1.3 Acceleration Due to Gravity

acceleration due to gravity ($\vec{g}$) acceleration of an object falling vertically toward Earth's surface

free fall the motion of an object toward Earth with no other force acting on it than gravity

Figure 1
Aristotle (384 B.C.–322 B.C.)

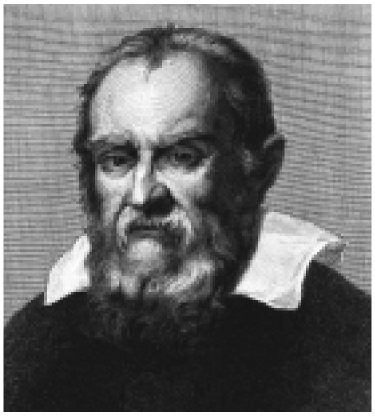

Figure 2
Galileo Galilei (1564–1642)

DID YOU KNOW?

"Quintessence"
Aristotle and his contemporaries from Greece classified all matter on Earth as one of four elements: earth, air, fire, or water. They also believed that objects beyond Earth, such as the stars, were composed of a fifth element which they called quintessence. This word stems from "quinte," meaning fifth, and "essentia," meaning essence.

A diver using a 3-m high board enters the water at a speed of about 28 km/h. From the 10-m high board, on the other hand, the speed is about 50 km/h. The farther an object falls toward Earth's surface, the faster its landing speed becomes, as long as air resistance remains negligible. The acceleration of an object falling vertically toward Earth's surface is called the **acceleration due to gravity**.

Not all objects accelerate at the same rate toward the ground. If you drop a rubber stopper and a flat piece of paper from the same height at the same instant, the stopper lands first. However, if you crumple the paper into a tight ball, the paper and the stopper land at about the same time. If the air resistance is negligible, the acceleration due to gravity at a particular location is constant, and all dropped objects accelerate downward at the same rate. An object falling toward Earth with no other force acting on it than gravity experiences **free fall**.

In ancient times, people thought that heavier objects fell faster than lighter ones. The Greek philosopher Aristotle (**Figure 1**), who was a successful teacher and scientist and the accepted scientific authority of his day, based his belief on the observation that a rock falls more quickly than a leaf or a feather. He even "proved" that heavy objects fell faster than light ones and that a force is necessary for all motion. Physics based on Aristotle's ideas was known as "Aristotelian physics." (After Newton, physics became known as "Newtonian physics.") Aristotle's ideas, including his theory of falling objects, were accepted for nearly 2000 years.

The renowned Italian scientist Galileo Galilei (**Figure 2**) discovered that both heavy and light objects fall toward Earth with the same acceleration if the effect of air resistance is eliminated. Galileo performed numerous experiments and made many scientific discoveries, some of which led to important inventions, such as the pendulum clock and the astronomical telescope. Using the telescope, he was able to view sunspots on the Sun's surface, close-up views of craters on the Moon, the phases of Venus, and some of the larger moons orbiting Jupiter. His observations supported the view that Earth was not at the centre of the solar system (geocentric theory); rather, Earth and the other planets orbited the Sun (heliocentric theory). Church authorities did not accept this theory and Galileo was placed under house arrest for writing about it. Despite the persecution, Galileo continued to write about his scientific discoveries, inventions, and theories until he died, the same year another great scientist, Isaac Newton, was born in England.

Practice

Understanding Concepts

1. Air resistance is not negligible for a skydiver who has jumped out of an airplane and is falling toward the ground; however, if that same person dives from a diving board into a swimming pool, air resistance is negligible. Explain the difference.
2. Explain the disadvantage of using only reasoning rather than experimentation to determine the dependency of one variable on another. Use an example to illustrate your answer.

Applying Inquiry Skills

3. What experimental setup would demonstrate that in the absence of air resistance, a feather and a coin, released simultaneously, fall toward Earth at the same rate.

Making Connections

4. When an astronaut on the Moon dropped a feather and a rock simultaneously from a height of about 2 m, both objects landed at the same instant. Describe the difference between the motion of falling objects on the Moon and falling objects on Earth.

Measuring the Acceleration Due to Gravity

Various methods are used to measure the acceleration due to gravity experimentally. For example, a stroboscope flashing at known time intervals records the position of an object undergoing free fall (**Figure 3**). To determine the displacement of the object after each time interval, we measure the photograph with a ruler. We can arrange the kinematics equation to solve for $\vec{a}$:

$$\Delta\vec{d} = \vec{v}_i\Delta t + \frac{1}{2}\vec{a}(\Delta t)^2$$

If $\vec{v}_i = 0$, then

$$\vec{a} = \frac{2\Delta\vec{d}}{(\Delta t)^2}$$

Whichever method is used to determine the average acceleration of a freely falling object, the result is found to be constant at any specific location. Near Earth's surface, to two significant digits, the acceleration is 9.8 m/s^2 [down]. This value is common and has the symbol $\vec{g}$, the acceleration due to gravity.

Government standards laboratories such as the Bureau International des Poids et Mesures (BIPM) in Paris determine the local $\vec{g}$ with high precision. At BIPM, a special elastic band propels an object upward in a vacuum chamber. Mirrors at the top and bottom of the object reflect laser beams, permitting such an exact measurement of the time of flight that the local magnitude of $\vec{g}$ is calculated to seven significant digits.

The magnitude of the acceleration due to gravity varies slightly depending on location. In general, the greater the distance from Earth's centre, the lower the acceleration due to gravity. The value is slightly lower at the equator than at the North and South Poles (at the same elevation) because Earth bulges outward slightly at the equator. Also, the value is slightly lower at higher altitudes than at lower ones. **Table 1** lists the value of $\vec{g}$ at several locations. Notice that the average value is 9.8 m/s^2 [down] to two significant digits. More details about $\vec{g}$ are presented in Chapters 2 and 3.

Table 1 $\vec{g}$ at Various Locations on Earth

Location	Latitude	Altitude (m)	$\vec{g}$ (m/s^2 [down])
North Pole	90° [N]	0	9.832
Equator	0	0	9.780
Java	6° [S]	7	9.782
Mount Everest	28° [N]	8848	9.765
Denver	40° [N]	1638	9.796
Toronto	44° [N]	162	9.805
London, UK	51° [N]	30	9.823
Washington, D.C.	39° [N]	8	9.801
Brussels	51° [N]	102	9.811

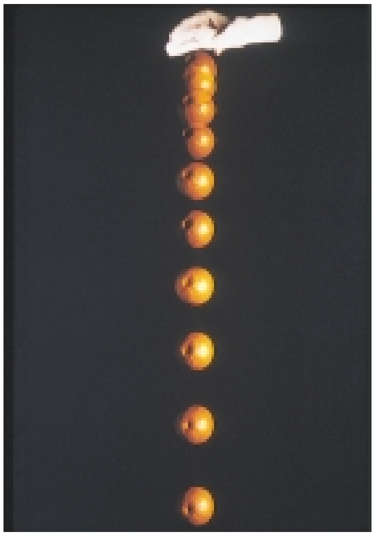

Figure 3
The accelerating object is seen in the photograph each instant that the strobe light flashes on. The time interval Δt between strobe flashes is constant.

DID YOU KNOW?

Precise Measurements
Knowing the acceleration due to gravity to seven or more significant digits is of great interest to certain professionals. Geophysicists and geologists can use the information to determine the structure of Earth's interior and near-surface features, and to help locate areas with high concentrations of mineral and fossil fuel deposits. Military experts are concerned with variations in the acceleration due to gravity in the deployment of such devices as cruise missiles. Space scientists use the data to help calculate the paths of artificial satellites.

Case Study Predicting Earthquake Accelerations

Geologists create models of potential earthquake scenarios to analyze the structure of Earth's surface. One such model is the map of ground accelerations in **Figure 4**. This particular map shows the Pacific Northwest region near the border between Canada and the United States. The map shows sideways ground accelerations that may occur from several earthquakes, each with an estimated recurrence time. The colours indicate potential sideways accelerations as a percentage of *g*. For example, the area in red represents a range of 40% to 60% of *g*, meaning that the ground would accelerate at approximately 5 m/s^2. The accelerations have a 10% chance of being exceeded in 50 years.

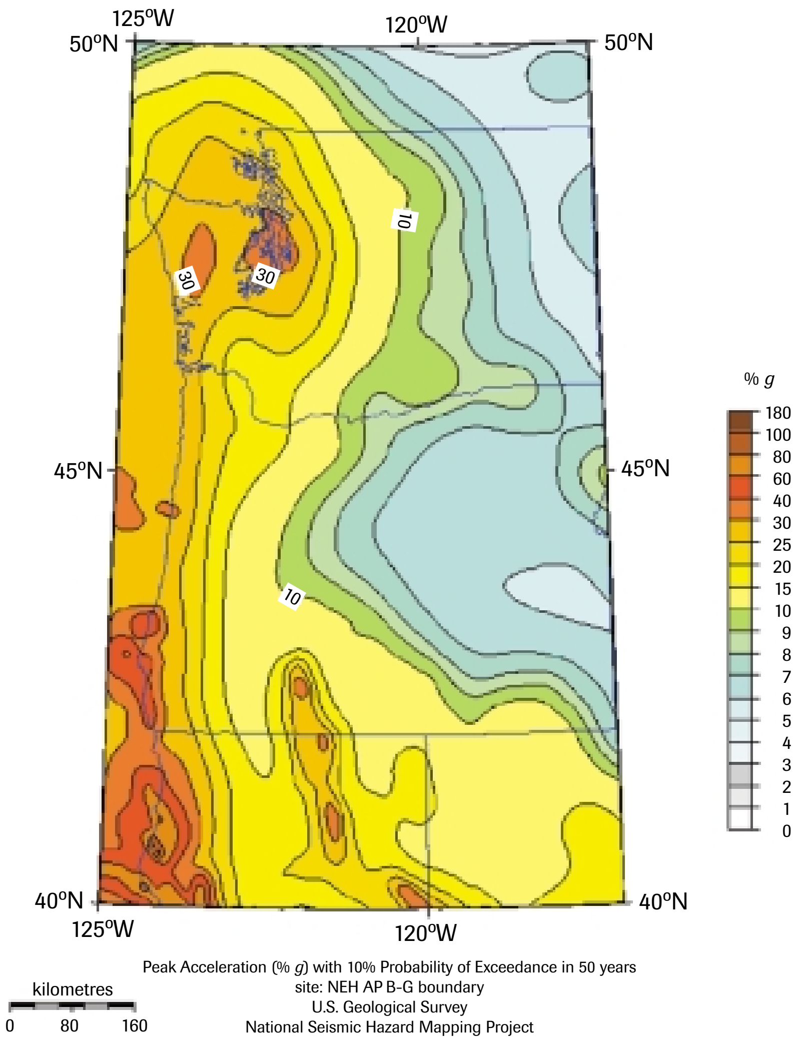

Figure 4
This map of potential ground accelerations from earthquakes covers a large area of the Pacific Northwest. Since latitudes and longitudes are marked, you can find the corresponding locations in an atlas.

(a) Look up the region in a conventional atlas, and write a short scenario for possible earthquakes in the Pacific Northwest, describing which regions are affected severely, moderately, slightly, or not at all.

(b) Explain how you used the acceleration map to construct your scenario.

Practice

Understanding Concepts

5. A diver steps off a 10.0-m high diving board with an initial vertical velocity of zero and experiences an average acceleration of 9.80 m/s^2 [down]. Air resistance is negligible. Determine the diver's velocity in metres per second and in kilometres per hour, after falling (a) 5.00 m and (b) 10.0 m.

Applying Inquiry Skills

6. You drop an eraser from your hand to your desk, a distance that equals your hand span.
   (a) Estimate the time interval this motion takes in milliseconds.
   (b) Measure your hand span and calculate the time interval, using the appropriate constant acceleration equation(s).
   (c) Compare your answers in (a) and (b). Describe ways in which you can improve your estimation skills.
7. **Table 2** gives position-time data for a very light ball dropped vertically from rest.
   (a) Use the final data pair and the appropriate equation for constant acceleration to determine the acceleration.
   (b) Describe how you would find the acceleration with graphing techniques.
   (c) If the value of the acceleration due to gravity in the place where the ball was dropped is 9.81 m/s^2 [down], what is the percentage error of the experimental value?
   (d) Describe reasons why there is a fairly high percentage error in this example.

Making Connections

8. Olympic events have been held at locations with very different altitudes. Should Olympic records for events, such as the shot put, be adjusted for this?

Answers

5. (a) 9.90 m/s [down]; 35.6 km/h [down]
   (b) 14.0 m/s [down]; 50.4 km/h [down]
7. (a) 8.61 m/s^2 [down]
   (c) 12.2%

Table 2 Position-Time Data

t (s)	$\vec{d}$ (m [down])
0	0
0.200	0.172
0.400	0.688
0.600	1.55

Calculations Involving Free Fall

During free fall, the vertical acceleration is constant, so the kinematics equations developed for constant acceleration in Section 1.2 can be applied. However, the equations can be simplified. Since we are considering vertical motion only, the displacement, velocity, and acceleration variables will be treated as components; thus, we will replace the vector quantities $\Delta\vec{d}$, $\vec{v}_i$, $\vec{v}_f$, and $\vec{a}$ with their corresponding components: Δy, v_{iy}, v_{fy}, and a_y. When using equations involving components, it is essential to choose which direction—up or down—is positive and then assign positive or negative signs to the components appropriately.

Table 3 gives the constant acceleration equations for free-fall motion. Compare this table with **Table 4** in Section 1.2.

LEARNING TIP

Choosing the Positive Direction

It is important to use consistent directions with any single motion question. For an object experiencing only downward motion, it is convenient to choose downward as positive. However, if an object is thrown upward or if it bounces upward after falling downward, either upward or downward can be called positive. The important thing is to define your choice for the positive y direction and to use that choice throughout the entire solution.

Table 3 Constant Acceleration Equations for Free-Fall Motion

Variables Involved	General Equation	Variable Eliminated
a_y, v_{fy}, v_{iy}, Δt	$a_y = \dfrac{v_{fy} - v_{iy}}{\Delta t}$	Δy
Δy, v_{iy}, a_y, Δt	$\Delta y = v_{iy}\Delta t + \dfrac{1}{2}a_y(\Delta t)^2$	v_{fy}
Δy, v_{iy}, v_{fy}, Δt	$\Delta y = \dfrac{v_{iy} + v_{fy}}{2}\Delta t$	a_y
Δy, v_{iy}, v_{fy}, a_y	$v_{fy}^2 = v_{iy}^2 + 2a_y\Delta y$	Δt
Δy, v_{fy}, a_y, Δt	$\Delta y = v_{fy}\Delta t - \dfrac{1}{2}a_y(\Delta t)^2$	v_{iy}

LEARNING TIP

Alternative Solutions
There is often more than one way of solving problems involving constant acceleration. A problem usually begins by giving three known quantities. After using one of the five possible equations to solve for one unknown quantity, you now know four quantities. To find the fifth and final quantity, you can choose any of the constant acceleration equations containing the fifth quantity.

LEARNING TIP

Care with Vectors
Some students think that $g = -9.8 \text{ m/s}^2$, which is incorrect. The symbol g represents the magnitude of the vector $\vec{g}$, and the magnitude of a nonzero vector is always positive.

SAMPLE problem 1

A ball is thrown with an initial velocity of 8.3 m/s [up]. Air resistance is negligible.

(a) What maximum height above its starting position will the ball reach?

(b) After what time interval will the ball return to its initial position?

Solution

We will use upward as the $+y$ direction for the entire solution.

(a) We know that $v_{fy} = 0$ m/s because at the maximum height required, the ball stops for an instant before falling downward.

$$a_y = -g = -9.8 \text{ m/s}^2 \qquad v_{fy} = 0 \text{ m/s}$$
$$v_{iy} = +8.3 \text{ m/s} \qquad \Delta y = ?$$

$$v_{fy}^2 = v_{iy}^2 + 2a_y\Delta y$$
$$0 = v_{iy}^2 + 2a_y\Delta y$$
$$\Delta y = \frac{-v_{iy}^2}{2a_y}$$
$$= \frac{-(8.3 \text{ m/s})^2}{2(-9.8 \text{ m/s}^2)}$$
$$\Delta y = +3.5 \text{ m}$$

The maximum height reached by the ball is 3.5 m above its initial position.

(b) One way to solve this problem is to determine the time interval during which the ball rises, then double that value to get the total time. We assume that the time for the ball to fall equals the time for it to rise (a valid assumption if air resistance is neglected).

$$a_y = -g = -9.8 \text{ m/s}^2 \qquad v_{fy} = 0 \text{ m/s}$$
$$v_{iy} = +8.3 \text{ m/s} \qquad \Delta t = ?$$

$$\Delta t = \frac{v_{fy} - v_{iy}}{a_y}$$
$$= \frac{0 - 8.3 \text{ m/s}}{-9.8 \text{ m/s}^2}$$
$$\Delta t = 0.85 \text{ s}$$

total time $= 2 \times 0.85 \text{ s} = 1.7 \text{ s}$

Therefore 1.7 s will elapse before the ball returns to its initial position.

SAMPLE problem 2

An arrow is shot vertically upward beside a building 56 m high. The initial velocity of the arrow is 37 m/s [up]. Air resistance is negligible. At what times does the arrow pass the top of the building on its way up and down?

Solution

We take the ground as the origin and [up] as the $+y$ direction.

$$\Delta y = +56 \text{ m} \qquad v_{iy} = +37 \text{ m/s}$$
$$a_y = -g = -9.8 \text{ m/s}^2 \qquad \Delta t = ?$$

The equation involving these variables is

$$\Delta y = v_{iy}\Delta t + \frac{1}{2}a_y(\Delta t)^2$$

Since both terms on the right-hand side of the equation are not zero, we must apply the quadratic formula to solve for Δt. Thus, we substitute the given quantities into the equation:

$$+56 \text{ m} = 37 \text{ m/s } \Delta t - 4.9 \text{ m/s}^2 (\Delta t)^2$$

$$4.9 \text{ m/s}^2 (\Delta t)^2 - 37 \text{ m/s } \Delta t + 56 \text{ m} = 0$$

Using the quadratic formula:

$$\Delta t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \text{where } a = 4.9 \text{ m/s}^2,\ b = -37 \text{ m/s, and } c = 56 \text{ m}$$

$$= \frac{-(-37 \text{ m/s}) \pm \sqrt{(-37 \text{ m/s})^2 - 4(4.9 \text{ m/s}^2)(56 \text{ m})}}{2(4.9 \text{ m/s}^2)}$$

$$\Delta t = 5.5 \text{ s and } 2.1 \text{ s}$$

There are two positive roots of the equation, which means that the arrow passes the top of the building on the way up (at $t = 2.1$ s) and again on the way down (at $t = 5.5$ s).

Practice

Understanding Concepts

9. You throw a ball vertically upward and catch it at the height from which you released it. Air resistance is negligible.
(a) Compare the time the ball takes to rise with the time the ball takes to fall.
(b) Compare the initial and final velocities.
(c) What is the instantaneous velocity at the top of the flight?
(d) What is the ball's acceleration as it is rising? at the top of the flight? as it is falling?
(e) Sketch the position-time graph, the velocity-time graph, and the acceleration-time graph for the ball's motion during its flight. Use [up] as the positive direction.

10. Write all the equations that could be used to solve for the time interval in Sample Problem 1(b). Choose a different equation and solve for Δt.

11. Determine the speed at impact in the following situations. Air resistance is negligible.
(a) A seagull drops a shellfish onto a rocky shore from a height of 12.5 m to crack the shell.
(b) A steel ball is dropped from the Leaning Tower of Pisa, landing 3.37 s later.

12. A steel ball is thrown from the ledge of a tower so that it has an initial velocity of magnitude 15.0 m/s. The ledge is 15.0 m above the ground. Air resistance is negligible.
(a) What are the total flight time and the speed of impact at the ground if the initial velocity is upward?
(b) What are these two quantities if the initial velocity is downward?
(c) Based on your answers to (a) and (b), write a concluding statement.

13. Show that a free-falling ball dropped vertically from rest travels three times as far from $t = 1.0$ s to $t = 2.0$ s as from $t = 0.0$ s to $t = 1.0$ s.

14. A baseball pitcher throws a ball vertically upward and catches it at the same level 4.2 s later.
(a) With what velocity did the pitcher throw the ball?
(b) How high does the ball rise?

LEARNING TIP

The Quadratic Formula

The quadratic formula is useful for finding the roots of a quadratic equation, that is, an equation involving a squared quantity, such as Δt^2. In the constant acceleration examples, if the equation is written in the form $a(\Delta t)^2 + b(\Delta t) + c = 0$, where $a \neq 0$, its roots are

$$\Delta t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

A negative root may be physically meaningful depending on the details of the problem.

Answers

11. (a) 15.6 m/s
 (b) 33.0 m/s

12. (a) 3.86 s; 22.8 m/s
 (b) 0.794 s; 22.8 m/s

14. (a) 21 m/s [up]
 (b) 22 m

Answers

15. (a) 63 m
    (b) 35 m/s [down]
16. (a) 1.6 m/s^2 [down]
    (b) 6.1 : 1
17. (a) 9.20 m/s^2 [down]; 9.70 m/s^2 [down]
    (b) 5.3%

15. A hot-air balloon is moving with a velocity of 2.1 m/s [up] when the balloonist drops a ballast (a large mass used for height control) over the edge. The ballast hits the ground 3.8 s later.
(a) How high was the balloon when the ballast was released?
(b) What was the velocity of the ballast at impact?

16. An astronaut drops a camera from rest while exiting a spacecraft on the Moon. The camera drops 2.3 m [down] in 1.7 s.
(a) Calculate the acceleration due to gravity on the Moon.
(b) Determine the ratio of $|\vec{g}_{Earth}|$ to $|\vec{g}_{Moon}|$.

Applying Inquiry Skills

17. A 60.0-Hz ticker-tape timer and a photogate timer are used by two different groups in the lab to determine the acceleration due to gravity of a falling metal mass. The results of the experiments are shown in **Table 4**.
(a) Use the data to determine the acceleration of the metal mass in each trial.
(b) Calculate the percent difference between the two accelerations.
(c) Which results are likely attributable to the ticker-tape timer? Explain why you think so.

Table 4 Data for Question 17

t (s)	$\vec{d}$ (cm [↓])	$\vec{d}$ (cm [↓])
0	0	0
0.10	4.60	4.85
0.20	18.4	19.4
0.30	41.4	43.6
0.40	73.6	77.6

Making Connections

18. How would your daily life be affected if the acceleration due to gravity were to increase to twice its present value? Name a few drawbacks and a few advantages.

Terminal Speed

The skydiver who exits a flying aircraft (**Figure 5**) experiences free fall for a short time. However, as the diver's speed increases, so does the air resistance. (You know from the experience of putting your hand out the window of a moving vehicle that air resistance becomes high at high speeds.) Eventually this resistance becomes so great that it prevents any further acceleration. At this stage, the acceleration is zero and the diver has reached a constant **terminal speed**, as depicted in the graph in **Figure 6**.

Figure 5
A skydiver's downward acceleration decreases as the downward velocity increases because of increasing air resistance.

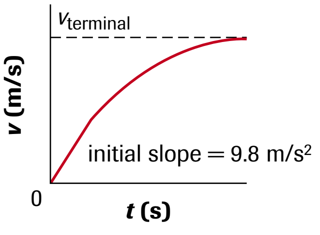

Figure 6
The general shape of a speed-time graph for a falling object that reaches terminal speed

terminal speed maximum speed of a falling object at which point the speed remains constant and there is no further acceleration

The terminal speeds for various objects falling in air are listed in **Table 5**. An object with a fairly large mass, such as a human, has a high terminal speed. The terminal speed is reduced greatly if the surface area increases, as when a skydiver opens a parachute.

Terminal speeds are also important in fluids other than air. Investigation 1.3.1, in the Lab Activities section at the end of this chapter, looks at the dependence of terminal speed on the mass of an object.

Table 5 Approximate Terminal Speeds of Objects Falling in Air

Object	Terminal speed	
	(m/s)	(km/h)
human	53	190
human with open parachute	5 to 10	18 to 36
dandelion seed	0.5	1.8
typical dust particle	0.02	0.07

Practice

Understanding Concepts

19. What factors affect an object's terminal speed? How does each factor affect the terminal speed?

20. Does the concept of terminal speed apply on the Moon? Why or why not?

21. Sketch a graph of the vertical speed as a function of time for a skydiver who jumps from an aircraft, reaches terminal speed, opens the parachute, and reaches a new terminal speed.

Applying Inquiry Skills

22. Relief organizations use airplanes to drop packages of supplies in areas inaccessible by surface transport. A package that hits the ground at a high speed may be damaged.
(a) Describe several factors to consider in the design of a package to maximize the chances of a safe landing.
(b) Describe how you would test your package design.

Making Connections

23. There are many well-documented cases of people falling from tremendous heights without parachutes and surviving. The record is held by a Russian who fell from an astounding 7500 m. The chances of survival depend on the "deceleration distance" at the time of landing. Why is a fall from a height of 7500 m no more dangerous than one from half that height? How can the deceleration distance upon landing be maximized?

SUMMARY Acceleration Due to Gravity

- Free fall is the motion of an object falling toward the surface of Earth with no other force acting on it than gravity.
- The average acceleration due to gravity at Earth's surface is $\vec{g} = 9.8\ \text{m/s}^2$ [down].
- The acceleration due to gravity depends on latitude, altitude, and local effects, such as the distribution of mineral deposits.
- The constant acceleration equations can be applied to analyze motion in the vertical plane.
- Terminal speed is the maximum speed reached by an object falling in air or other fluids. When a falling object reaches terminal speed, its downward acceleration becomes zero and its velocity becomes constant.

INVESTIGATION 1.3.1

Comparing Terminal Speeds **(p. 58)**

Flat-bottom coffee filters fall in a fairly straight line when dropped vertically. These filters can be used to study the relation between the mass of an object and its terminal speed. Predict how you think the terminal speed of a stack of flat coffee filters depends on its mass—in other words, on the number of filters in the stack.

DID YOU KNOW?

Climate Changes

Dust and smoke particles in the atmosphere can cause climate changes. This 1980 eruption of Mount St. Helens expelled particles of ash high into the atmosphere. Because of their low terminal speed, such particles can remain suspended for months, or even years. These particles can be carried by the prevailing winds all around the world, reducing the amount of solar radiation reaching the ground. The decline in incoming radiation triggers climate changes, including a decline in average temperatures. A similar effect could be caused by smoke and ashes from huge fires, such as major forest fires or fires that would follow nuclear attacks.

Section 1.3 Questions

Understanding Concepts

1. Describe several different conditions under which air resistance is negligible for a falling object.
2. Compare and contrast Aristotle's and Galileo's notions of falling objects.
3. Determine the landing speed in both metres per second and kilometres per hour for the following situations. Neglect air resistance and assume the object starts from rest.
   (a) Divers entertain tourists in Acapulco, Mexico, by diving from a cliff 36 m above the water.
   (b) A stone falls from a bridge, landing in the water 3.2 s later.
4. Two high jumpers, one in Java, the other in London, UK, each have an initial velocity of 5.112 m/s [up]. Use the data in **Table 1** to calculate, to four significant digits, the heights each jumper attains.
5. During the first minute of blastoff, a space shuttle has an average acceleration of 5*g* (i.e., five times the magnitude of the acceleration due to gravity on the surface of Earth). Calculate the shuttle's speed in metres per second and kilometres per hour after 1.0 min. (These values are approximate.)
6. A person throws a golf ball vertically upward. The ball returns to the same level after 2.6 s.
   (a) How long did the ball rise?
   (b) Determine the initial velocity of the ball.
   (c) How long would the ball remain in flight on Mars, where $\vec{g}$ is 3.7 m/s^2 [down], if it were given the same initial velocity?
7. In a laboratory experiment, a computer determines that the time for a falling steel ball to travel the final 0.80 m before hitting the floor is 0.087 s. With what velocity does the ball hit the floor?
8. A stone is thrown vertically with a velocity of 14 m/s [down] from a bridge.
   (a) How long will the stone take to reach the water 21 m below?
   (b) Explain the meaning of both roots of the quadratic equation used to solve this problem.
9. A tennis ball and a steel ball are dropped from a high ledge. The tennis ball encounters significant air resistance and eventually reaches terminal speed. The steel ball essentially undergoes free fall.
   (a) Draw a velocity-time graph comparing the motions of the two balls. Take the downward direction to be positive.
   (b) Repeat (a) with the upward direction positive.
10. A flowerpot is dropped from the balcony of an apartment, 28.5 m above the ground. At a time of 1.00 s after the pot is dropped, a ball is thrown vertically downward from the balcony one storey below, 26.0 m above the ground. The initial velocity of the ball is 12.0 m/s [down]. Does the ball pass the flowerpot before striking the ground? If so, how far above the ground are the two objects when the ball passes the flowerpot?
11. Based on your estimates, rank the following objects in order of highest to lowest terminal speed in air: a ping-pong ball, a basketball, a skydiver in a headfirst plunge, a skydiver in a spread-eagle plunge, and a grain of pollen.

Applying Inquiry Skills

12. State the number of significant digits, indicate the possible error, and calculate the percent possible error for each of the following measurements:
   (a) 9.809 060 m/s^2
   (b) 9.8 m/s^2
   (c) 9.80 m/s^2
   (d) 9.801 m/s^2
   (e) 9.8×10^{-6} m/s^2
13. (a) How could you use a metre stick, together with one or more of the constant acceleration equations, to determine your lab partner's reaction time? Illustrate your method with an example, including a calculation with plausible numerical values.
   (b) How would talking on a cell phone affect the results of the reaction time?

Making Connections

14. In a group, share responsibility for researching the life and contributions of Aristotle or Galileo. Share your results with other groups in your class.
15. There are two different processes of logical thinking. One is called *deductive reasoning*, the other *inductive reasoning*. Use a resource, such as a dictionary or an encyclopedia, to find out more about these types of reasoning.
   (a) Which process did Aristotle and other ancient scientists use?
   (b) Which process did Galileo use?
   (c) Describe other facts you discover about these forms of reasoning.
16. Dr. Luis Alvarez has suggested that the extinction of the dinosaurs and numerous other species 65 million years ago was caused by severe temperature drops following the insertion of dust into the atmosphere. The enormous quantities of dust resulted from an asteroid impact in the Yucatán area of what is now Mexico. Research this topic and write a brief report on what you discover.

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