Motion

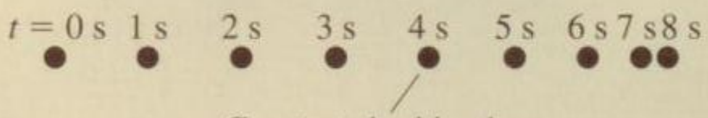
As this skier moves in a graceful arc through the air, the direction of his motion, and the distance between each of his positions and the next, are constantly changing. What language should we use to describe this motion?

Describing Motion

Pictures like the one above or the one at right give us valuable clues about motion.

This picture shows successive images of a frog jumping. The images of the frog are getting farther apart, so the frog must be speeding up.

You will learn to make much simpler pictures to describe the key features of motion.



This diagram tells us everything we need to know about the motion of a car.

Numbers and Units

For a full description of motion, we need to assign numbers to physical quantities such as speed.

This speedometer gives speed in both miles per hour and kilometers per hour. You will learn how to use and convert units and how to describe large and small numbers.

1.1 Motion: A First Look

The concept of motion is a theme that will appear in one form or another throughout this entire book. You have a well-developed intuition about motion, based on your experiences, but you'll see that some of the most important aspects of motion can be rather subtle. We need to develop some tools to help us explain and understand motion, so rather than jumping immediately into a lot of mathematics and calculations, this first chapter focuses on visualizing motion and becoming familiar with the concepts needed to describe a moving object.

One key difference between physics and other sciences is how we set up and solve problems. We'll often use a two-step process to solve motion problems. The first step is to develop a simplified *representation* of the motion so that key elements stand out. For example, the photo of the skier at the start of the chapter allows us to observe his position at many successive times. It is precisely by considering this sort of picture of motion that we will begin our study of this topic. The second step is to analyze the motion with the language of mathematics. The process of putting numbers on nature is often the most challenging aspect of the problems you will solve. In this chapter, we will explore the steps in this process as we introduce the basic concepts of motion.

Motion Diagrams

FIGURE 1.2 Several frames from the video of a car.

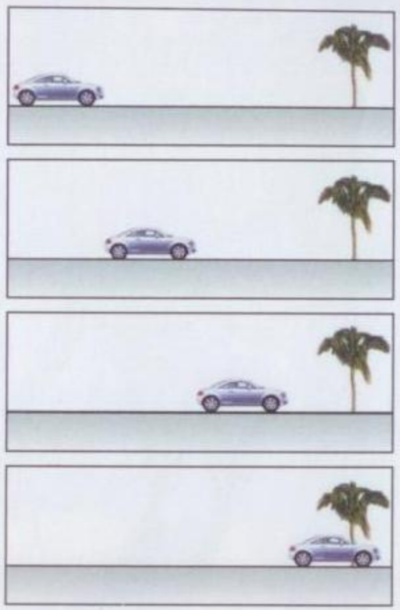
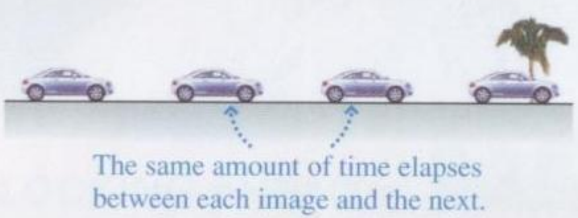


FIGURE 1.3 A motion diagram of the car shows all the frames simultaneously.



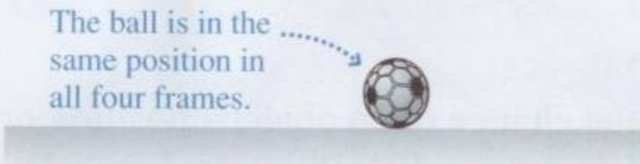
Making a Motion Diagram

An easy way to study motion is to record a video of a moving object with a stationary camera. A video camera takes images at a fixed rate, typically 30 images every second. Each separate image is called a *frame*. As an example, **FIGURE 1.2** shows several frames from a video of a car going past. Not surprisingly, the car is in a different position in each frame.

> **NOTE** ► It's important to keep the camera in a *fixed position* as the object moves by. Don't "pan" it to track the moving object. ◄

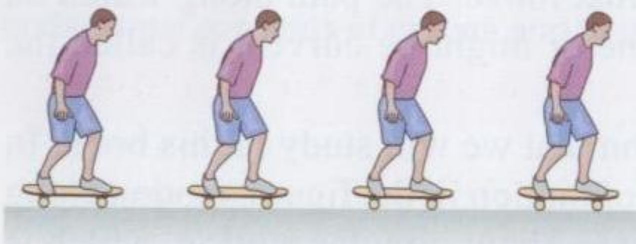
Suppose we now edit the video by layering the frames on top of each other and then look at the final result. We end up with the picture in **FIGURE 1.3**. This composite image, showing an object's positions at several *equally spaced instants of time,* is called a **motion diagram.** As simple as motion diagrams seem, they will turn out to be powerful tools for analyzing motion.

Examples of motion diagrams



An object that occupies only a *single position* in a motion diagram is *at rest.*

A stationary ball on the ground.



Images that are *equally spaced* indicate an object moving with *constant speed.*

A skateboarder rolling down the sidewalk.

An *increasing distance* between the images shows that the object is *speeding up.*

A sprinter starting the 100-meter dash.

A *decreasing distance* between the images shows that the object is *slowing down.*

A car stopping for a red light.

A more complex motion diagram shows changes in speed and direction.

A basketball free throw.

The Particle Model

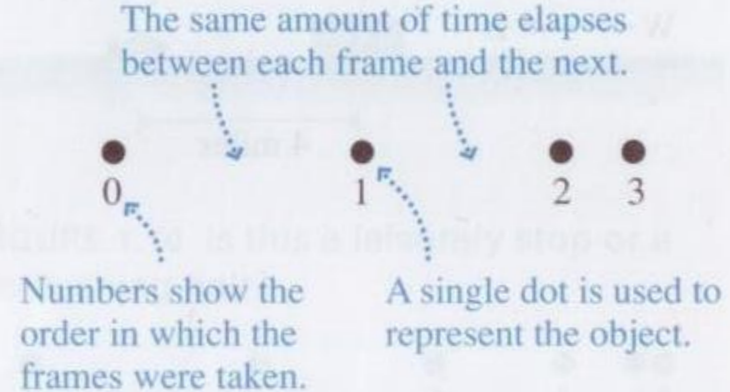
For many objects, the motion of the object *as a whole* is not influenced by the details of the object's size and shape. To describe the object's motion, all we really need to keep track of is the motion of a single point: You could imagine looking at the motion of a dot painted on the side of the object.

In fact, for the purposes of analyzing the motion, we can often consider the object *as if* it were just a single point, without size or shape. We can also treat the object *as if* all of its mass were concentrated into this single point. An object that can be represented as a mass at a single point in space is called a **particle.**

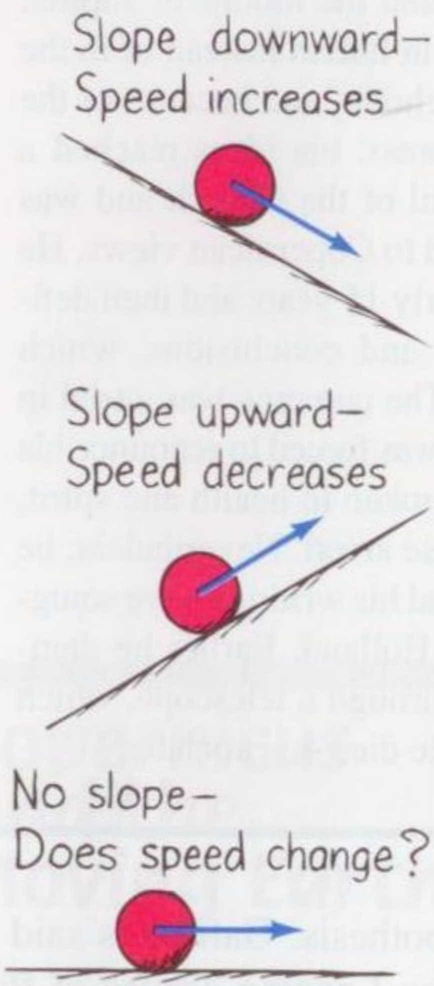
If we treat an object as a particle, we can represent the object in each frame of a motion diagram as a simple dot. FIGURE 1.4 shows how much simpler motion diagrams appear when the object is represented as a particle. Note that the dots have been numbered 0, 1, 2, . . . to tell the sequence in which the frames were exposed. These diagrams still convey a complete understanding of the object's motion.

(a) Motion diagram of a car stopping

(b) Same motion diagram using the particle model



Galileo's Inclined Planes



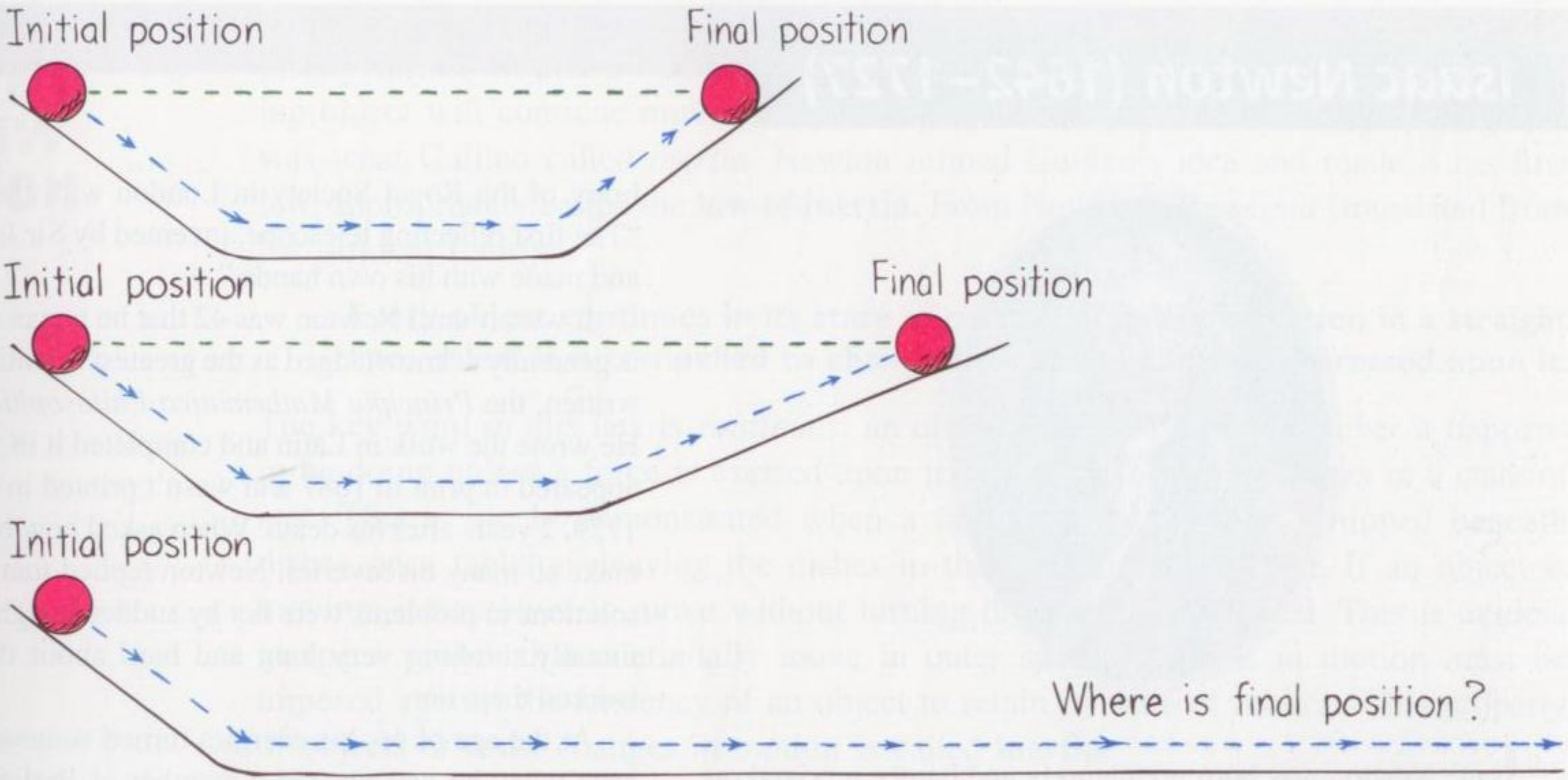
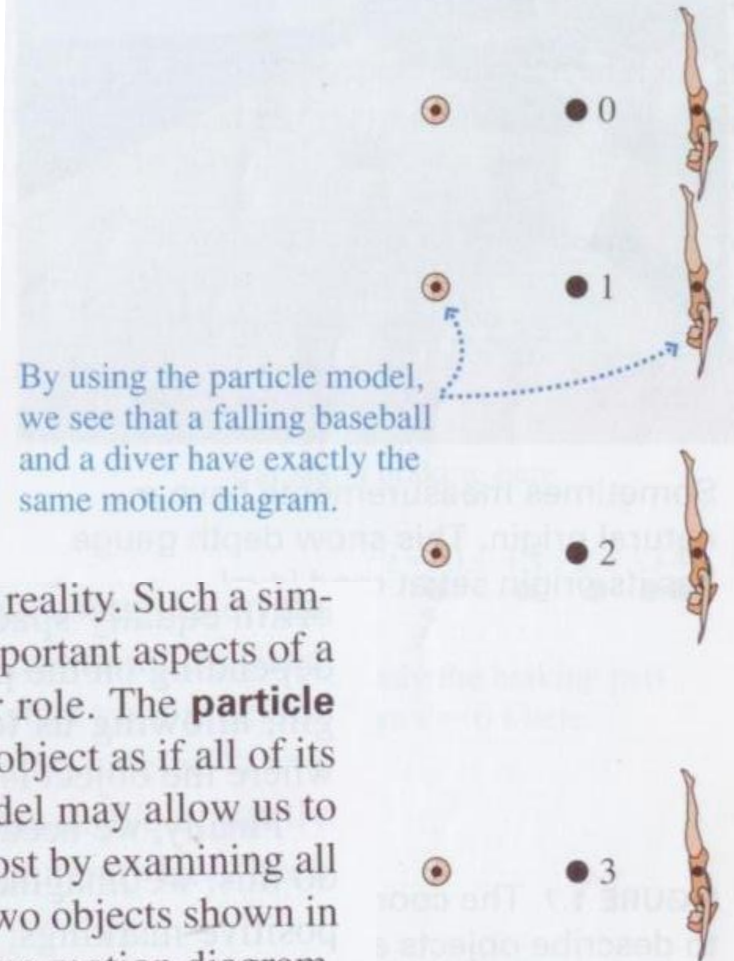


FIGURE 2.3 A ball rolling down an incline on the left tends to roll up to its initial height on the right. The ball must roll a greater distance as the angle of incline on the right is reduced.

Getting up to speed BIO A bird must have a minimum speed to fly. Generally, the larger the bird, the faster the takeoff speed. Small birds can get moving fast enough to fly with a vigorous jump, but larger birds may need a running start. This swan must accelerate for a long distance in order to achieve the high speed it needs to fly, so it makes a frenzied dash across the frozen surface of a pond. Swans require a long, clear stretch of water or land to become airborne. Airplanes require an even faster takeoff speed and thus an even longer runway, as we will see.

Free Fall

FIGURE 1.5 The particle model for two falling objects.



Treating an object as a particle is, of course, a simplification of reality. Such a simplification is called a **model.** Models allow us to focus on the important aspects of a phenomenon by excluding those aspects that play only a minor role. The **particle model** of motion is a simplification in which we treat a moving object as if all of its mass were concentrated at a single point. Using the particle model may allow us to see connections that are very important but that are obscured or lost by examining all the parts of an extended, real object. Consider the motion of the two objects shown in FIGURE 1.5. These two very different objects have exactly the same motion diagram. As we will see, all objects falling under the influence of gravity move in exactly the same manner if no other forces act. The simplification of the particle model has revealed something about the physics that underlies both of these situations.

Not all motions can be reduced to the motion of a single point, as we'll see. But for now, the particle model will be a useful tool in understanding motion.

Galileo easily demolished Aristotle's falling-body hypothesis. Galileo is said to have dropped objects of various weights from the top of the Leaning Tower of Pisa and compared their falls. Contrary to Aristotle's assertion, Galileo found that a stone twice as heavy as another did not fall twice as fast. Except for the small effect of air resistance, he found that objects of various weights, when released at the same time, fell together and hit the ground at the same time. On one occasion, Galileo allegedly attracted a large crowd to witness the dropping of two objects of different weight from the top of the tower. Legend has it that many observers of this demonstration who saw the objects hit the ground together scoffed at the young Galileo and continued to hold fast to their Aristotelian teachings.

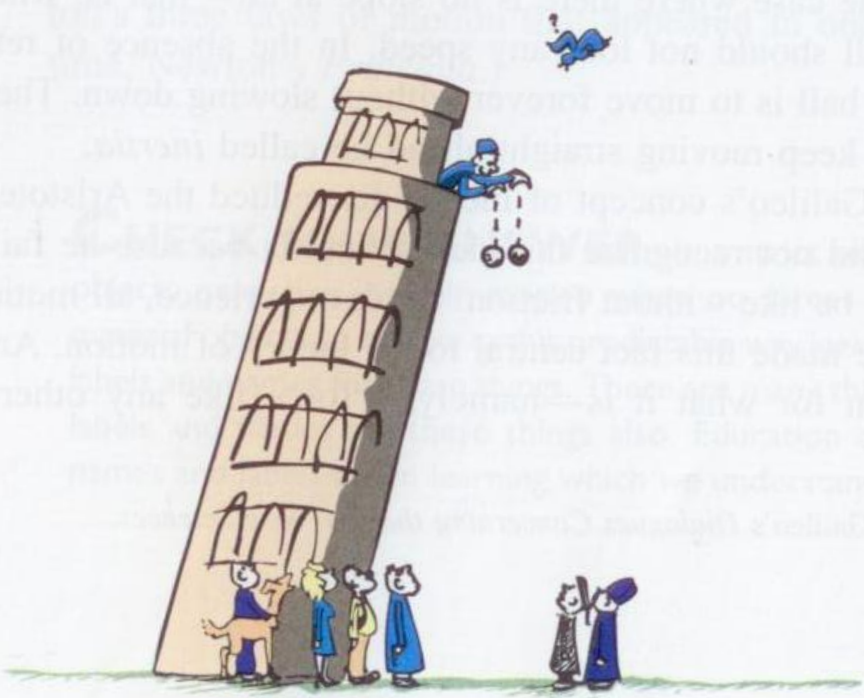
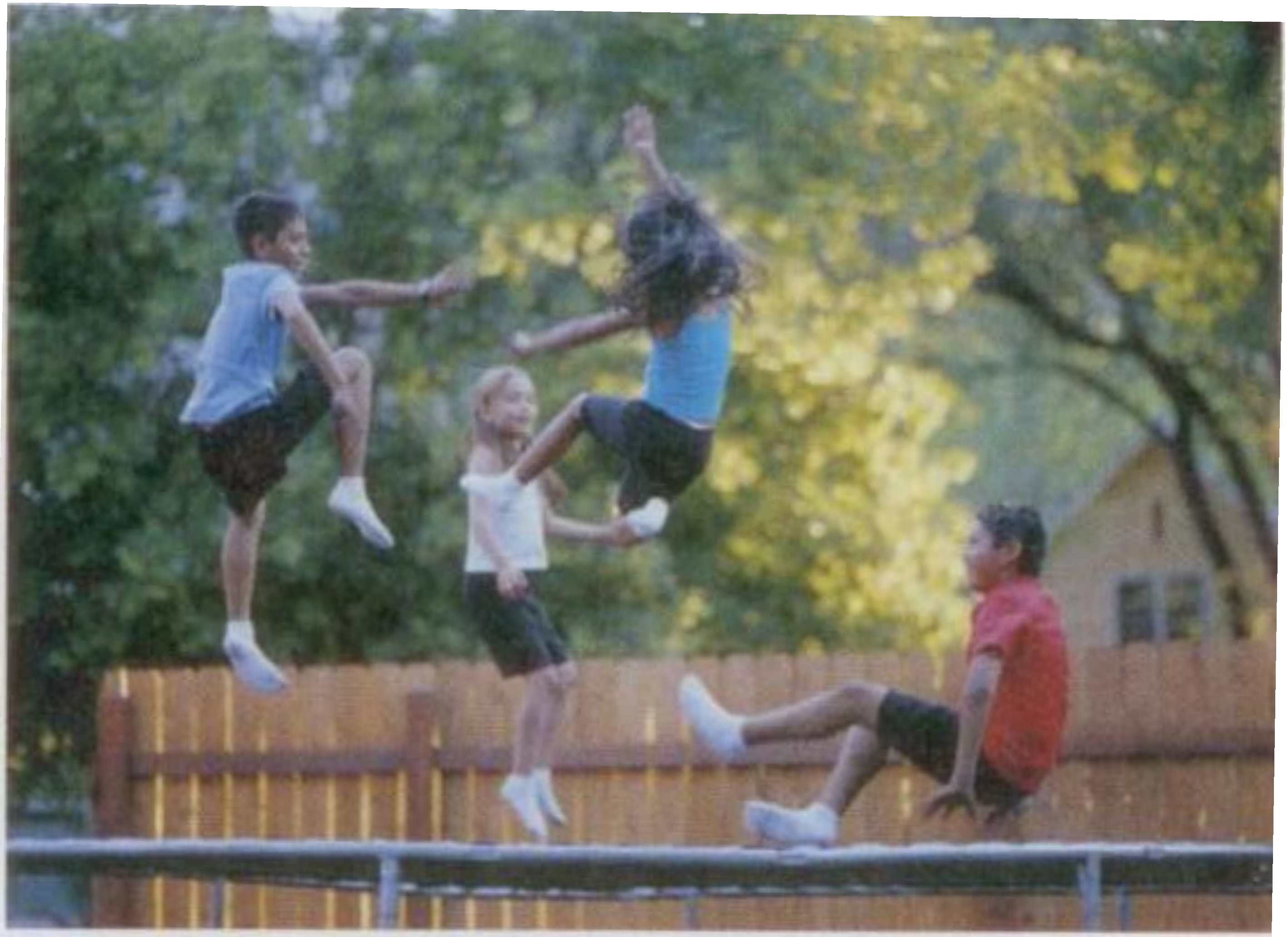


FIGURE 2.1 Galileo's famous demonstration.

"Looks like Mr. Galileo was correct . . ." was the comment made by Apollo 15 astronaut David Scott, who dropped a hammer and a feather on the moon. The objects were dropped from the same height at the same time and hit the ground simultaneously—something that would not happen in the atmosphere of the earth!



Some of the children are moving up and some are moving down, but all are in free fall—and so are accelerating downward at $9.8\ m/s^2$.

Free Fall

NOTE ▶ Despite the name, free fall is not restricted to objects that are literally falling. Any object moving under the influence of gravity only, and no other forces, is in free fall. This includes objects falling straight down, objects that have been tossed or shot straight up, objects in projectile motion (such as a passed football), and, as we will see, satellites in orbit. In this chapter we consider only objects that move up and down along a vertical line; projectile motion will be studied in Chapter 3. ◀

The free-fall acceleration is always in the same direction, and on earth, it always has approximately the same magnitude. Careful measurements show that the value of the free-fall acceleration varies slightly at different places on the earth, but for the calculations in this book we will use the the following average value:

$$\vec{a}_{\text{free fall}} = (9.80 \text{ m/s}^2, \text{ vertically downward}) \tag{2.15}$$

Standard value for the acceleration of an object in free fall