two runners?

A STEP FURTHER—MATH

ANSWERING OTHER QUESTIONS

So far we have used the definition of speed to answer the question: How fast? Sometimes we need to answer different, but related, questions. How long will it take to get to Milwaukee? How far can we travel before it gets dark? Fortunately, the definition of speed is versatile.

Suppose you are traveling from Minneapolis to Milwaukee, a distance of about 450 km, and your speed is 90 km/h. How long will it take to make the trip? Since speed and distance are both known, we can rearrange the definition of speed (in equation form) to isolate time, the unknown.

$$\text{Speed} = \frac{\text{distance}}{\text{time}} \quad \text{becomes} \quad \text{time} = \frac{\text{distance}}{\text{speed}}$$

Substituting the values for distance and speed, we find that

$$\text{Time} = \frac{450\text{ km}}{90\text{ km/h}} = 5\text{ h}$$

The trip will take five hours.

Suppose you have six more hours until dark and want to figure out how much farther you will get before stopping for the night. You can figure on averaging 70 kilometers/hour during the six hours. Here the question we're asking is: How far? Again, we can manipulate the definition of speed to isolate distance.

$$\begin{aligned}\text{Distance} &= (\text{speed}) \times (\text{time})\\ &= (70\text{ km/h}) \times (6\text{ h}) = 420\text{ km}\end{aligned}$$

You would travel 420 kilometers before dark.

A single definition enables us to answer three categories of questions, most of which crop up rather frequently. We can relate each category of questions to one of the three variables in the definition. How fast? describes speed. How long? describes time. How far? describes distance. You will find that this same procedure applies to nearly every definition we will introduce in later chapters. Definitions that allow us to summarize relationships among several variables can be very useful!

Velocity

In the 1929 Rose Bowl, a Georgia Tech halfback fumbled. Roy Riegels, the California center, scooped up the loose ball and dashed toward the goal line. Faster than the other players, he neared the goal line virtually untouched. Suddenly, his teammate tackled him—it was the wrong goal! "Wrong Way" Riegels had the right speed but the wrong velocity.

Velocity is defined as the ratio of the displacement of an object to the time interval required for the displacement.

$$\textbf{Velocity} = \frac{\textbf{displacement}}{\text{time}}$$

Velocity (a vector)

Displacement (a vector)

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

Time

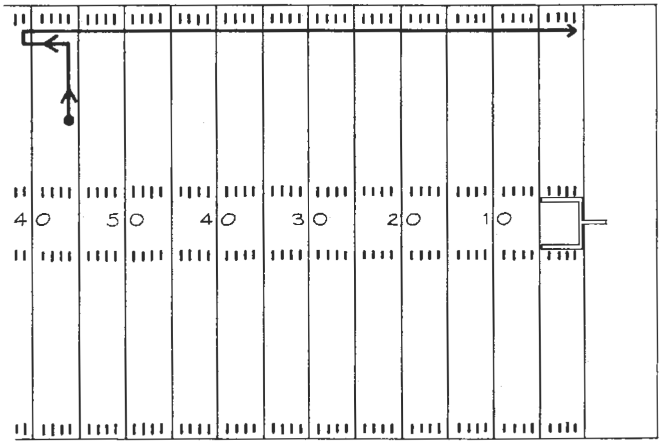


Figure 2-2

Roy Riegels picked up the fumble on about the 44-yard (yd) line, ran 2 yd toward the sidelines and then 5 yd in the right direction. In the process of dodging tacklers, he became disoriented, ran 60 yd in the wrong direction, and was tackled at the Georgia Tech 1-yd line. He traveled a distance of 67 yd and a displacement of 55 yd, wrong way.

Displacement is a vector quantity while time is a scalar. A displacement of 50 kilometers (km), north, divided by a time interval of 2 h gives us a velocity of 25 kilometers/hour (km/h), north. The direction of the velocity is the same as the direction of the displacement. Velocity is a vector—we need a number, a unit, and a direction in order to describe it completely. Thus 50 km/h, north, is a velocity; 90 km/h is not.

Speed and velocity are related to each other in the same way that distance and displacement are related. As an example, consider "Wrong Way" Riegels' infamous run. His path is shown in Figure 2-2. The distance he traveled was 67 yards (yd), while his displacement was 55 yd, wrong way. We estimate that his run took about 15 s. Using this information, we can compare his speed and velocity. Riegels' speed was 67 yd divided by 15 s, which equals 4.47 yd/s. By contrast, his velocity was 55 yd, wrong way, divided by 15 s, or 3.67 yd/s, wrong way. Riegel probably had good speed for a center in 1929. However, it was his velocity during the play that made him famous.

SMALL WARNING

In everyday life we frequently use the terms *speed* and *velocity* interchangeably. In physics each term has a different meaning. Speed is a scalar quantity, related to the distance and time involved in the motion. Velocity is a vector quantity, derived from displacement and time.

SELF-CHECK 2B

Because of limited air service, you have to fly from Chicago to Albany via New York City. The straight-line distance between Chicago and New York City is 1294 km; between New York City and Albany, 250 km; and between Chicago and Albany, 1306 km. The total time for the trip was 4 h. What was your velocity? (Albany is roughly east of Chicago.)

AVERAGE AND INSTANTANEOUS DESCRIPTIONS OF MOTION

When we say that a runner's speed is 8 m/s, someone might imagine the runner being motionless one instant and running down the track at 8 m/s an instant later, much in the style that cartoon characters take off. From experience, we realize that such an image is absurd. Sprinters begin moving slowly, increasing their speed continuously until they reach their maximum speed. They may run only briefly at a speed of 8 m/s.

Figure 2-3 illustrates this situation more clearly. The photograph recorded images of a ball at 0.033-s intervals as it was being dropped. A meterstick was placed beside the ball's path to provide a coordinate system against which we could measure the ball's distance or displacement. If someone were to ask you the ball's speed, what would you answer? Using the definitions provided in the last section, the ball's speed from B to C is 0.07 m/0.033 s = 2.12 m/s. Yet, moving during an equal time interval from D to E, the ball's speed is 0.19 m/0.033 s = 5.76 m/s. If we made similar calculations between any two images, we would have many different speeds. To eliminate this ambiguity, we distinguish between average and instantaneous motion.

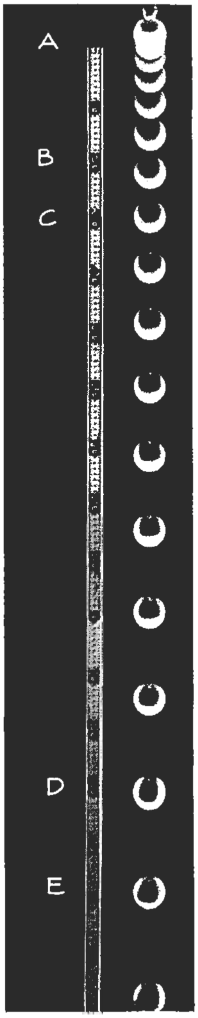


Figure 2-3
The ball's speed can be calculated from its distance and time measurements. The speed from *A* to *E*, however, is not the same as the speed from *D* to *E*.

Average Motion

When we say that the sprinter runs at a speed of 8 m/s, we mean that the average speed during the 10-s time interval is 8 m/s. **Average speed** is defined to be the total distance traveled during a time interval divided by that time interval. Analogously, the **average velocity** is the displacement during a given time interval divided by that time interval. You may choose any time interval you wish, but you must specify it so others know which average speed or velocity you mean.

To illustrate the process, we return to the example in Figure 2-3. If we want to describe the speed of the ball during its entire fall, then we calculate its average speed during the time interval taken to go from A to E (0.561 s). The average speed over the entire trip is 1.587 m divided by 0.561 s, which is 2.83 m/s. Earlier, we calculated the average speed over smaller time intervals—from B to C and from D to E. The same process would apply in calculating average velocity, once displacements were substituted for distances. In this particular example, the magnitude of the displacements are equal to the distances traveled; consequently, we need only to add a direction. The average velocity in moving from A to E is 2.83 m/s, down.

When people describe speeds or velocities, they are usually talking about average speeds or average velocities. Generally, we know what time interval they mean—like the time required for a sprinter to complete a race. While these "averages" do not describe the detailed motion of the runner during the entire race, they resolve the issue important to the runner: Who wins.

Instantaneous Motion

To describe a runner's motion in detail, we need to know his speed at each instant of time. Such a speed is called his **instantaneous speed.** Analogously, an **instantaneous velocity** is the velocity of an object at a particular instant of time. Practically speaking, we cannot measure speed or velocity at an instant of time. Measurements over smaller and smaller time intervals, however, allow us to estimate instantaneous speeds and velocities. Some instruments, like speedometers and police radar, measure average speeds over extremely short time intervals, so we often think of them as measuring instantaneous speeds. When we have indirect measurements like the strobe photo in Figure 2-3, then the best we can do is simply to estimate the instantaneous speed based on the smallest time interval available.

The procedure used to estimate an instantaneous speed is similar to that used to calculate average speeds. The only difference is that we choose the smallest time interval possible. In Figure 2-3, the best we can do is to calculate the speed between successive images, like from B to C. Earlier we calculated the average speed of the ball in moving from B to C to be 2.12 m/s. This represents our best estimate of the instantaneous speed of the ball midway through the time interval. Consequently, we say that the ball's instantaneous speed at 0.214 s (halfway between 0.198 s and 0.231 s) is 2.12 m/s. The only way that we could make a better estimate of the instantaneous speed at 0.214 seconds is to take another strobe photograph in which the time interval between flashes was even shorter. This would produce a photograph with additional images of the ball between B and C, and we could calculate an average speed over a smaller time interval. Theoretically, our best measurement of the instantaneous speed occurs when the elapsed time between images is zero. Practically, however, we cannot make such measurements, so we make the best approximation from the measurements available.

Instantaneous Motion Describes Change

The distinction between average and instantaneous motion is important only when the object's motion is changing. A car moving down the highway at a constant velocity of 90 km/h, east, has the same average and instantaneous velocity—90 km/h, east. Only when the car slows down, speeds up, or changes direction do the values of average and instantaneous velocity differ.

Figure 2-4 illustrates this distinction. The displacements of a Corvette, a Volkswagen, and a Model T are recorded at 1-s intervals in a series of strobelike drawings. For the moment we will contrast the motions of just the Volkswagen and the Model T. The average velocity of each is simply the total displacement divided by the total time: 15 m/s, east, for the Model T and 11.5 m/s, east, for the Volkswagen. Successive images allow us to estimate instantaneous velocities midway through each time interval, at 0.5 s, 1.5 s, 2.5 s, and 3.5 s. These values for both the Model T and the Volkswagen are listed in Table 2-1.

Let's compare the average velocity over the entire 4 seconds with the instantaneous velocity during each 1-second interval. The Model T moved at a constant velocity throughout. Its instantaneous velocity always equaled its average velocity, 15 m/s, east. We really did not need to bother with instantaneous velocities. By contrast, the Volkswagen changed velocity. Its instantaneous velocity increased from 10 m/s, east, to 11 m/s, east, to 12 m/s, east, and finally to 13 m/s, east. Because the Volkswagen's motion changed, its

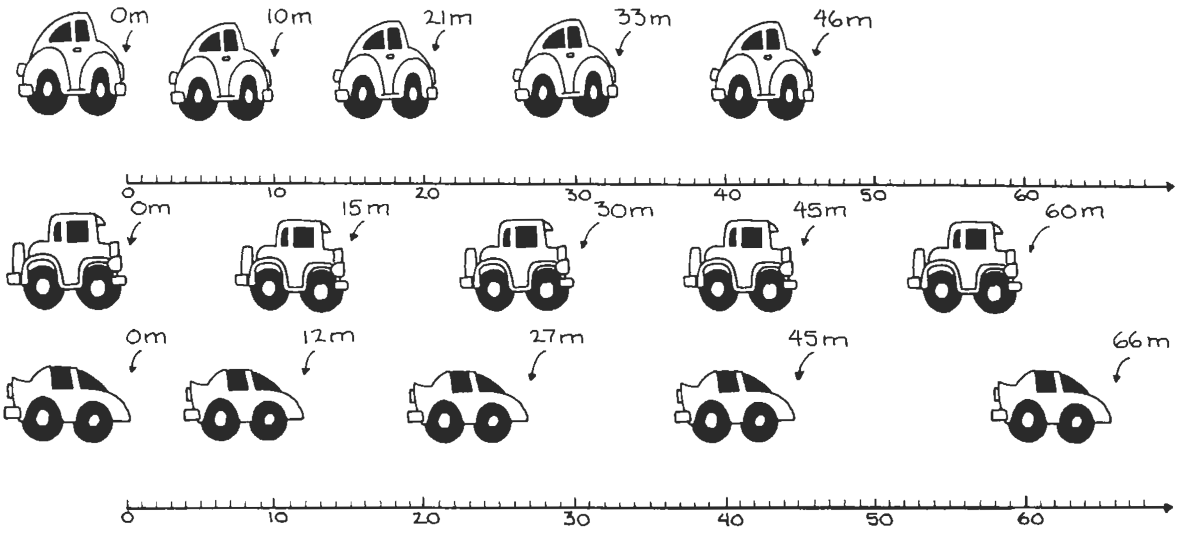


Figure 2-4

The Model T moves at a constant velocity—15 m/s, E. The Volkswagen changes speed—increasing its speed during each 1-s time interval. The Corvette increases its speed at a faster rate.

Table 2-1 Instantaneous Velocities for Figure 2-4

Time Interval	Time	Instantaneous Velocity (Model T)	Instantaneous Velocity (Volkswagen)
0-1 s	0.5 s	$\frac{15\text{ m}}{1\text{ s}} = 15\text{ m/s, E}$	$\frac{10\text{ m}}{1\text{ s}} = 10\text{ m/s, E}$
1-2 s	1.5 s	$\frac{15\text{ m}}{1\text{ s}} = 15\text{ m/s, E}$	$\frac{11\text{ m}}{1\text{ s}} = 11\text{ m/s, E}$
2-3 s	2.5 s	$\frac{15\text{ m}}{1\text{ s}} = 15\text{ m/s, E}$	$\frac{12\text{ m}}{1\text{ s}} = 12\text{ m/s, E}$
3-4 s	3.5 s	$\frac{15\text{ m}}{1\text{ s}} = 15\text{ m/s, E}$	$\frac{13\text{ m}}{1\text{ s}} = 13\text{ m/s, E}$

average and instantaneous velocities are no longer the same. While an average velocity of 11.5 m/s, east, provides a general description of the Volkswagen's motion, it does not tell us whether the motion ever changed or not. The various instantaneous velocities provide a more complete picture.

Changes in motion are generally obvious in strobelike drawings or photographs. Since the object's position has been recorded at the end of equal time intervals, we need only compare displacements to see if the motion has changed. Figure 2-5 shows an exaggerated comparison of the motion of two cars. Successive images of the Model T are equally spaced, since the displacements during each 1-s time interval are equal. Successive images of the Volkswagen are not equally spaced. Displacements during each time interval increase, reflecting the Volkswagen's change in motion.

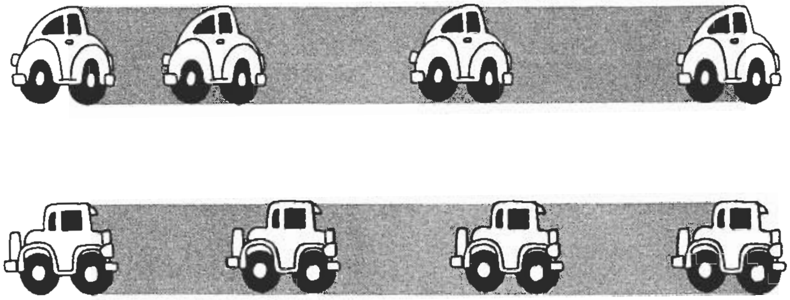


Figure 2-5
In this exaggerated drawing, the Volkswagen is accelerating, but the Model T is not. The spacing between images increases when an object accelerates.

SELF-CHECK 2C

Turnpike authorities often monitor speed by checking the travel time of cars. A car travels from Kansas City to Topeka, a distance of 100 km. If the time of entry was 9:06 A.M. and the time of exit was 10:36 A.M., the travel time would be 1.5 h. Calculate the car's speed. Did it exceed the posted speed limit, 90 km/h? Does this procedure measure instantaneous or average speeds? Could the car still have exceeded the speed limit at some time during the trip?

DESCRIBING CHANGES IN MOTION

Now let's turn to the motion of the Corvette in Figure 2-4. Like the Volkswagen, successive images of the Corvette are further and further apart. Its motion is changing. However, the Corvette's motion is changing more rapidly than the Volkswagen's. If we compare instantaneous velocities during each time interval, as in Table 2-2, our qualitative observations are confirmed. The Volkswagen's instantaneous velocity increased from 10 m/s, east, to 11 m/s, east, to 12 m/s, east, and—finally—to 13 m/s, east. During each 1-s time interval its instantaneous velocity increased by 1 m/s, east. The Corvette's instantaneous velocity increased from 12 m/s, east, to 15 m/s, east, to 18 m/s, east, and—finally—to 21 m/s, east. Its instantaneous velocity increased by 3 m/s, east, during each time interval—three times as much as the Volkswagen. We say that the Corvette had a greater acceleration than the Volkswagen.

$$\underset{\text{Acceleration}}{a} = \frac{\overset{\text{Final velocity}}{v_f} - \overset{\text{Initial velocity}}{v_i}}{\underset{\text{Time}}{t}}$$

Acceleration

The **acceleration** of an object is the ratio of the change of velocity of an object to the time interval during which that change occurs.

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

Table 2-2 Instantaneous Velocities for Figure 2-4

Time Interval	Time	Instantaneous Velocity (Corvette)	Instantaneous Velocity (Volkswagen)
0-1 s	0.5 s	$\frac{12\text{ m}}{1\text{ s}} = 12\text{ m/s, E}$	$\frac{10\text{ m}}{1\text{ s}} = 10\text{ m/s, E}$
1-2 s	1.5 s	$\frac{15\text{ m}}{1\text{ s}} = 15\text{ m/s, E}$	$\frac{11\text{ m}}{1\text{ s}} = 11\text{ m/s, E}$
2-3 s	2.5 s	$\frac{18\text{ m}}{1\text{ s}} = 18\text{ m/s, E}$	$\frac{12\text{ m}}{1\text{ s}} = 12\text{ m/s, E}$
3-4 s	3.5 s	$\frac{21\text{ m}}{1\text{ s}} = 21\text{ m/s, E}$	$\frac{13\text{ m}}{1\text{ s}} = 13\text{ m/s, E}$

The change in velocity is the difference between the final instantaneous velocity and the initial instantaneous velocity during the time interval over which they were measured. Let's use the motions of the Volkswagen and the Corvette to illustrate how to apply this definition.

Compare the accelerations of the two cars during the time interval from 0.5 s to 2.5 s. The velocity of the Volkswagen changed from 10 m/s, east, to 12 m/s, east. Its change of velocity was 2 m/s, east. The time interval during which the velocity changed was 2.5 s minus 0.5 s, which equals 2.0 s. Applying the definition, the acceleration of the Volkswagen was 2 m/s, east, divided by 2.0 s, equals 1 (m/s)/s, east, which we read as "one meter per second per second, east." By contrast the Corvette changed its velocity from 12 m/s, east, to 18 m/s, east, during the same time interval. Its acceleration was 6 m/s, east, divided by 2.0 s, equals 3 (m/s)/s, east. While the unit (meters per second) per second looks strange, it is descriptive of what is occurring physically. The velocity, measured in meters per second, is changing during each second. (For convenience, these units are often written as m/s^2, read "meters per second squared.")

Acceleration is defined in terms of velocity; consequently, acceleration is a vector. It requires a number, a unit, and a direction. Any change in velocity results in an acceleration. Since velocity involves both a magnitude (number and unit) and a direction, a change in either magnitude or direction means that an acceleration occurred. In Figure 2-6 the Volkswagen changed the magnitude of its velocity but not its direction. On a merry-go-round that is rotating at a constant speed, we change direction but not magnitude. Other motions, such as a car traveling along a winding road, can involve both a change in magnitude and a change in direction. In each case, acceleration occurs.

In conversations we often distinguish between speeding up and slowing down by saying that vehicles *accelerate* and *decelerate*. In physics the single

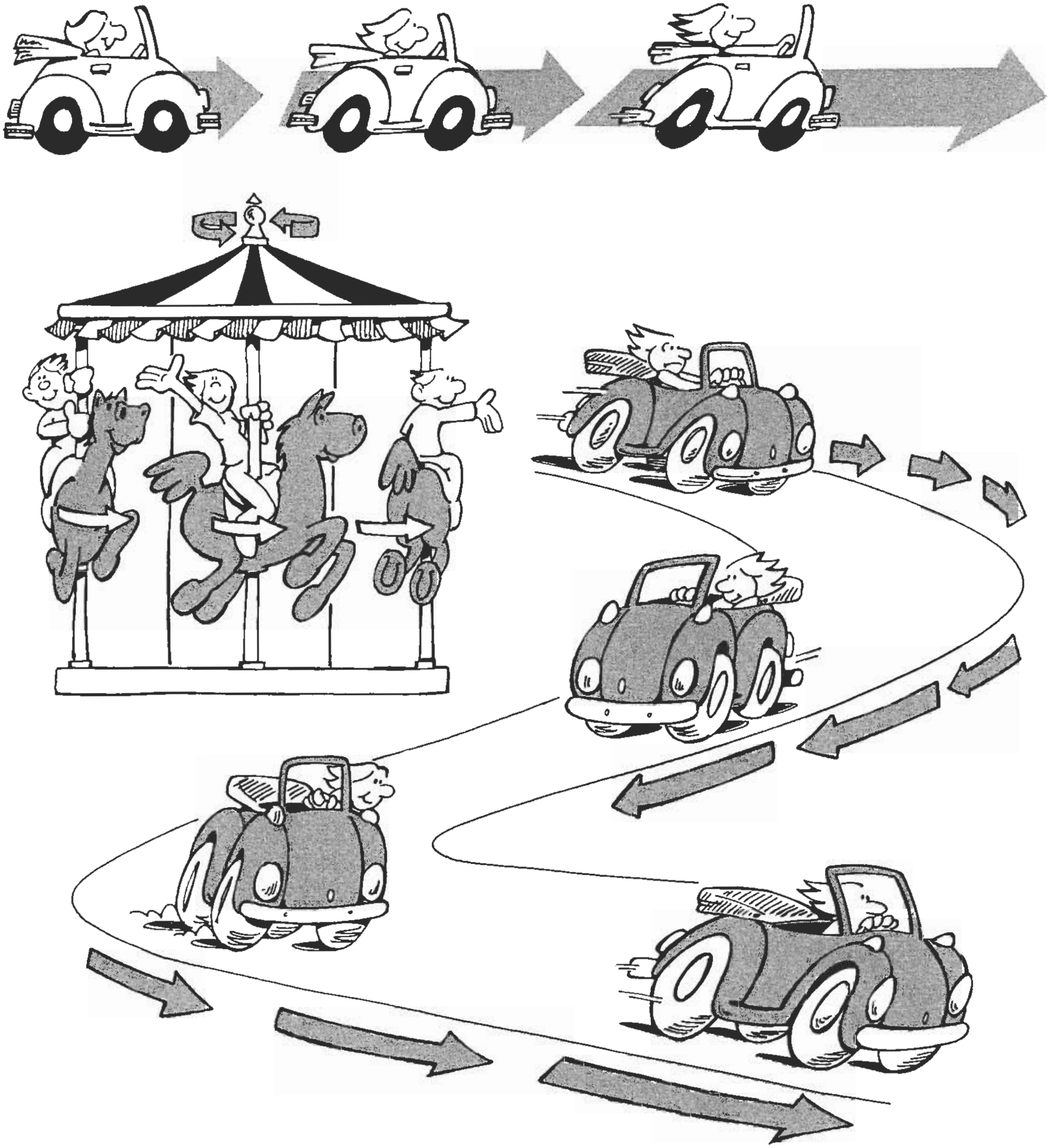


Figure 2-6

Acceleration occurs if an object's velocity changes in direction, changes in magnitude, or changes in both magnitude and direction.

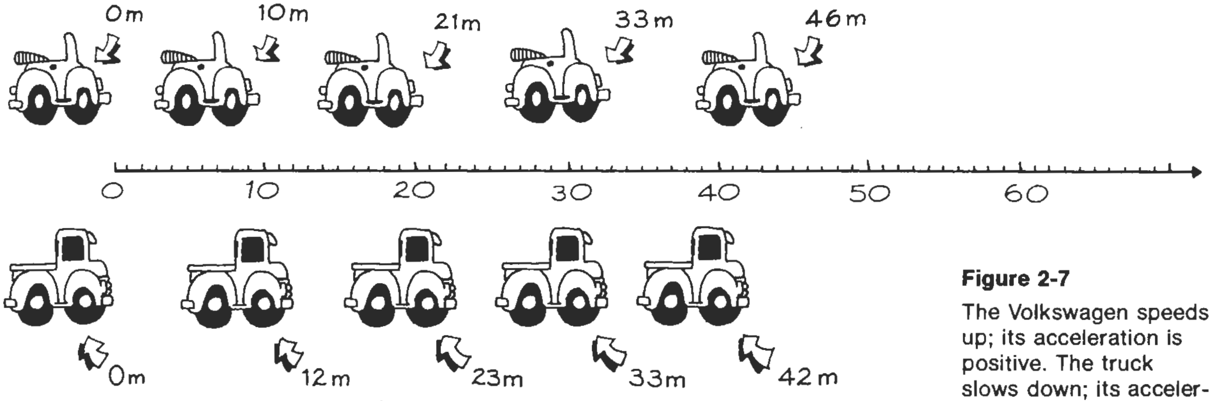


Figure 2-7
The Volkswagen speeds up; its acceleration is positive. The truck slows down; its acceleration is negative.

concept—acceleration—is used to describe both an increase and decrease in speed. For example, compare the motion of the Volkswagen and truck in Figure 2-7. The Volkswagen is accelerating, while the truck is decelerating. The Volkswagen increases its velocity from 10 m/s, east, to 12 m/s, east, during the 2 s. Its acceleration is 1 (m/s)/s, east. The truck decreases its velocity from 12 m/s, east, to 10 m/s, east, during the same time interval. Its acceleration is −1 (m/s)/s, east. The accelerations of the two vehicles differ in sign. A positive sign—positive acceleration—indicates that the vehicle is speeding up. A negative sign—negative acceleration—indicates that the vehicle is slowing down. A negative acceleration is a deceleration.

SELF-CHECK 2D

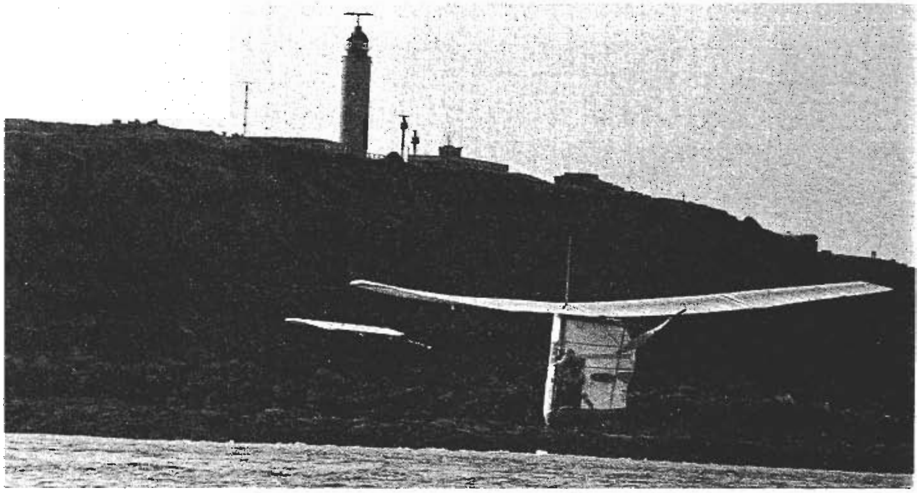
What is the acceleration of a bicycle whose velocity is initially 4 m/s, north, if 10 s later it has slowed to 1 m/s, north?

Acceleration Due to Gravity

Our environment provides us plenty of experience with acceleration. Pencils, books, apples—all objects fall to the ground when not supported by another object. If we examine their motions carefully, we find that they accelerate at a common rate—the **acceleration due to gravity.**

Figure 2-3 shows a ball being dropped near the surface of the earth. The images of the ball become more and more separated—our visual clue for acceleration. Careful measurements would show a constant acceleration of 9.8 (m/s)/s, down. The same is true for all other objects dropped near the surface of the earth, except for objects that are measurably affected by air resistance. Air resistance makes the motion of very light objects, like feathers, slower than that of heavier objects, like balls. But when we perform experiments in containers from which the air has been evacuated, as illustrated in Figure 2-8, light and heavy objects fall with the same acceleration.

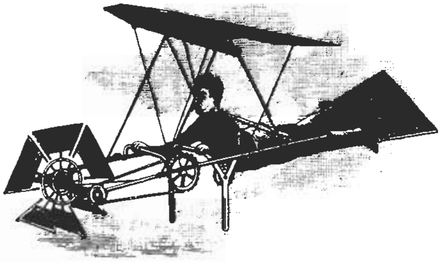
In the now-famous, but perhaps fictional, Leaning Tower of Pisa experiment, Galileo first demonstrated that objects fall with the same acceleration.

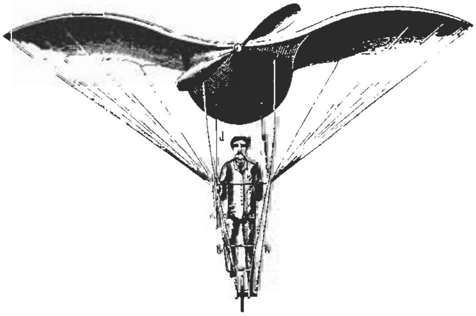


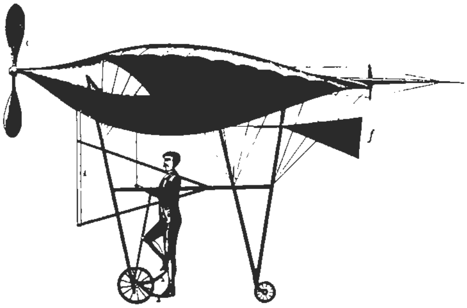
PEDAL POWER PLUS

We are always in a hurry. We run when we could walk; drive when bicycling would do; fly when a train would suffice. Sometimes we get the impression that some people would fly everywhere if it were convenient. And, flying would be convenient if only we could do it under our own power.

The idea of increasing speed and acceleration by flying under human power (no engines) has fascinated inventors for centuries. Leonardo da Vinci designed but never built a device that would enable humans to imitate birds by flapping wings. Some nineteenth-century inventors attempted similar devices, while others created bicyclelike flying machines. Unfortunately, none of them worked. However, in the late 1970s a group of engineers successfully built human-powered aircraft. One of them, called the Gossamer Albatross, crossed the English Channel. It traveled the 36 kilometers from England to France in 2 hours 49 minutes—an average speed of 12.8 km/h, or 3.5 m/s. While the speed of the Gossamer Albatross does not yet rival that of a Boeing 747, the dream of human-powered flight is coming true.







Since air resistance posed a problem, he cleverly chose objects heavy enough that the effect of air resistance was minimal. Today, we simply go to the moon. Since the moon has no atmosphere, air resistance is conveniently absent. Apollo Astronaut David Scott dropped a hammer and feather at the surface of the moon. Both fell with the same acceleration, 1.6 (m/s)/s, down. While the value of the acceleration due to gravity differs on the earth and moon, acceleration toward the ground is a natural part of all planetary environments.

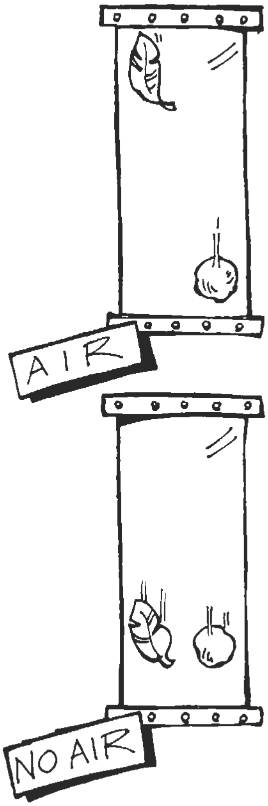


Figure 2-8

In an evacuated tube, a rock and feather fall together at an acceleration equal to the acceleration due to gravity.

ANALYZING MOTION WITH PHOTOGRAPHY

Photographs such as Figure 2-1A and C are often used to study motion. These photos are created by two processes. With very slow motion, such as the motion of the sun across the sky in Figure 2-1A, the camera shutter is opened and closed at several equal time intervals, such as once an hour. Each time the shutter opens, an image of the sun is recorded at a different location on the photographic film. In the case of very rapid motion, like the motion of the golf club in Figure 2-1C, the camera shutter is left open and a strobe light is used to illuminate the golfer. Each time the strobe light flashes, the film records an image of the golfer. Successive strobe flashes are always separated by equal time intervals.

These photographic techniques allow us to study motion both qualitatively and quantitatively. Qualitatively, we can use the spacing between images to compare both speed and acceleration. In Figure 2-1A the distance between images seems rather constant, suggesting that the sun moves across the sky at a constant speed. By contrast the distance between successive images of the golf club varies. The golf club changes speed. The spacing between images also allows us to compare speeds. Slower speeds result in images more closely spaced than higher speeds. For example, the golf club is moving faster at the bottom of the swing than at the top. Quantitatively, we can superimpose coordinate systems to calculate speeds, velocities, and accelerations. The procedures are exactly the same as those used throughout the chapter.

Athletes have been particularly interested in using stroboscopic photographs to analyze the various techniques of their given sport. Golfers were amazed to discover that the golf club and ball (Figure 2-9A) are actually in contact for less than a centimeter of the swing. The golfer is essentially unable to guide the ball with follow-through contact. Stroboscopic pictures were used extensively in studying the introduction of the fiberglass pole in pole vaulting competition (Figure 2-9B). Strobelike drawings are frequently used to teach correct body position and posture in a variety of sports (Figure 2-9C). Because the goal in any competitive sport is continued improvement, this detailed analysis of motion has become an important part of an athlete's training.

Stroboscopic analysis of motion has led us into fascinating new worlds, where things move either too quickly or too slowly for the naked eye to follow. Yet these worlds can be described with the same vocabulary as our everyday perceptions. Speed, velocity, and acceleration describe motion—for dancers, athletes, car designers, naturalists, and physicists alike.

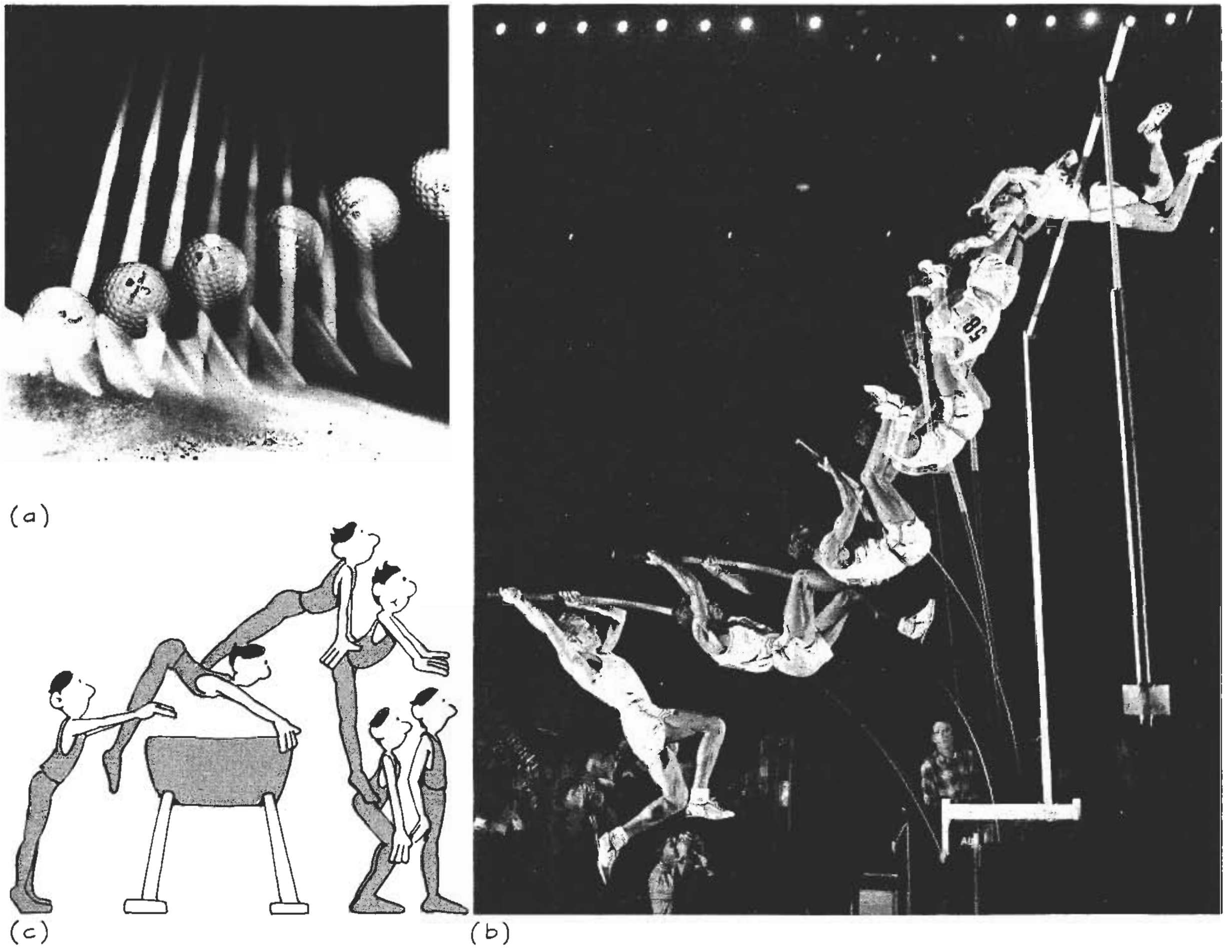


Figure 2-9 Stroboscopic pictures and drawings aid athletes in learning and perfecting various sports.

CHAPTER SUMMARY

Motion occurs when an object changes its position. Two concepts, speed and velocity, describe the rate at which a change in position occurs. *Speed* is the ratio of the distance traveled to the time interval in which the motion occurs. *Velocity* is the ratio of the displacement to the time interval. Speed is a scalar; velocity is a vector.

In describing motion, we distinguish between average and instantaneous speeds or velocities. *Average speed* is the total distance traveled during a time interval divided by that time interval. *Instantaneous speed* is the speed at one instant of time. We estimate instantaneous speed by calculating an average speed over as short a time interval as possible. *Average* and *instantaneous* *velocities* are defined in the same fashion, except that displacements are used instead of distances.

Acceleration is the ratio of the change of velocity of an object to the time interval during which the change occurs. An acceleration occurs when an object changes the magnitude or direction of its velocity. Like velocity, acceleration is a vector. A positive acceleration means that the object is speeding up; a negative acceleration means that the object is slowing down. Objects falling freely near the surface of the earth experience a common acceleration—the *acceleration due to gravity*. Measurements show the acceleration due to gravity at the earth's surface to be 9.8 (m/s)/s, down.

ANSWERS TO SELF-CHECKS

2A. Speed = distance/time = 200 m/10 s = 20 m/s. The bicyclist travels more than twice as fast as the runners.

2B. **Velocity** = **displacement**/time = (1306 km, east)/4 h = 326.5 km/h, east.

2C. Speed = distance/time = 100 km/1.5 h = 66.7 km/h. The car's speed did not exceed the posted speed limit. This procedure measures the average speed of the car. The driver could have exceeded the speed limit during the trip and then compensated by stopping for lunch. The instantaneous speed could have exceeded the speed limit, while the average speed did not.

2D. **Acceleration** = (change in **velocity**)/(time interval) = (1 m/s, north − 4 m/s, north)/10 s = −0.3 (m/s)/s, north. The bicycle slowed down.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define the terms listed below:
Speed
Average speed
Instantaneous speed
Acceleration
Velocity
Average velocity
Instantaneous velocity
Acceleration due to gravity

A2. Which of the terms in Question A1 are vectors? Which are scalars?

A3. What properties of a photograph indicate that motion occurred while the photograph was being taken?

A4. Why do we use the concepts of speed and velocity rather than simply comparing travel times or distances?

A5. Explain the difference between average and instantaneous speeds. When do instantaneous speeds provide a better picture of an object's motion than average speeds?

A6. What two possibilities for change in an object's motion result in an acceleration?

A7. Explain the meaning of the units (m/s)/s.

A8. Describe the motion of an object experiencing positive acceleration; experiencing negative acceleration.

A9. When is the acceleration due to gravity a constant? When does it change?

A10. Describe the motion shown by a strobe photograph when:
   a. Images are a constant distance apart.
   b. Images are becoming further and further apart.
   c. Images are becoming closer and closer together.

   In which situation(s) is there acceleration?

B. Using the Chapter Material

B1. The average speed of travel has changed enormously:
   a. The longest foot race was in 1929 from New York to Los Angeles, a distance of 6000 km. The winning time was slightly less than 526 h. What was the average speed?
   b. In 1934 a cross-country train ride from New York to Los Angeles took 57 h. What was the average speed?
   c. Today, jets travel from New York to Los Angeles in 5.5 h. What is their average speed?

B2. You walk 100 m in 50 s. What is your average speed? Why can you not give the average velocity for this situation?

B3. You wish to travel from St. Louis to Chicago (465 km). If you average 80 km/h, how long will the trip take?

B4. Describe the direction of the instantaneous velocity of the skater in Figure 2-B4 for each of the four images. What is the direction of the average velocity from the first to the last image?

B5. Calculate the best estimate of the instantaneous velocity of the ball between points *A* and *B* in Figure 2-3. At what time, relative to the time at which the ball was released, does this instantaneous velocity occur?

B6. In a 100-m dash, a sprinter is timed at 10-m, 50-m, and 100-m distances from the starting block. It takes 2 s to reach the 10-m mark, 6.5 s to reach the 50-m mark, and 14 s to complete the entire 100-m race.
   a. What is the runner's average speed over the entire race?
   b. What is our best estimate of the runner's instantaneous speed at the beginning of the race? At what time, relative to the beginning of the race, does this instantaneous speed occur?
   c. How does this instantaneous speed compare to the average speed?

B7. Calculate the accelerations for the motions described below. Then compare each to the magnitude of the acceleration of gravity, 9.8 (m/s)/s.
   a. A good sprinter can change speed from 0 m/s to 12 m/s in 6 s.
   b. An average automobile can increase its speed from 0 m/s to 30 m/s in 20 s.
   c. At liftoff a rocket will increase its speed from 0 m/s to 56 m/s in 4 s.

B8. A baby slides on a floor and changes speed from 2 m/s to 1 m/s in 5 s. The direction of motion does not change. What is the baby's acceleration?

B9. On a merry-go-round you make five complete revolutions in 250 s. Each revolution covers a circular distance of 100 m.
   a. What is your average speed?
   b. What is your average velocity?
   c. Does acceleration occur? Why or why not?

B10. In Figure 2-9(a) you can see the motion of both the golf ball and the golf club after impact. Compare the velocity of the golf ball to the velocity of the golf club.

C. Extensions to New Situations

C1. When variables like speed, time, and distance are related by an equation, we find it useful to see how one variable changes with another one. We can do this by changing one variable and determining how the others change.

a. A person moves 10 m. What is the average speed if the trip takes each of the following times: 1 s, 2 s, 4 s, 8 s?
b. Moving from one place to another takes 2 s. What is the average speed if the places are separated by: 1 m, 2 m, 4 m, 8 m?
c. You walk at a speed of 1.5 m/s. How far will you travel in: 0.5 s, 2 s, 6 s, 12 s?

Use the results from parts (a), (b), and (c) to answer parts (d), (e), and (f).

d. If the distance traveled stays the same and the average speed doubles, how does the time change? What happens if the average speed triples?
e. If the time stays the same and the average speed doubles, what happens to the distance? What happens if again the time stays the same and the average speed becomes 12 times what it was before?
f. If the average speed stays the same and the time doubles, what happens to the distance? What happens to the distance if the average speed again stays the same and the time becomes five times as great as it was?

C2. You are taking a trip of 400 km and wish to complete the trip in 5 h.

a. What average speed must you maintain?
b. After 2 h you find that you have averaged only 50 km/h. How far do you have left to go?
c. Before calculating, estimate the average speed required for the rest of the trip in order for you to arrive on time. Explain how you made your estimate.
d. What is the distance and time you have yet to travel?
e. Calculate the average speed for the rest of the trip.
f. If your estimate was different from your calculation, can you explain why?

C3. We all know what happens to a ball when it is thrown straight up. It rises to some height, reverses direction, and returns to the earth. During its flight, the only acceleration is that due to gravity.

a. On the way up, how does the ball's velocity change?
b. On the way down, how does the ball's velocity change?
c. Does the acceleration of the ball ever change during the flight?
d. Is there any time during the flight when the ball's velocity is zero? (If you have trouble with this part, throw an object up and watch it carefully.)
e. Use the answers to parts (a) through (d) to describe the changes in velocity and the acceleration of an object going up and coming down.

C4. In which of the situations below do you expect the object's instantaneous speed at some point to be very different from its average speed?

a. A car is moving in heavy traffic.
b. A baseball has been released by the pitcher and is moving toward the batter.
c. A runner is competing in the Boston Marathon.
d. The sun moves across the sky.
e. An airplane takes you from the terminal in Chicago to the terminal in Kansas City.

C5. We can rearrange the definition of acceleration to answer a variety of interesting questions about motion. Algebraically the procedure is the same as that used to rearrange the definition of speed. In each of the situations below, rearrange the definition of acceleration to answer the questions posed.

a. Initially at rest, a ball is dropped from a rooftop. How long will the ball fall before its velocity reaches 39.2 m/s, down? (Since the ball falls freely, its acceleration is the acceleration due to gravity.)
b. What will be the ball's velocity after it has fallen for 10 s?

C6. Speed, velocity and acceleration introduce the use of the ratio as a convenient mathematical tool. Describe why ratios are useful and try to think of other ratios you might have encountered.

C7. An astronaut floating in space has no acceleration. Suppose the astronaut gently releases a screwdriver so that it also has no acceleration.

a. Will the screwdriver have a velocity? If yes, how does the screwdriver's velocity compare to the astronaut's?

b. How far will the screwdriver move from the astronaut's hand?

C8. Objects thrown both upward and outward near the surface of the earth follow the path shown in Figure 2-C8. The path looks more complex than the ones we have studied, partially because motion occurs in two directions. We can analyze this motion by looking at the horizontal and vertical motions separately.

a. Does the object move with constant velocity or accelerate along the horizontal dimension?

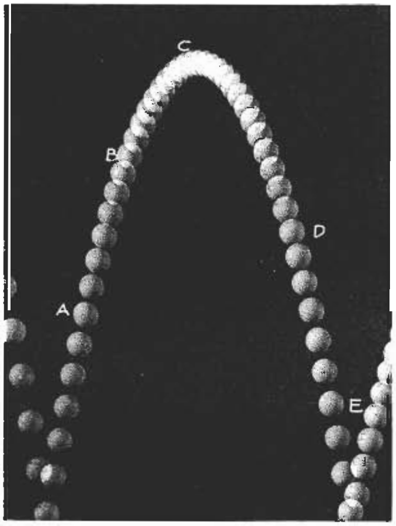
b. Does the object move with constant velocity or accelerate along the vertical dimension?

c. Sketch the horizontal and vertical motions separately. (Draw the horizontal motion as though there were no vertical motion and vice versa.)

d. Show that the path illustrated in Figure 2-C8 is the sum of the two motions sketched in (c).

e. Will the average speed and the average velocity of the object be the same?

f. How would you expect this motion to be different on the surface of the moon? Sketch the motion you would expect to see.



C9. Sprinters often begin a race from a crouched position, while long-distance runners start from a normal standing position. Some research suggests that a crouched position produces a greater acceleration than the standing position. Why would a large acceleration be important to the sprinter but not to the long-distance runner?

C10. Figure 2-1C shows the complete swing of a golfer as he tees off. If you are not a golfer, swing once or twice so you can relate the experience to the photograph.

a. Where does the speed of the golf club increase? Decrease? Remain relatively constant?

b. Where does the velocity of the golf club increase? Decrease? Remain relatively constant?

c. Describe the acceleration of the golf club.

D. Activities

D1. As a scientist investigating Mars you are assigned the task of measuring the speeds of small pebbles that are blown across the ground. The measurements will be made by an unmanned space vehicle, which will land on the Martian surface and send photos back to Earth. What measurements would you need to take and how would you obtain them from the photographs?

D2. The San Andreas fault in California is one of many places where one part of the earth's surface is moving in a direction different from another part. Suppose you are trying to measure the speed with which the land at the edge of the fault is moving. How would you do it? (Include all measurements you would take and how you would use those measurements.)

D3. If you are active in a sport, consult some textbooks to learn about the use of stroboscopic photographs or drawings in describing the motions involved. Describe the use of the concepts introduced in this chapter in analyzing the various techniques used in the sport.

D4. If you are not interested in sports but enjoy photography, you might look at *Moments of Vision* by Harold E. Edgerton and James R. Killian, Jr. (MIT Press, 1979). It reveals a fascinating world!