4

CHAPTER 4

Gravity, Projectiles, and Satellites

4.1 The Universal Law of Gravity
LEARNING OBJECTIVE: Define and describe Newton's law of universal gravitation.

4.2 Gravity and Distance: The Inverse-Square Law
LEARNING OBJECTIVE: Describe the rule by which gravity diminishes with distance.

4.3 Weight and Weightlessness
LEARNING OBJECTIVE: Describe how weight is a support force.

4.4 Universal Gravitation
LEARNING OBJECTIVE: Connect and extend the law of gravity to areas beyond science.

4.5 Projectile Motion
LEARNING OBJECTIVE: Apply the independence of horizontal and vertical motion to projectiles.

4.6 Fast-Moving Projectiles—Satellites
LEARNING OBJECTIVE: Relate a projectile trajectory that matches Earth's curvature to satellite motion.

4.7 Circular Satellite Orbits
LEARNING OBJECTIVE: Describe why speed remains constant for a satellite in circular orbit.

4.8 Elliptical Orbits
LEARNING OBJECTIVE: Describe why the speed of a satellite changes in an elliptical orbit.

4.9 Escape Speed
LEARNING OBJECTIVE: Describe how a projectile can escape Earth's influence.

THE TIME exposure shows the trajectory of a Falcon 9 rocket on the way to the International Space Station. Can you see where the second stage was fired? When the trajectory matches Earth's curvature, orbit is attained. Satellite motion was understood by Isaac Newton, who developed the law of gravity in the 17th century. This force of gravity was the same force that pulls an apple off a tree. Newton's stroke of intuition, that the force between Earth and an apple is the same as the force that acts between moons and planets and everything else in our universe, was a revolutionary break with the prevailing notion that there were two sets of natural laws: one for earthly events and an altogether different set for motion in the heavens. This union of terrestrial laws and cosmic laws is called the *Newtonian synthesis*.

4.1 The Universal Law of Gravity

SCREENCAST: Gravity

EXPLAIN THIS What exactly did Newton discover about gravity?

According to popular legend, Newton was sitting under an apple tree when the idea struck him that gravity extends beyond Earth. Perhaps he looked up through tree branches toward the origin of the falling apple and noticed the Moon. Perhaps the apple hit him on the head, as popular stories tell us. In any event, Newton had the insight to see that the force between Earth and a falling apple is the same force that pulls the Moon in an orbital path around Earth, a path similar to a planet's path around the Sun.

To test this hypothesis, Newton compared the fall of an apple with the "fall" of the Moon. He realized that the Moon falls in the sense that *it falls away from the straight line it would follow if there were no forces acting on it.* Because of its tangential velocity, it "falls around" the round Earth (as we shall investigate later in this chapter). By simple geometry, the Moon's distance of fall per second could be compared with the distance that an apple or anything that far away would fall in one second. Newton's calculations didn't check. Disappointed, but recognizing that brute fact must always win over a beautiful hypothesis, he placed his papers in a drawer, where they remained for nearly 20 years. During this period, he founded and developed the field of geometric optics, for which he first became famous.

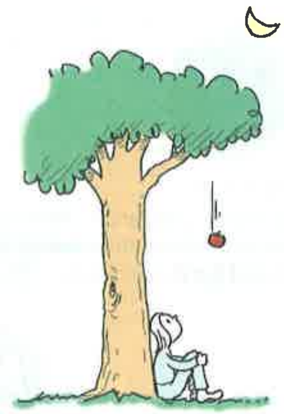

FIGURE 4.1
Could the gravitational pull on the apple reach to the Moon?

Newton's interest in mechanics was rekindled with the advent of a spectacular comet in 1680 and another two years later. He returned to the Moon problem at the prodding of his astronomer friend, Edmund Halley, for whom the second comet was later named. Newton made corrections in the experimental data used in his earlier method and obtained excellent results. Only then did he publish what is one of the most far-reaching generalizations of the human mind: the **law of universal gravitation.***

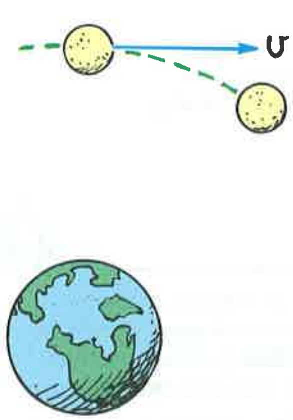

FIGURE 4.2
The tangential velocity of the Moon about Earth allows it to fall around Earth rather than directly into it. If this tangential velocity were reduced to zero, what would be the fate of the Moon?

Everything pulls on everything else in a beautifully simple way that involves only mass and distance. According to Newton, any body attracts any other body with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance separating them.

This statement can be expressed as

$$\text{Force} \sim \frac{\text{mass}_1 \times \text{mass}_2}{\text{distance}^2}$$

or symbolically as

$$F \sim \frac{m_1 m_2}{d^2}$$

where m_1 and m_2 are the masses of the bodies and d is the distance between their centers. Thus, the greater the masses m_1 and m_2, the greater the force of attraction between them, in direct proportion to the masses.** The greater the distance of separation d, the weaker the force of attraction, in inverse proportion to the square of the distance between their centers of mass.

The tangential velocity of a planet or moon moving in a circle is at right angles to the force of gravity.

* This is a dramatic example of the painstaking effort and cross-checking that go into the formulation of a scientific theory. Contrast Newton's approach with the failure to "do one's homework," the hasty judgments, and the absence of cross-checking that so often characterize the pronouncements of people advocating less-than-scientific theories.

** Note the different role of mass here. Thus far, we have treated mass as a measure of inertia, which is called *inertial mass*. Now we see mass as a property that affects gravitational force, which in this context is called *gravitational mass*. It is experimentally established that the two are equal, and, as a matter of principle, the equivalence of inertial and gravitational mass is the foundation of Einstein's general theory of relativity.

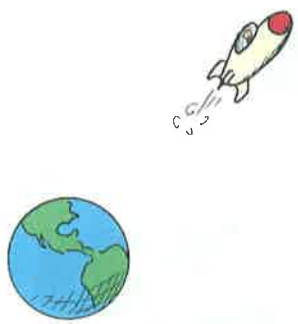

FIGURE 4.3
As the rocket gets farther from Earth, gravitational strength between the rocket and Earth decreases.

Just as sheet music guides a musician playing music, equations guide a physical science student to understand how concepts are connected.

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Just as π relates circumference and diameter for circles, G relates gravitational force with mass and distance.

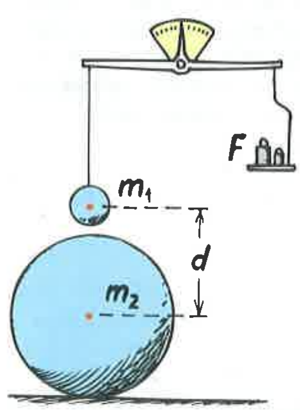

FIGURE 4.4
Von Jolly's method of measuring G. Balls of mass m_1 and m_2 attract each other with a force F equal to the weights needed to restore balance.

CHECKPOINT

1. **In Figure 4.2, we see that the Moon falls around Earth rather than straight into it. If the Moon's tangential velocity were zero, how would it move?**
2. **According to the equation for gravitational force, what happens to the force between two bodies if the mass of one of the bodies is doubled? If both masses are doubled?**
3. **Gravitational force acts on all bodies in proportion to their masses. Why, then, doesn't a heavy body fall faster than a light body?**

Were these your answers?

1. If the Moon's tangential velocity were zero, it would fall straight down and crash into Earth!
2. When one mass is doubled, the force between it and the other one doubles. If both masses double, the force is four times as much.
3. The answer goes back to Chapter 2. Recall Figure 2.9, in which heavy and light bricks fall with the same acceleration because both have the same ratio of weight to mass. Newton's second law ($a = F/m$) reminds us that greater force acting on greater mass does not result in greater acceleration.

The Universal Gravitational Constant, G

The proportionality form of the universal law of gravitation can be expressed as an exact equation when the constant of proportionality G is introduced. G is called the *universal gravitational constant.* Then the equation is

$$F = G\frac{m_1 m_2}{d^2}$$

In words,,the force of gravity between two objects is found by multiplying their masses, dividing by the square of the distance between their centers, and then multiplying this result by the constant G. The magnitude of G is identical to the magnitude of the force between a pair of 1-kg masses that are 1 m apart: 0.0000000000667 N. This small magnitude indicates an extremely weak force. In standard units and in scientific notation:*

$$G = 6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$$

Interestingly, Newton could calculate the product of G and Earth's mass, but not either one alone. Calculating G alone was first done by the English physicist Henry Cavendish in the 18th century, a century after Newton's time.

Cavendish found G by measuring the tiny force between lead masses with an extremely sensitive torsion balance. A simpler method was later developed by Philipp von Jolly, who attached a spherical flask of mercury to one arm of a sensitive balance (Figure 4.4). After the balance was put in equilibrium, a 6-ton lead sphere was rolled beneath the mercury flask. The gravitational force between the two masses was measured by the weight needed on the opposite

* The numerical value of G depends entirely on the units of measurement we choose for mass, distance, and time. The international system of choice uses the following units: for mass, the kilogram; for distance, the meter; and for time, the second. Scientific notation is discussed in the Lab Manual for this text.

end of the balance to restore equilibrium. All the quantities—m_1, m_2, F, and d—were known, from which the constant G was calculated:

$$G = \frac{F}{\left(\frac{m_1 m_2}{d^2}\right)} = 6.67 \times 10^{-11}\ \text{N/kg}^2/\text{m}^2 = 6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2$$

You can never change only one thing! Every equation reminds us of this—you can't change a term on one side without affecting the other side.

The force of gravity is the weakest of the four known fundamental forces. (The other three are the electromagnetic force and two kinds of nuclear forces.) We sense gravitation only when masses like that of Earth are involved. If you stand on a large ship, the force of attraction between you and the ship is too weak for ordinary measurement. The force of attraction between you and Earth, however, can be measured. It is your weight.

VIDEO: Von Jolly's Method of Measuring the Attraction Between Two Masses

Your weight depends not only on your mass but also on your distance from the center of Earth. At the top of a mountain, your mass is the same as it is anywhere else, but your weight is slightly less than it is at sea level. That's because your distance from Earth's center is greater.

Once the value of G was known, the mass of Earth was easily calculated. The force that Earth exerts on a mass of 1 kg at its surface is 9.8 N. The distance between the 1-kg mass and the center of Earth is Earth's radius, 6.4×10^6 m. Therefore, from $F = G(m_1 m_2/d^2)$, where m_1 is the mass of Earth,

$$9.8\ \text{N} = 6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2 \frac{1\ \text{kg} \times m_1}{(6.4 \times 10^6\ \text{m})^2}$$

from which the mass of Earth is calculated to be $m_1 = 6 \times 10^{24}$ kg.

In the 18th century, when G was first measured, people all over the world were excited about it. Newspapers everywhere announced the discovery as one that measured the mass of the planet Earth. How exciting that Newton's formula gives the mass of the entire planet, with all its oceans, mountains, and inner parts yet to be discovered. G and the mass of Earth were measured when a great portion of Earth's surface was still undiscovered.

4.2 Gravity and Distance: The Inverse-Square Law

EXPLAIN THIS How much smaller does your hand look when it is twice as far from your eye?

VIDEO: Inverse-Square Law

We can better understand how gravity is diluted with distance by considering how paint from a paint gun spreads with increasing distance (Figure 4.5, next page). Suppose we position a paint gun at the center of a sphere with a radius of 1 m, and a burst of paint spray travels 1 m to produce a square patch of paint that is 1 mm thick. How thick would the patch be if the experiment were done in a sphere with twice the radius? If the same amount of paint travels in straight lines for 2 m, it spreads to a patch twice as tall and twice as wide. The paint is then spread over an area four times as big, and its thickness would be only $\frac{1}{4}$ mm.

Can you see from Figure 4.5 that for a sphere of radius 3 m, the thickness of the paint patch would be only $\frac{1}{9}$ mm? Can you see that the thickness of the paint decreases as the square of the distance increases? This is known as the **inverse-square law.** The inverse-square law holds for gravity and for all phenomena in which the effect from a localized source spreads uniformly throughout the

Saying that F is inversely proportional to the *square* of d means, for example, that if d gets bigger by a factor of 3, F gets *smaller* by a factor of 9.

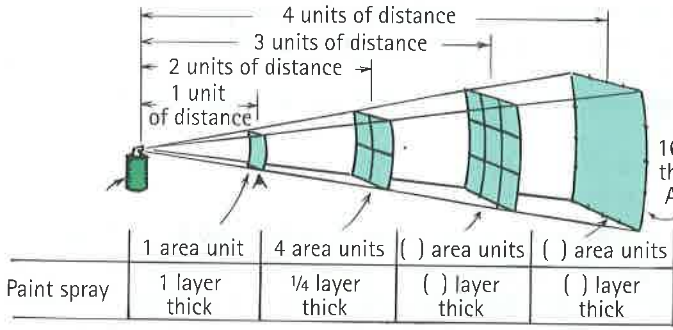

FIGURE 4.5
The inverse-square law. Paint spray travels radially away from the nozzle of the can in straight lines. Like gravity, the "strength" of the spray obeys the inverse-square law.

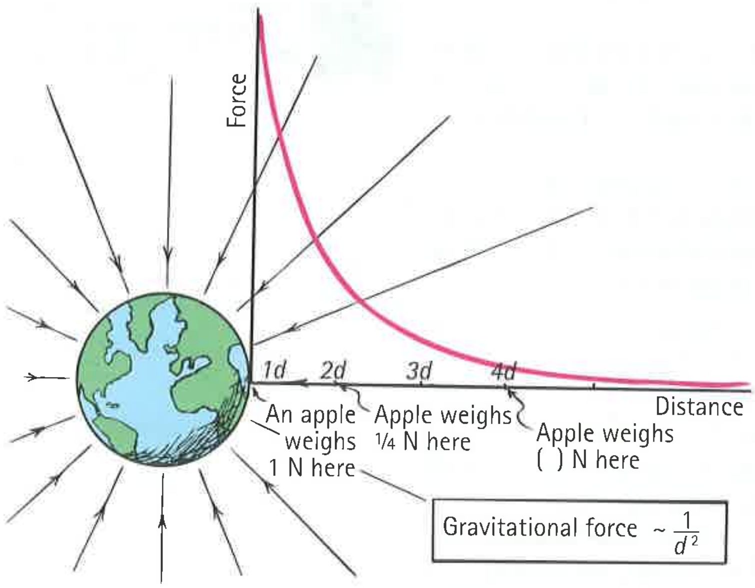

FIGURE 4.6
INTERACTIVE FIGURE MP
The weight of an apple depends on its distance from Earth's center.

surrounding space: the electric field about an isolated electron, light from a match, radiation from a piece of uranium, and sound from a cricket.

Newton's law of gravity as written applies to particles and spherical bodies, as well as to nonspherical bodies sufficiently far apart. The distance term d in Newton's equation is the distance between the centers of masses of the objects. Note in Figure 4.6 that the apple that normally weighs 1 N at Earth's surface weighs only $\frac{1}{4}$ as much when it is twice the distance from Earth's center. The greater an object's distance from Earth's center, the less the object weighs. A child who weighs 300 N at sea level weighs only 299 N atop Mt. Everest. For greater distances, force is less. For very great distances, Earth's gravitational force approaches zero. The force *approaches* zero, but it never gets there. Even if you were transported to the far reaches of the universe, the gravitational influence of home would still be with you. It may be overwhelmed by the gravitational influences of nearer and/or more massive bodies, but it is there. The gravitational influence of every material object, however small or however far, is exerted through all of space.

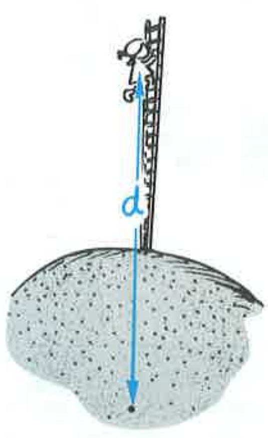

FIGURE 4.7
The person's weight (not her mass) decreases as she increases her distance from Earth's center.

CHECKPOINT

1. **By how much does the gravitational force between two objects decrease when the distance between their centers is doubled? Tripled? Increased tenfold?**
2. **Consider an apple at the top of a tree that is pulled by Earth's gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity be only $\frac{1}{4}$ as strong? Defend your answer.**

Were these your answers?

1. It decreases to one-fourth, one-ninth, and one-hundredth the original value.
2. No, because an apple at the top of the twice-as-tall apple tree is not twice as far from Earth's center. The taller tree would need a height equal to the radius of Earth (6370 km) for the apple's weight at its top to reduce to $\frac{1}{4}$ N. Before its weight decreases by 1%, an apple or any object must be raised 32 km—nearly four times the height of Mt. Everest. So, as a practical matter, we disregard the effects of everyday changes in elevation.

4.3 Weight and Weightlessness

SCREENCAST: Weight/Weightlessness

EXPLAIN THIS How does your weight change when you're inside an accelerating elevator?

When you step on a bathroom scale, you effectively compress a spring inside. When the pointer stops, the elastic force of the deformed spring balances the gravitational attraction between you and Earth—nothing moves, because you and the scale are in static equilibrium. The pointer is calibrated to show your **weight.** If you stand on a bathroom scale in a moving elevator, you'll find variations in your weight. If the elevator accelerates upward, the springs inside the bathroom scale are more compressed and your weight reading is greater. If the elevator accelerates downward, the springs inside the scale are less compressed and your weight reading is less. If the elevator cable breaks and the elevator falls freely, the reading on the scale goes to zero. According to the scale's reading, you would be **weightless.** Would you really be weightless? We can answer this question only if we agree on what we mean by *weight.*

In Chapter 1 we treated the weight of an object as the force due to gravity upon it. When in equilibrium on a firm surface, weight is evidenced by a support force, or, when in suspension, by a supporting rope tension. In either case, with no acceleration, weight equals mg. In future rotating habitats in space, where rotating environments act as giant centrifuges, support force can occur without regard to gravity. So a broader definition of the weight of something is the force it exerts against a supporting floor or a weighing scale. According to this definition, you are as heavy as you feel; in an elevator that accelerates downward, the supporting force of the floor is less and you weigh less. If the elevator is in free fall, your weight is zero (Figure 4.10). Even in this weightless condition, however, a gravitational force is still acting on you, causing your downward acceleration. But gravity now is not felt as weight because there is no support force.

Astronauts in orbit are without a support force and are in a sustained state of weightlessness. They sometimes experience "space sickness" until they become accustomed to a state of sustained weightlessness. Astronauts in orbit are in a state of continual free fall.

The International Space Station (ISS), shown in Figure 4.11 (next page), provides a weightless environment. The station facility and astronauts all accelerate equally toward Earth, at somewhat less than 1 g because of their altitude. This accelera-tion is not sensed at all. With respect to the station, the astronauts experience zero g. Over extended periods of time, this causes loss of muscle strength and other detrimental changes in the body. Future space travelers, however, need not be subjected to weightlessness. Habitats that lazily rotate as giant wheels or pods at the end of a tether will likely replace today's nonrotating

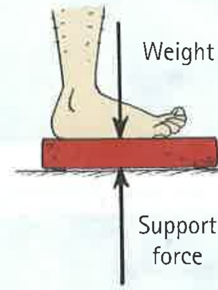

FIGURE 4.8
Two forces act on a weighing scale: a downward force of gravity (your weight, mg, if there is no accelera-tion) and an upward support force. These equal and opposite forces squeeze an inner springlike device that is calibrated to show weight.

FIGURE 4.9
Both are weightless.

VIDEO: Weight and Weightlessness

VIDEO: Apparent Weightlessness

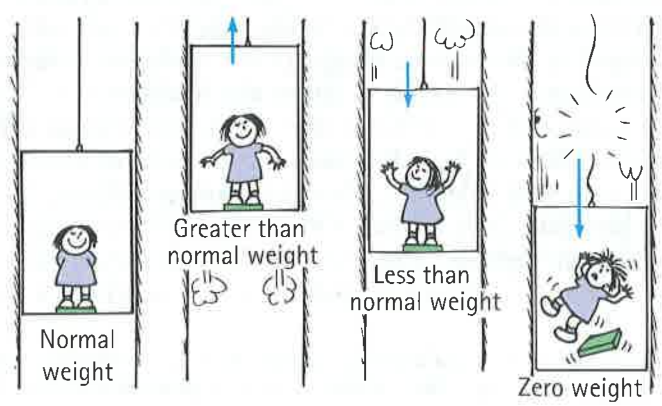

FIGURE 4.10
Your weight equals the force with which you press against the supporting floor. If the floor accelerates up or down, your weight varies (even though the gravitational force mg that acts on you remains the same).

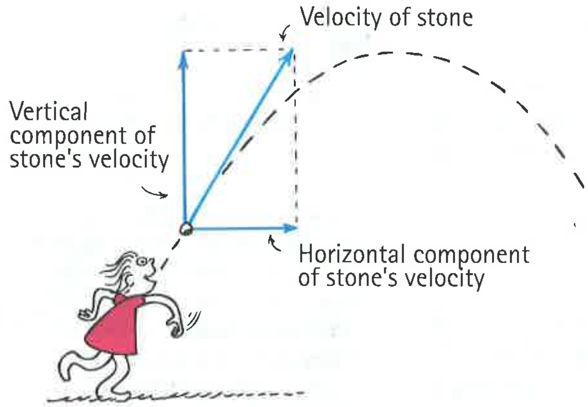

FIGURE 4.13
Vertical and horizontal components of a stone's velocity.

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The curved path of a projectile is a combination of horizontal and vertical motion. Velocity is a vector quantity, and a velocity vector at an angle has horizontal and vertical components, as seen in Figure 4.13. When air resistance is small enough to ignore, the horizontal and vertical components of a projectile's velocity are completely independent of one another. Their combined effect produces the trajectories of projectiles.

Projectiles Launched Horizontally

Projectile motion is nicely analyzed in Figure 4.14, which shows a simulated multiple-flash exposure of a ball rolling off the edge of a table. Investigate it carefully, for there's a lot of good physics there. On the left we notice equally timed sequential positions of the ball without the effect of gravity. Only the effect of the ball's horizontal component of motion is shown. Next we see vertical motion without a horizontal component. The curved path in the third view is best analyzed by considering the horizontal and vertical components of motion separately. There are two important things to notice. The first is that the ball's horizontal component of velocity doesn't change as the falling ball moves forward. The ball travels the same horizontal distance in equal times between each flash. That's because there is no component of gravitational force acting horizontally. Gravity acts only *downward,* so the only acceleration of the ball is *downward.* The second thing to notice is that the vertical positions become farther apart with time. The vertical distances traveled are the same as if the ball were simply dropped. Note that the curvature of the ball's path is the combination of horizontal motion, which remains constant, and vertical motion, which undergoes acceleration due to gravity.

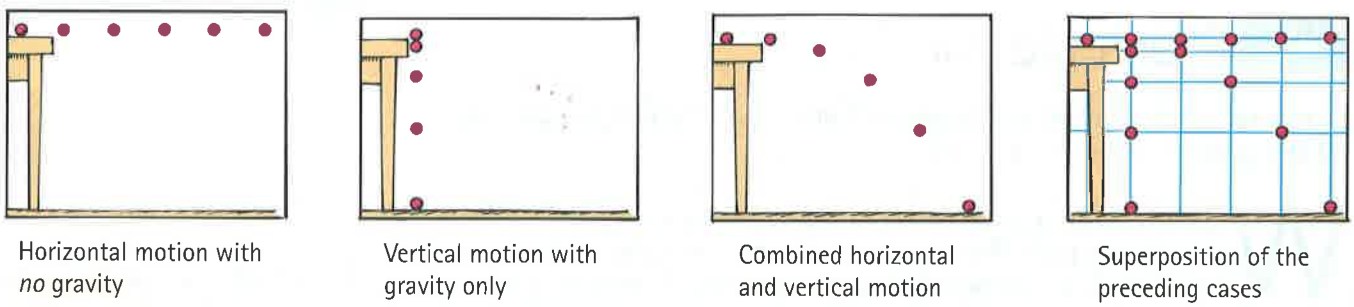


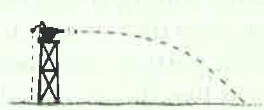
FIGURE 4.14
INTERACTIVE FIGURE MP
Simulated photographs of a moving ball illuminated with a strobe light.

The trajectory of a projectile that accelerates only in the vertical direction while moving at a constant horizontal velocity is a **parabola.** When air resistance is small enough to neglect, as it is for a heavy object without great speed, the trajectory is parabolic.

SCREENCAST:
Sideways Drop

CHECKPOINT

At the instant a cannon fires a cannonball horizontally over a level range, another cannonball held at the side of the cannon is released and drops to the ground. Which ball, the one fired downrange or the one dropped from rest, strikes the ground first?



Was this your answer?
Both cannonballs hit the ground at the same time, because both fall *the same vertical distance*. Note that the physics is the same as the physics of Figures 4.14 through 4.16. We can reason this another way by asking which one would hit the ground first if the cannon were pointed at an *upward* angle. Then the dropped cannonball would hit first, while the fired ball is still airborne. Now consider the cannon pointing *downward*. In this case, the fired ball hits first. So projected upward, the dropped one hits first; downward, the fired one hits first. Is there some angle at which there is a dead heat, where both hit at the same time? Can you see that this occurs when the cannon is horizontal?

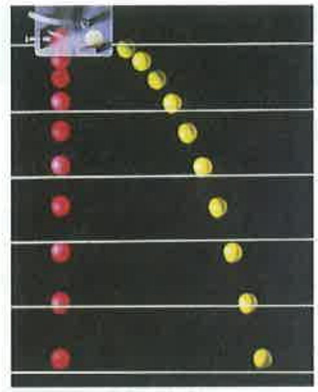


FIGURE 4.15
INTERACTIVE FIGURE MP
A strobe-light photograph of two golf balls released simultaneously from a mechanism that allows one ball to drop freely while the other is projected horizontally.

Projectiles Launched at an Angle

In Figure 4.17, we see the paths of stones thrown at an angle upward (left) and downward (right). The dashed straight lines at the top show the ideal trajectories of the stones if there were no gravity. Notice that the vertical distance that each stone falls beneath the idealized straight-line path is the same for equal times. This vertical distance is independent of what's happening horizontally.

Figure 4.18 shows specific vertical distances for a cannonball shot at an upward angle. If there were no gravity the cannonball would follow the straight-line path shown by the dashed line. But there is gravity, so this doesn't occur. What happens is that the cannonball continuously falls beneath the imaginary line until it finally strikes the ground. Note that the vertical distance it falls

SCREENCAST: Ball Toss

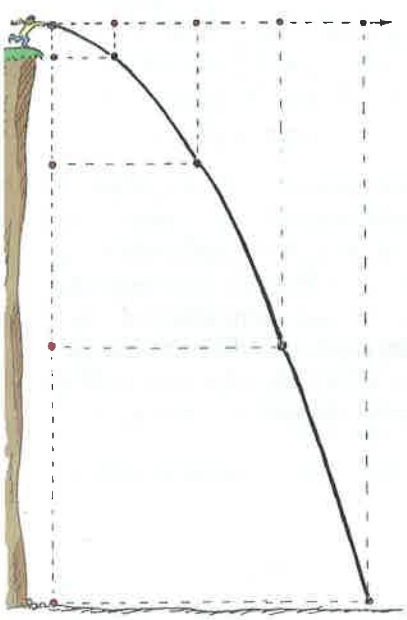


FIGURE 4.16
The vertical dashed line at left is the path of a stone dropped from rest. The horizontal dashed line at the top would be its path if there were no gravity. The curved solid line shows the resulting trajectory that combines horizontal and vertical motion.

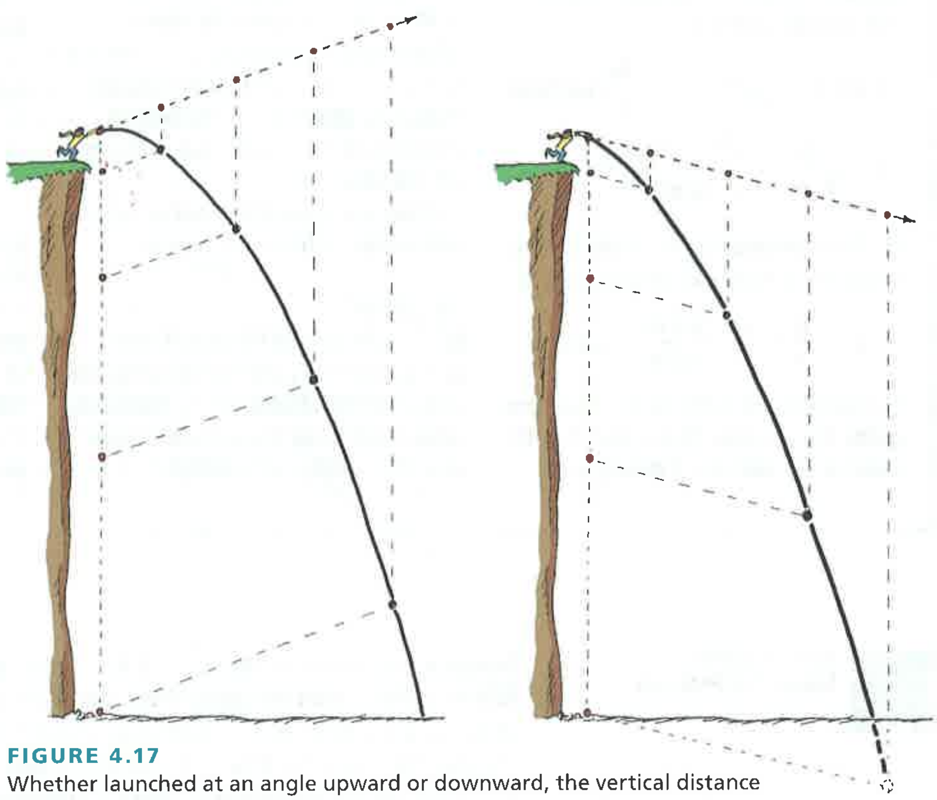


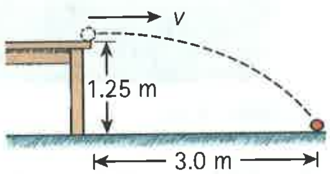
FIGURE 4.17
Whether launched at an angle upward or downward, the vertical distance of fall beneath the idealized straight-line path is the same for equal times.

FIGURING PHYSICAL SCIENCE

Problem Solving

SAMPLE PROBLEM 1

A ball of mass 1.0 kg rolls off of a 1.25-m-high lab table and hits the floor 3.0 m from the base of the table.



(a) Show that the ball takes 0.5 s to hit the floor.
(b) Show that the ball leaves the table at 6.0 m/s.

Solution:

(a) We want the time of the ball in the air. First, some physics. The time t it takes for any ball to hit the floor would be the same as if it were dropped from rest a vertical distance y. We say from rest because initially it moves horizontally off the desk, with zero velocity in the vertical direction.

From $y = \frac{1}{2}gt^2 \Rightarrow t^2 = \frac{2y}{g}$, we have

$$t = \sqrt{\frac{2y}{g}} = \sqrt{\frac{2(1.25 \text{ m})}{10 \text{ m/s}^2}} = 0.5 \text{ s}$$

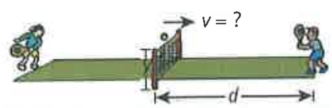
(b) The horizontal speed of the ball as it leaves the table, using time 0.5 s, is

$$v_x = \frac{d}{t} = \frac{x}{t} = \frac{3.0 \text{ m}}{0.5 \text{ s}} = 6.0 \text{ m/s}$$

Notice how the terms of the equations guide the solution. Notice also that the mass of the ball, not showing in the equations, is extraneous information (as would be the color of the ball).

SAMPLE PROBLEM 2

A horizontally moving tennis ball barely clears the net, a distance y above the surface of the court. To land within the tennis court, the ball must not be moving too fast.



(a) To remain within the court's border, a horizontal distance d from the bottom of the net, ignoring air resistance and any spin effects of the ball, show that the ball's maximum speed over the net is

$$v = \frac{d}{\sqrt{\frac{2y}{g}}}$$

(b) Suppose the height of the net is 1.00 m, and the court's border is 12.0 m from the bottom of the net. Use $g = 10 \text{ m/s}^2$ and show that the maximum speed of the horizontally moving ball clearing the net is about 27 m/s (about 60 mi/h).
(c) Does the mass of the ball make a difference? Defend your answer.

Solution:

(a) As with Sample Problem 1, the physics concept here involves projectile motion in the absence of air resistance, where horizontal and vertical components of velocity are independent. We're asked for horizontal speed, so we write

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

where d is horizontal distance traveled in time t. As with Sample Problem 1, the time t of the ball in flight is the same as if we had just dropped it from rest a vertical distance y from the top of the net. As the ball clears the net, its highest point in its path, its vertical component of velocity is zero.

From $y = \frac{1}{2}gt^2 \Rightarrow t^2 = \frac{2y}{g} \Rightarrow t = \sqrt{\frac{2y}{g}}$,

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

Can you see that solving in terms of symbols better shows that these two problems are one and the same? All the physics occurs in steps (a) and (b) in Sample Problem 1. These steps are combined in step (a) of Sample Problem 2.

(b) $$v = \frac{d}{\sqrt{\frac{2y}{g}}} = \frac{12.0 \text{ m}}{\sqrt{\frac{2(1.00 \text{ m})}{10 \text{ m/s}^2}}} = 26.8 \text{ m/s} \approx 27 \text{ m/s}$$

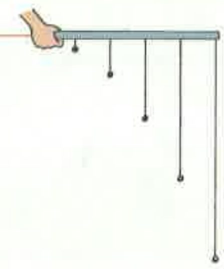
(c) We can see that the mass of the ball (in both problems) doesn't show up in the equations for motion, which tells us that mass is irrelevant. Recall from Chapter 2 that mass has no effect on a freely falling object—and the tennis ball is a freely falling object (as is every projectile when air resistance can be neglected).

SCREENCAST:
Tennis-Ball Problem

beneath any point on the dashed line is the same vertical distance it would have fallen if it had been dropped from rest and had been falling for the same amount of time. This distance, as introduced in Chapter 1, is given by $d = \frac{1}{2}gt^2$, where t is the elapsed time. For $g = 10 \text{ m/s}^2$, this becomes $d = 5t^2$.

We can put it another way: Shoot a projectile skyward at some angle and pretend there is no gravity. After so many seconds t, it should be at a certain point along a straight-line path. But because of gravity, it isn't. Where is it? The answer is that it's directly below this point. How far below? The answer in meters is $5t^2$ (or, more precisely, $4.9t^2$). How about that!

DOING PHYSICAL SCIENCE



Hands-On Dangling Beads

Make your own model of projectile paths. Divide a ruler or a stick into five equal spaces. At position 1, hang a bead from a string that is 1 cm long, as shown. At position 2, hang a bead from a string that is 4 cm long. At position 3, do the same with a 9-cm length of string. At position 4, use 16 cm of string, and for position 5, use 25 cm of string. If you hold the stick horizontally, you will have a version of Figure 4.16. Hold it at a slight upward angle to show a version of Figure 4.17 (left). Hold it at a downward angle to show a version of Figure 4.17 (right).

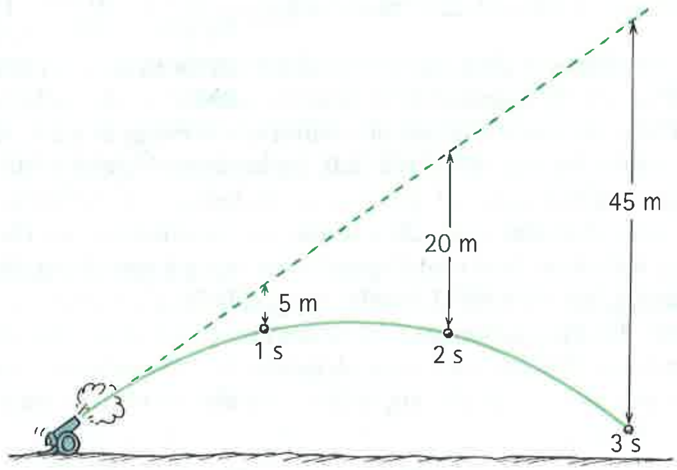


FIGURE 4.18
With no gravity, the projectile would follow a straight-line path (dashed line). But because of gravity, the projectile falls beneath this line the same vertical distance it would fall if it were released from rest. Compare the distances fallen with those given in Table 1.2 in Chapter 1. (With g = 9.8 m/s^2, these distances are more precisely 4.9 m, 19.6 m, and 44.1 m.)

CHECKPOINT

1. **Suppose the cannonball in Figure 4.18 were fired faster. How many meters below the dashed line would it be at the end of the 5 s?**
2. **If the horizontal component of the cannonball's velocity is 20 m/s, how far downrange will the cannonball be in 5 s?**

Were these your answers?

1. The vertical distance beneath the dashed line at the end of 5 s is 125 m [looking at magnitudes only: $d = 5t^2 = 5(5)^2 = 5(25) = 125$ m]. This distance doesn't depend on the angle of the cannon. With no air resistance any projectile will fall $5t^2$ below the green dashed line.
2. With no air resistance, the cannonball will travel a horizontal distance of 100 m [$d = v_x t$ = (20 m/s)(5 s) = 100 m]. Note that because gravity acts only vertically and there is no acceleration in the horizontal direction, the cannonball travels equal horizontal distances in equal times. This distance is simply its horizontal component of velocity multiplied by the time (and not $5t^2$, which applies only to vertical motion under the acceleration of gravity).

Figure 4.19 (next page) shows the paths of several projectiles, all with the same initial speed but different launching angles. The figure neglects the effects of air resistance, so the trajectories are all parabolas. Notice that these projectiles reach different *altitudes,* or heights above the ground. They also have different *horizontal ranges,* or distances traveled horizontally. The remarkable thing to note from Figure 4.19 is that the same range is obtained from two different launching angles when the angles add up to 90°! An object thrown into the air at an angle of 60°, for example, has the same range as if it were thrown at the same speed at an angle of 30°. For the smaller angle, of course, the object remains in the air for a shorter time. The greatest range occurs when the launching angle is 45°—and when air resistance is negligible.

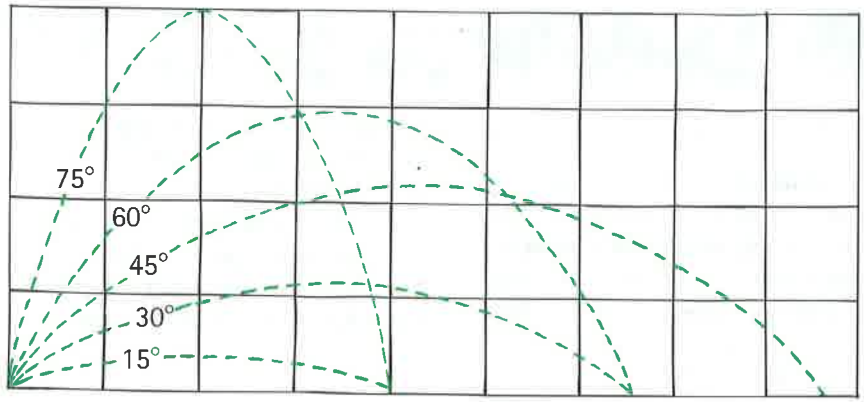


FIGURE 4.19
INTERACTIVE FIGURE MP
Ranges of a projectile shot at the same speed at different projection angles.

FIGURE 4.20
Maximum range would be attained when a ball is batted at an angle of nearly 45°—but only in the absence of air drag.

Without the effects of air, a baseball would reach the maximum range when it is batted 45° above the horizontal. Without air resistance, the ball rises just like it falls, covering the same amount of ground while rising as while falling. But not so when air resistance slows the ball. Its horizontal speed at the top of its path is lower than its horizontal speed when the ball leaves the bat, *so it covers less ground while falling than while rising.* As a result, for maximum range the ball must leave the bat with more horizontal speed than vertical speed—at about 25° to 34°, considerably less than 45°. Likewise for golf balls. (As Chapter 5 will show, the ball's spin also affects the range.) For heavy projectiles like javelins and the shot, air has less effect on the range. A javelin, being heavy and presenting a very small cross section to the air, follows an almost perfect parabola when

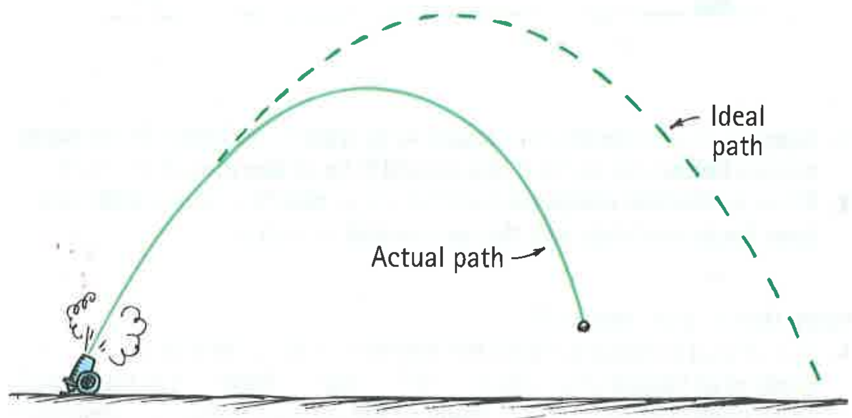


FIGURE 4.21
INTERACTIVE FIGURE MP
In the presence of air resistance, the trajectory of a high-speed projectile falls short of the idealized parabolic path.

HANG TIME REVISITED

In Chapter 1, we stated that airborne time during a jump is independent of horizontal speed. Now we see why this is so—horizontal and vertical components of motion are independent of each other. The rules of projectile motion apply to jumping. Once one's feet are off the ground, only the force of gravity acts on the jumper (neglecting air resistance). Hang time depends only on the vertical component of liftoff velocity. However, the action of running can make a difference. When the jumper is running, the liftoff force during jumping can be somewhat increased by the pounding of the feet against the ground (and the ground pounding against the feet in action–reaction fashion), so hang time for a running jump can often exceed hang time for a standing jump. But once the runner's feet are off the ground, only the vertical component of liftoff velocity determines hang time.

thrown. So does a shot. Aha, but *launching speeds* are not equal for heavy projectiles thrown at different angles. When a javelin or a shot is thrown, a significant part of the launching *force* goes into lifting—combating gravity—so launching at 45° means a lower launching speed. You can test this yourself: Throw a heavy boulder horizontally, then at an angle upward—you'll find the horizontal throw to be considerably faster. So the maximum range for heavy projectiles thrown by humans is attained for angles of less than 45°—and not because of air resistance.

FIGURE 4.22
The physics of projectile motion is the same for Alex and his skateboard as it is for a soccer ball. Both trajectories are the same for equal launching velocities.

CHECKPOINT

1. **A baseball is batted at an angle into the air. Once the ball is airborne, and neglecting air resistance, what is the ball's acceleration vertically? Horizontally?**
2. **At what part of its trajectory does the baseball have minimum speed?**
3. **Consider a batted baseball following a parabolic path on a day when the Sun is directly overhead. How does the speed of the ball's shadow across the field compare with the ball's horizontal component of velocity?**

Were these your answers?

1. Vertical acceleration is g because the force of gravity is vertical. Horizontal acceleration is zero because no horizontal force acts on the ball.
2. A ball's minimum speed occurs at the top of its trajectory. If it is launched vertically, its speed at the top is zero. If launched at an angle, the vertical component of velocity is zero at the top, leaving only the horizontal component. So the speed at the top is equal to the horizontal component of the ball's velocity at any point. Doesn't this make sense?
3. They are the same!

When air resistance is small enough to be negligible, the time that a projectile takes to rise to its maximum height is the same as the time it takes to fall back to its initial level (Figure 4.23). This is because its deceleration by gravity while going up is the same as its acceleration by gravity while coming down. The speed it loses while going up is therefore the same as the speed gained while coming down. So the projectile arrives at its initial level with the same speed it had when it was initially projected.

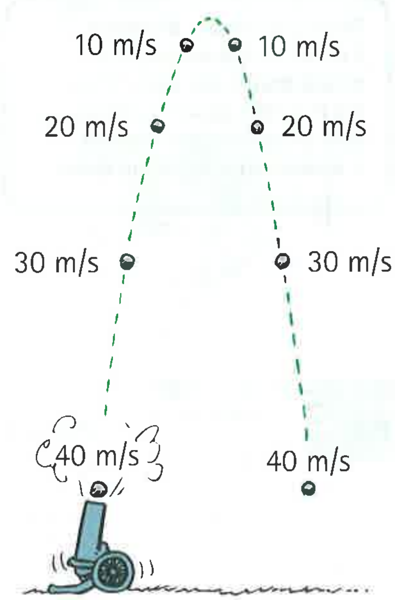


FIGURE 4.23
Without air resistance, speed lost while going up equals speed gained while coming down: Time going up equals time coming down.

CHECKPOINT

What is the approximate time of flight for the cannonball shown in Figure 4.23?

Was this your answer?

The cannonball's total time in the air is 8 seconds. Since speed changes by 10 m/s each second when there is no air resistance, the time to go upward from 40 m/s to zero at the top is 4 seconds. By symmetry, the time to fall the same distance is also 4 seconds.

Baseball games normally take place on level ground. For the short-range projectile motion on the playing field, Earth can be considered flat because the flight of the baseball is not affected by Earth's curvature. For very long-range projectiles, however, the curvature of Earth's surface must be taken into account. We'll now see that, if an object is projected fast enough, it falls all the way around Earth and becomes an Earth satellite.

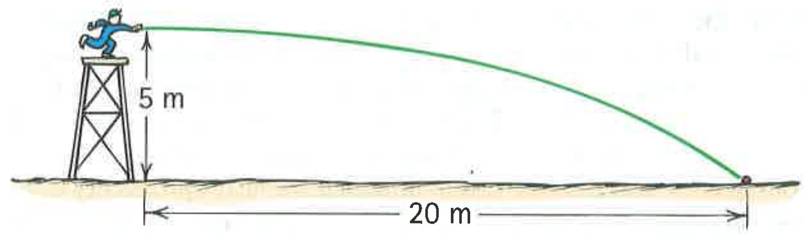


FIGURE 4.24
How fast is the ball thrown?

CHECKPOINT

The boy on the tower in Figure 4.24 throws a ball 20 m downrange. What is his pitching speed?

Was this your answer?

The ball is thrown horizontally, so the pitching speed is horizontal distance divided by time. A horizontal distance of 20 m is given, but the time is not stated. However, knowing the vertical drop is 5 m, you remember that a 5-m drop takes 1 s! From the equation for constant speed (which applies to horizontal motion), $v = d/t = (20\text{ m})/(1\text{ s}) = 20\text{ m/s}$. It is interesting to note that the equation for constant speed, $v = d/t$, guides our thinking about the crucial factor in this problem—the *time*.

4.6 Fast-Moving Projectiles—Satellites

EXPLAIN THIS What does Earth's curvature have to do with Earth satellites?

Consider the girl pitching a ball on the cliff in Figure 4.25. If gravity did not act on the ball, the ball would follow a straight-line path shown by the dashed line. But gravity does act, so the ball falls below this straight-line path. In fact, as just discussed, 1 s after the ball leaves the pitcher's hand it has fallen a vertical distance of 5 m below the dashed line—whatever the pitching speed. It is important to understand this, for it is the crux of satellite motion.

An Earth **satellite** is simply a projectile that falls *around* Earth rather than *into* it. The speed of the satellite must be great enough to ensure that its falling distance matches Earth's curvature. A geometrical fact about the curvature of Earth is that its surface drops a vertical distance of 5 m for every 8000 m

Earth's curvature, dropping 5 m for each 8-km tangent, means that if you were floating in a calm ocean, you'd be able to see only the top of a 5-m mast on a ship 8 km away.

SCREENCAST: Satellite Speed

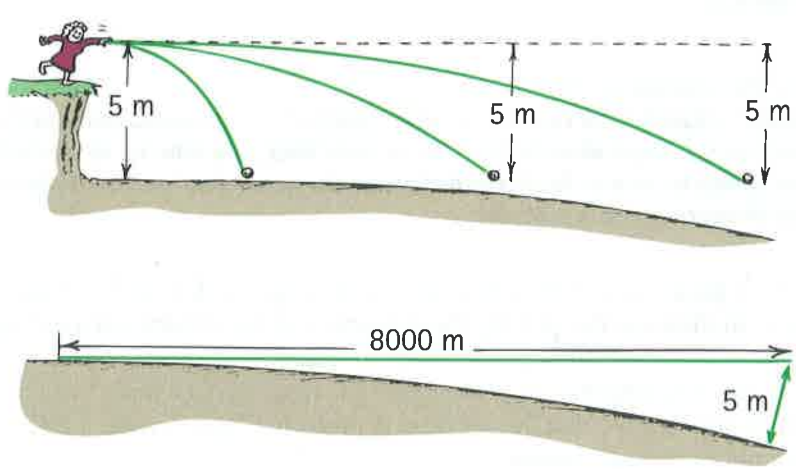


FIGURE 4.25
If you throw a stone at any speed, 1 s later it will have fallen 5 m below where it would have been without gravity.

tangent to the surface (Figure 4.25). If a baseball could be thrown fast enough to travel a horizontal distance of 8 km during the 1 s it takes to fall 5 m, then it would follow the curvature of Earth. This is a speed of 8 km/s. If this doesn't seem fast, convert it to kilometers per hour and you get an impressive 29,000 km/h (or 18,000 mi/h)!

At this speed, atmospheric friction would burn the baseball—or even a piece of iron—to a crisp. This is the fate of bits of rock and other meteorites that enter Earth's atmosphere and burn up, appearing as "falling stars." That is why satellites, such as the space shuttles, are launched to altitudes of 150 kilometers or more—to be above almost all of the atmosphere and to be nearly free of air resistance. A common misconception is that satellites orbiting at high altitudes are free from gravity. Nothing could be further from the truth. The force of gravity on a satellite 200 kilometers above Earth's surface is nearly as strong as it is at the surface. Otherwise the satellite would go in a straight line and leave Earth. The high altitude positions the satellite not beyond Earth's gravity, but beyond Earth's atmosphere, where air resistance is almost totally absent.

Satellite motion was understood by Isaac Newton, who reasoned that the Moon was simply a projectile circling Earth under the attraction of gravity. This concept is illustrated in a drawing by Newton (Figure 4.28). He compared the motion of the Moon to that of a cannonball fired from the top of a high mountain. He imagined that the mountaintop was above Earth's atmosphere, so that air resistance would not impede the motion of the cannonball. If fired with a low horizontal speed, a cannonball would follow a curved path and soon hit Earth below. If it were fired faster, its path would be less curved and it would hit Earth farther away. If the cannonball were fired fast enough, Newton reasoned, the curved path would become a circle and the cannonball would circle Earth indefinitely. It would be in orbit.

Both the cannonball and the Moon have tangential velocity (parallel to Earth's surface) sufficient to ensure motion *around* Earth rather than *into* it. Without resistance to reduce its speed, the Moon or any Earth satellite "falls" around Earth indefinitely. Similarly, the planets continuously fall around the Sun in closed paths. Why don't the planets crash into the Sun? They don't because of sufficient tangential velocities. What would happen if their tangential velocities were reduced to zero? The answer is simple enough: Their falls would be straight toward the Sun, and they would indeed crash into it. Any objects in the solar system without sufficient tangential velocities have long ago crashed into the Sun. What remains is the harmony we observe.

FIGURE 4.26
Earth's curvature (not to scale).

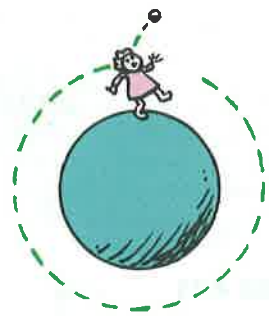


FIGURE 4.27
If the speed of the stone and the curvature of its trajectory are great enough, the stone may become a satellite.

An Earth satellite is a projectile in a constant state of free fall. Because of its tangential velocity, it falls around Earth rather than vertically into it.

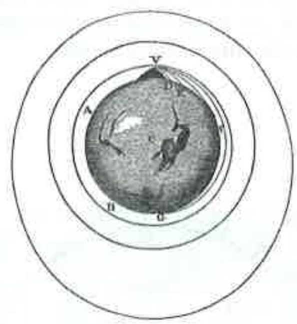


FIGURE 4.28
"The greater the velocity . . . with which (a stone) is projected, the farther it goes before it falls to the Earth. We may therefore suppose the velocity to be so increased, that it would describe an arc of 1, 2, 5, 10, 100, 1000 miles before it arrived at the Earth, till at last, exceeding the limits of the Earth, it should pass into space without touching."
—Isaac Newton, *System of the World*

CHECKPOINT

One of the beauties of physics is that there are usually different ways to view and explain a given phenomenon. Is the following explanation valid? "Satellites remain in orbit instead of falling to Earth because they are beyond the main pull of Earth's gravity."

Was this your answer?

No, no, a thousand times no! If any moving object were beyond the pull of gravity, it would move in a straight line and would not curve around Earth. Satellites remain in orbit because they *are* being pulled by gravity, not because they are beyond it. For the altitudes of most Earth satellites, Earth's gravitational force on a satellite is only a few percent weaker than it is at Earth's surface.

4.7 Circular Satellite Orbits

EXPLAIN THIS Why does kinetic energy and momentum remain constant for a satellite in a circular orbit?

An 8-km/s cannonball fired horizontally from Newton's mountain would follow Earth's curvature and glide in a circular path around Earth again and again (provided the cannoneer and the cannon got out of the way). Fired at a slower speed, the cannonball would strike Earth's surface; fired at a faster speed, it would overshoot a circular orbit, as we will discuss shortly. Newton calculated the speed for circular orbit, and because such a cannon-muzzle velocity was clearly impossible, he did not foresee the possibility of humans launching satellites (and he likely didn't consider multistage rockets).

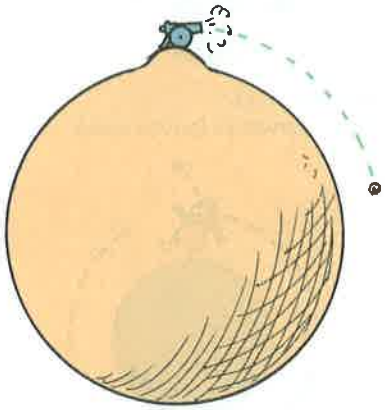


FIGURE 4.29
INTERACTIVE FIGURE MP
Fired fast enough, the cannonball goes into orbit.

VIDEO: Circular Orbits

Note that in circular orbit, the speed of a satellite is not changed by gravity; only the direction changes. We can understand this by comparing a satellite in circular orbit with a bowling ball rolling along a bowling lane. Why doesn't the gravity that acts on the bowling ball change its speed? The answer is that gravity pulls straight downward with no component of force acting forward or backward.

Consider a bowling lane that completely surrounds Earth, elevated high enough to be above the atmosphere and air resistance (Figure 4.30). The bowling ball rolls at constant speed along the lane. If a part of the lane were cut away (Figure 4.31), the ball would roll off its edge and would hit the ground below. A faster ball encountering the gap would hit the ground farther along the gap. Is there a speed at which the ball will clear the gap (like a motorcyclist who drives off a ramp and clears a gap to meet a ramp on the other side)? The answer is yes: 8 km/s will be enough to clear that gap—and any gap, even a 360° gap. The ball would be in circular orbit.

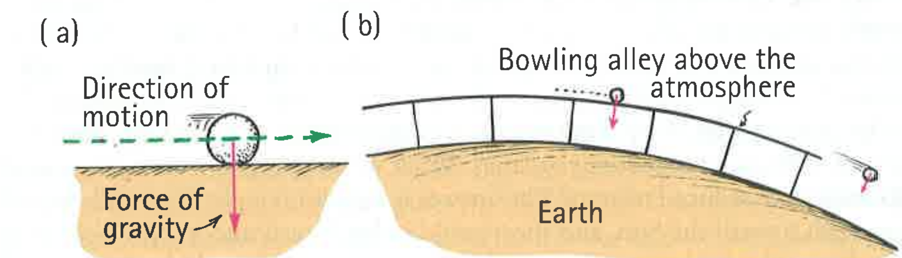


FIGURE 4.30
(a) The force of gravity on the bowling ball is at 90° to its direction of motion, so it has no component of force to pull it forward or backward, and the ball rolls at constant speed. (b) The same is true even if the bowling alley is larger and remains "level" with the curvature of Earth.

Note that a satellite in circular orbit is always moving in a direction perpendicular to the force of gravity that acts upon it. No component of force is acting in the direction of satellite motion to change its speed. Only a change in direction occurs. So we see why a satellite in circular orbit moves parallel to the surface of Earth at constant speed—a very special form of free fall.

For a satellite close to Earth, the period (the time for a complete orbit about Earth) is about 90 min. For higher altitudes, the orbital speed is less, the distance is more, and the period is longer. For example, communication satellites located in orbit 5.5 Earth radii above the surface of Earth have a period of 24 h. This period matches the period of daily Earth rotation. For an orbit around the equator, these satellites remain above the same point on the ground. The Moon is even farther away and has a period of 27.3 days. The higher the orbit of a satellite, the lower its speed, the longer its path, and the longer its period.*

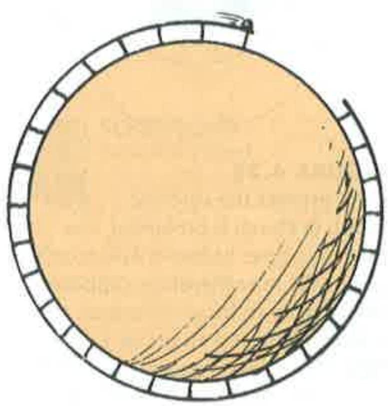


FIGURE 4.31
What speed will allow the ball to clear the gap?

* The speed of a satellite in circular orbit is given by $v = \sqrt{GM/d}$, and the period of satellite motion is given by $T = 2\pi\sqrt{d^3/GM}$, where G is the universal gravitational constant, M is the mass of Earth (or whatever body the satellite orbits), and d is the distance of the satellite from the center of Earth or other parent body.

Putting a payload into Earth orbit requires control over the speed and direction of the rocket that carries it above the atmosphere. A rocket initially fired vertically is intentionally tipped from the vertical course. Then, once above the drag of the atmosphere, it is aimed horizontally, whereupon the payload is given a final thrust to orbital speed. We see this in Figure 4.32, where, for the sake of simplicity, the payload is the entire single-stage rocket. With the proper tangential velocity, it falls around Earth, rather than into it, and becomes an Earth satellite.

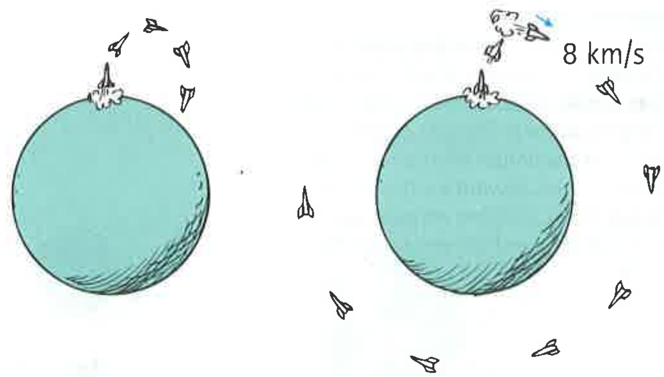


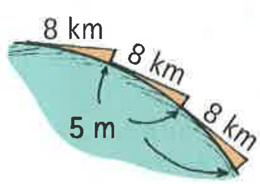
FIGURE 4.32
The initial thrust of the rocket lifts it vertically. Another thrust tips it from its vertical course. When it is moving horizontally, it is boosted to the required speed for orbit.

CHECKPOINT

1. **True or false: Earth satellites normally orbit at altitudes in excess of 150 km to be above both gravity and the atmosphere of Earth.**
2. **Satellites in close circular orbit fall about 5 m during each second of orbit. Why doesn't this distance accumulate and send satellites crashing into Earth's surface?**

Were these your answers?

1. False. Satellites are above the atmosphere and air resistance—*not* gravity! It's important to note that Earth's gravity extends throughout the universe in accord with the inverse-square law.
2. In each second, the satellite falls about 5 m below the straight-line tangent it would have followed if there were no gravity. Earth's surface also curves 5 m beneath a straight-line 8-km tangent. The process of falling with the curvature of Earth continues from tangent line to tangent line, so the curved path of the satellite and the curve of Earth's surface "match" all the way around Earth. Satellites do, in fact, crash to Earth's surface from time to time when they encounter air resistance in the upper atmosphere that decreases their orbital speed.



As the chapter-opening photo shows, the initial vertical climb of a rocket that quickly gets it through the denser part of the atmosphere tilts until the rocket acquires enough speed to match Earth's curvature, whereupon no further thrust is needed for orbit.

4.8 Elliptical Orbits

EXPLAIN THIS Why does the kinetic energy and momentum of a satellite change in an elliptical orbit?

If a projectile just above the drag of the atmosphere is given a horizontal speed somewhat greater than 8 km/s, it overshoots a circular path and traces an oval path called an **ellipse.**

An ellipse is a specific curve: the closed path taken by a point that moves in such a way that the sum of its distances from two fixed points (called *foci*) is constant. For a satellite orbiting a planet, one focus is at the center of the planet; the other focus could be internal or external to the planet. An ellipse can be easily constructed by using a pair of tacks (one at each focus), a loop of string, and a pen (Figure 4.33). The closer the foci are to each other, the closer the ellipse is to a circle. When both foci are together, the ellipse *is* a circle. So we can see that a circle is a special case of an ellipse.

Whereas the speed of a satellite is constant in a circular orbit, its speed varies in an elliptical orbit. For an initial speed greater than 8 km/s, the satellite

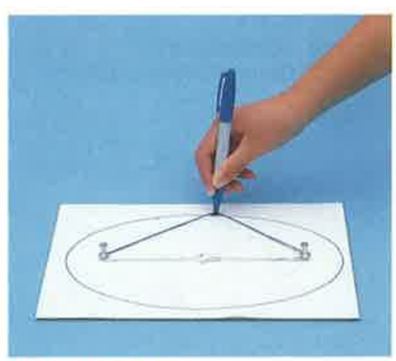


FIGURE 4.33
INTERACTIVE FIGURE MP
A simple method for constructing an ellipse.

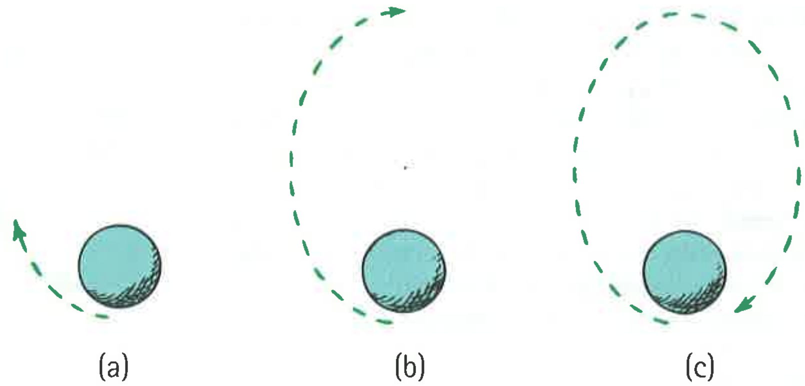


FIGURE 4.34
Elliptical orbit. When the speed of the satellite exceeds 8 km/s, (a) it overshoots a circular path and travels away from Earth against gravity. (b) At its maximum altitude it starts to come back toward Earth. (c) The speed it lost in going away is gained in returning, and the cycle repeats itself.

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- When a spacecraft enters the atmosphere at too steep an angle, more than about 6°, it can burn up. If it comes in too shallow, it could bounce back into space like a pebble skipped across water.

overshoots a circular path and moves away from Earth, against the force of gravity. It therefore loses speed. The speed it loses in receding is regained as it falls back toward Earth, and it finally rejoins its original path with the same speed it had initially (Figure 4.34). The procedure repeats over and over, and an ellipse is traced during each cycle.

Interestingly enough, the parabolic path of a projectile, such as a tossed baseball or a cannonball, is actually a tiny segment of a skinny ellipse that extends within and just beyond the center of Earth (Figure 4.35a). In Figure 4.35b, we see several paths of cannonballs fired from Newton's mountain. All these ellipses have the center of Earth as one focus. As muzzle velocity is increased, the ellipses are less *eccentric* (more nearly circular); and, when muzzle velocity reaches 8 km/s, the ellipse rounds into a circle and does not intercept Earth's surface. The cannonball coasts in circular orbit. At greater muzzle velocities, orbiting cannonballs trace the familiar external ellipses.

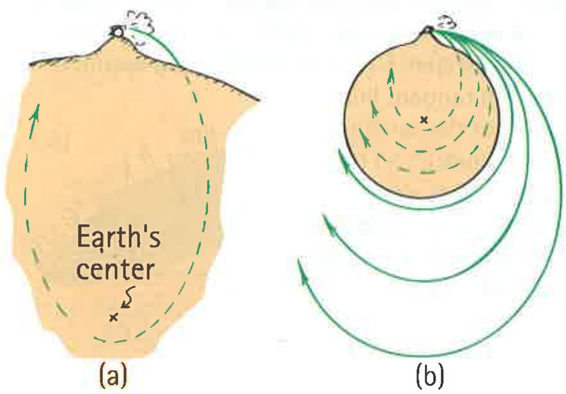
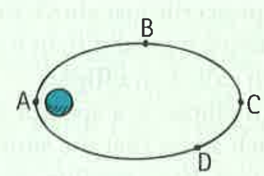


FIGURE 4.35
(a) The parabolic path of the cannonball approximates part of an ellipse that extends within Earth. Earth's center is the far focus. (b) All paths of the cannonball are ellipses. For less than orbital speeds, the center of Earth is the far focus; for a circular orbit, both foci are Earth's center; for greater speeds, the near focus is Earth's center.

SCREENCAST: Circular/Elliptical Orbit

CHECKPOINT

The orbital path of a satellite is shown in the sketch. At which of the marked positions A through D does the satellite have the highest speed? The lowest speed?



Were these your answers?

The satellite has its highest speed as it whips around A and has its lowest speed at position C. After passing C, it gains speed as it falls back to A to repeat its cycle.

4.9 Escape Speed

EXPLAIN THIS What is your fate if you are launched from Earth at a speed greater than 11.2 km/s?

We know that a cannonball fired horizontally at 8 km/s from Newton's mountain would find itself in orbit. But what would happen if the cannonball were instead fired at the same speed *vertically*? It would rise to some maximum height, reverse direction, and then fall back to Earth. Then the old saying "What goes up must come down" would hold true, just as surely as a stone tossed skyward is returned by gravity (unless, as we shall see, its speed is great enough).

In today's spacefaring age, it is more accurate to say, "What goes up *may* come down," for a critical starting speed exists that permits a projectile to escape Earth. This critical speed is called the **escape speed** or, if direction is involved, the *escape velocity*. From the surface of Earth, escape speed is 11.2 km/s. If you launch a projectile at any speed greater than that, it leaves Earth, traveling slower and slower, never stopping due to Earth's gravity.* We can understand the magnitude of this speed from an energy point of view.

How much work would be required to lift a payload against the force of Earth's gravity to a distance extremely far ("infinitely far") away? We might think that the change of potential energy would be infinite because the distance is infinite. But gravity diminishes with distance by the inverse-square law. The force of gravity on the payload would be strong only near Earth. Most of the work done in launching a rocket occurs within 10,000 km or so of Earth. It turns out that the change of potential energy of a 1-km body moved from the surface of Earth to an infinite distance is 62 million J (62 MJ). So to put a payload infinitely far from Earth's surface requires at least 62 million joules of energy per kilogram of load. We won't go through the calculation here, but 62 MJ/kg corresponds to a speed of 11.2 km/s, whatever the total mass involved. This is the escape speed from the surface of Earth.**

If we give a payload any more energy than 62 MJ/kg at the surface of Earth or, equivalently, any more speed than 11.2 km/s, then, neglecting air resistance, the payload will escape from Earth, never to return. As the payload continues outward, its potential energy increases and its kinetic energy decreases. Earth's gravitational pull continuously slows it down but never reduces its speed to zero. The payload escapes.

The escape speeds from various bodies in the solar system are shown in Table 4.1. Note that the escape speed from the surface of the Sun is 620 km/s. Even at 150,000,000 km from the Sun (Earth's distance), the escape speed to break free of the Sun's influence is 42.5 km/s—considerably more than the escape speed from Earth. An object projected from Earth at a speed greater than 11.2 km/s but less than 42.5 km/s will escape Earth but not the Sun. Rather than recede forever, it will take up an orbit around the Sun.

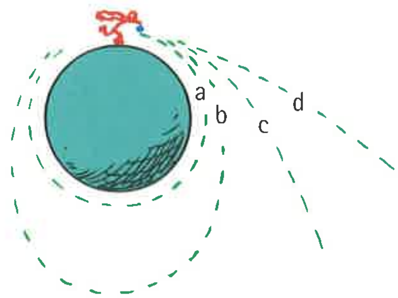


FIGURE 4.36
INTERACTIVE FIGURE MP

If Superman tosses a ball 8 km/s horizontally from the top of a mountain high enough to be just above air resistance (a), then about 90 min later he can turn around and catch it (neglecting Earth's rotation). Tossed slightly faster (b), it takes an elliptical orbit and returns in a slightly longer time. Tossed at more than 11.2 km/s (c), it escapes Earth. Tossed at more than 42.5 km/s (d), it escapes the solar system.

* Escape speed from any planet or any body is given by $v = \sqrt{2GM/d}$, where G is the universal gravitational constant, M is the mass of the attracting body, and d is the distance from its center. (At the surface of the body, d would simply be the radius of the body.) For a bit more mathematical insight, compare this formula with the one for orbital speed in the footnote on page 108.

** Interestingly enough, this might well be called the *maximum falling speed*. Any object, however far from Earth, released from rest and allowed to fall to Earth only under the influence of Earth's gravity would not exceed 11.2 km/s. (With air friction, it would be less.)

TABLE 4.1 ESCAPE SPEEDS AT THE SURFACE OF BODIES IN THE SOLAR SYSTEM

Astronomical Body	Mass (Earth masses)	Radius (Earth radii)	Escape Speed (km/s)
Sun	333,000	109	620
Sun (at a distance of Earth's orbit)		23,500	42.2
Jupiter	318	11	60.2
Saturn	95.2	9.2	36.0
Neptune	17.3	3.47	24.9
Uranus	14.5	3.7	22.3
Earth	1.00	1.00	11.2
Venus	0.82	0.95	10.4
Mars	0.11	0.53	5.0
Mercury	0.055	0.38	4.3
Moon	0.0123	0.27	2.4

fyi

- You won't fully appreciate the frontiers of physical science unless you're familiar with its foothills.

The first probe to escape the solar system, *Pioneer 10,* was launched from Earth in 1972 with a speed of only 15 km/s. The escape was accomplished by directing the probe into the path of oncoming Jupiter. It was whipped about by Jupiter's great gravitational field, picking up speed in the process—similar to the increase in the speed of a baseball encountering an oncoming bat. Its speed of departure from Jupiter was increased enough to exceed the escape speed from the Sun at the distance of Jupiter. *Pioneer 10* passed the orbit of Pluto in 1984. Unless it collides with another body, it will wander indefinitely through interstellar space. Like a note inside a bottle cast into the sea, *Pioneer 10* contains information about Earth that might be of interest to extraterrestrials, in hopes that it will one day "wash up" and be found on some distant "seashore."

Just as planets fall around the Sun, stars fall around the centers of galaxies. Those with insufficient tangential speeds are pulled into, and are gobbled up by, the galactic nucleus—usually a black hole.

It is important to stress that the escape speed of a body is the initial speed given by a brief thrust, after which there is no force to assist motion. One could escape Earth at *any* sustained speed more than zero, given enough time. For example, suppose a rocket is launched to a destination such as the Moon. If the rocket engines burn out when still close to Earth, the rocket needs a minimum speed of 11.2 km/s. But if the rocket engines can be sustained for long periods of time, the rocket could reach the Moon without ever attaining 11.2 km/s.

FIGURE 4.37
Pioneer 10, launched from Earth in 1972, passed Pluto in 1984 and is now drifting through the outer reaches of our solar system.

FIGURE 4.38
The European–U.S. spacecraft *Cassini* beams close-up images of Saturn and its giant moon Titan to Earth. It also measures surface temperatures, magnetic fields, and the size, speed, and trajectories of tiny surrounding space particles.

It is interesting to note that the accuracy with which an unoccupied rocket reaches its destination is not accomplished by staying on a planned path or by getting back on that path if the rocket strays off course. No attempt is made to return the rocket to its original path. Instead, the control center in effect asks, "Where is it now and what is its velocity? What is the best way to reach its destination, given its present situation?" With the aid of high-speed computers, the answers to these questions are used to find a new path. Corrective thrusters direct the rocket to this new path. This process is repeated all the way to the goal.*

The mind that encompasses the universe is as marvelous as the universe that encompasses the mind.

* Is there a lesson to be learned here? Suppose you find that you are off course. You may, like the rocket, find it more fruitful to follow a course that leads to your goal as best plotted from your present position and circumstances, rather than try to get back on the course you plotted from a previous position, perhaps under different circumstances.

For assigned homework and other learning materials, go to MasteringPhysics®.

SUMMARY OF TERMS (KNOWLEDGE)

Ellipse The oval path followed by a satellite. The sum of the distances from any point on the path to two points called foci is a constant. When the foci are together at one point, the ellipse is a circle. As the foci get farther apart, the ellipse becomes more *eccentric*.

Escape speed The speed that a projectile, space probe, or similar object must reach to escape the gravitational influence of Earth or of another celestial body to which it is attracted.

Inverse-square law The intensity of an effect from a localized source spreads uniformly throughout the surrounding space and weakens with the inverse square of the distance:

$$\text{Intensity} = \frac{1}{\text{distance}^2}$$

Gravity follows an inverse-square law, as do the effects of electric, light, sound, and radiation phenomena.

Law of universal gravitation Every body in the universe attracts every other body with a force the strength of which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers:

$$F = G\frac{m_1 m_2}{d^2}$$

Parabola The curved path followed by a projectile under the influence of constant gravity only.

Projectile Any object that moves through the air or through space under the influence of gravity.

Satellite A projectile or small celestial body that orbits a larger celestial body.

Weight The force that an object exerts on a supporting surface (or, if suspended, on a supporting string), which is often, but not always, due to the force of gravity.

Weightless Being without a support force, as in free fall.

READING CHECK QUESTIONS (UNDERSTANDING)

1. What did Newton discover about gravity?

4.1 The Universal Law of Gravity

2. In what sense does the Moon "fall"?
3. State Newton's law of universal gravitation in words. Then express it in one equation.
4. What is the magnitude of gravitational force between two 1-kg bodies that are 1 m apart?
5. What is the magnitude of the gravitational force between Earth and a 1-kg body at its surface?

4.2 Gravity and Distance: The Inverse-Square Law

6. How does the force of gravity between two bodies change when the distance between them is tripled?
7. Where do you weigh more—at sea level or atop one of the peaks of the Rocky Mountains? Defend your answer.

4.3 Weight and Weightlessness

8. Would the springs inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that accelerated upward? Accelerated downward?
9. Would the springs inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that moved upward at *constant velocity*? In an elevator that moved downward at *constant velocity*?
10. Explain why occupants of the International Space Station are firmly in the grip of Earth's gravity, even though they have no weight.
11. Under what conditions is your weight equal to mg?

4.4 Universal Gravitation

12. What was the cause of perturbations discovered in the orbit of planet Uranus?
13. The perturbations of Uranus led to what greater discovery?
14. What is the status of Pluto in the family of planets?
15. Which is thought to be more prevalent in the universe, dark matter or dark energy?

4.5 Projectile Motion

16. A stone is thrown upward at an angle. Neglecting air resistance, what happens to the horizontal component of its velocity along its trajectory?
17. A stone is thrown upward at an angle. Neglecting air resistance, what happens to the vertical component of its velocity along its trajectory?
18. A projectile is launched upward at an angle of 75° from the horizontal and strikes the ground a certain distance downrange. For what other angle of launch at the same speed would this projectile land just as far away?
19. A projectile is launched vertically at 100 m/s. If air resistance can be neglected, at what speed does it return to its initial level?

4.6 Fast-Moving Projectiles—Satellites

20. What connection does Earth's curvature have with the speed needed for a projectile to orbit Earth?
21. Why is it important that a satellite remain above Earth's atmosphere?
22. When a satellite is above Earth's atmosphere, is it also beyond the pull of Earth's gravity? Defend your answer.
23. If a satellite were beyond Earth's gravity, what path would it follow?

4.7 Circular Satellite Orbits

24. Why doesn't the force of gravity change the speed of a bowling ball as it rolls along a bowling lane?
25. Why doesn't the force of gravity change the speed of a satellite in circular orbit?
26. Is the period longer or shorter for orbits of greater altitude?

4.8 Elliptical Orbits

27. Why does the force of gravity change the speed of a satellite in an elliptical orbit?
28. At what part of an elliptical orbit does an Earth satellite have the greatest speed? The least speed?

4.9 Escape Speed

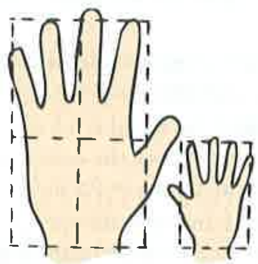
29. What happens to an object close to Earth's surface if it is given a speed exceeding 11.2 km/s?
30. A space vehicle can outrun Earth's gravity, but can it get entirely beyond Earth's gravity?

ACTIVITIES (HANDS-ON APPLICATION)

31. With a ballpoint pen, write your name on a piece of paper on your desk. No problem. Now try it with the pen upside down—for example, with the paper held against a book above your head. Note the pen "doesn't work." Now you see that gravity acts on the ink in the barrel through which the ink flows!

32. Hold your hands outstretched in front of you, one twice as far from your eyes as the other, and make a casual judgment as to which hand looks bigger. Most people see them to be about the same size, and many see the nearer hand as slightly bigger. Almost no one, upon casual inspection, sees the nearer hand as four times as big. But by the

inverse-square law, the nearer hand should appear to be twice as tall and twice as wide, and therefore it should seem to occupy four times as much of your visual field as the farther hand. Your belief that your hands are the same size is so strong that it overrules this information. However, if you overlap your hands slightly and view them with one eye closed, you'll see the nearer hand as clearly bigger. This raises an interesting question: What other illusions do you have that are *not* so easily checked?



33. Repeat the eyeballing experiment, only this time use two one-dollar bills: one unfolded and flat, and the other folded along its middle lengthwise, and again widthwise, so that it has $\frac{1}{4}$ the area. Now hold the two bills in front of your eyes. Where do you hold the folded dollar bill so that it looks the same size as the unfolded one? Nice?

34. With stick and strings, make a "trajectory stick" as shown in the Doing Physical Science feature "Hands-On Hanging Beads" on page 103.

35. With your friends, whirl a bucket of water in a vertical circle fast enough so the water doesn't spill out. As it happens, the water in the bucket *is* falling, but with less speed than you give to the bucket. Tell them how your bucket swing is linked to satellite motion—that satellites in orbit continually fall toward Earth, but not with enough vertical speed to get closer to the curved Earth below. Remind your friends that physics is about finding the connections in nature!

PLUG AND CHUG (FORMULA FAMILIARIZATION)

$$F = G\frac{m_1 m_2}{d^2}$$

36. Using the formula for gravity, show that the force of gravity on a 1-kg mass at Earth's surface is 9.8 N. You need to know that the mass of Earth is 6×10^{24} kg, and its radius is 6.4×10^6 m.

37. Calculate the force of gravity on the same 1-kg mass if it were 6.4×10^6 m above Earth's surface (that is, if it were two Earth radii from Earth's center).

38. Show that the average force of gravity between Earth (mass $= 6.0 \times 10^{24}$ kg) and the Moon (mass $= 7.4 \times 10^{22}$ kg) is 2.1×10^{20} N. (The average Earth–Moon distance is 3.8×10^8 m.)

39. Show that the force of gravity between Earth (mass $= 6.0 \times 10^{24}$ kg) and the Sun (mass $= 2.0 \times 10^{30}$ kg) is 3.6×10^{22} N. (The average Earth–Sun distance is 1.5×10^{11} m.)

40. Show that the force of gravity between a newborn baby (mass $= 3.0$ kg) and planet Mars (mass $= 6.4 \times 10^{23}$ kg) is 4.0×10^{-8} N when Mars is at its closest to Earth (distance $= 5.6 \times 10^{10}$ m).

41. Calculate the force of gravity between a newborn baby of mass 3.0 kg and the obstetrician of mass 100 kg who is 0.5 m from the baby. Which exerts more gravitational force on the baby, Mars or the obstetrician? By how much?

THINK AND SOLVE (MATHEMATICAL APPLICATION)

42. Suppose you stood atop a ladder that was so tall that you were three times as far from Earth's center as you presently are. Show that your weight would be one-ninth of its present value.

43. Show that the gravitational force between two planets is quadrupled if the masses of both planets are doubled but the distance between them stays the same.

44. Show that there is no change in the force of gravity between two objects when their masses are doubled and the distance between them is also doubled.

45. Find the change in the force of gravity between two planets when their distance apart is *decreased* by a factor of 10.

46. Consider a pair of planets in which the distance between them is decreased by a factor of 5. Show that the force between them becomes 25 times as strong.

47. Many people mistakenly believe that the astronauts who orbit Earth are "above gravity." Earth's mass is 6×10^{24} kg, and its radius is 6.38×10^6 m (6380 km). Use the inverse-square law to show that in "space shuttle territory," 200 kilometers above Earth's surface, the force of gravity on a shuttle is about 94% that at Earth's surface.

48. Newton's universal law of gravity tells us that $F = G\frac{m_1 m_2}{d^2}$. Newton's second law tells us that $a = \frac{F_{net}}{m}$.

(a) With a bit of algebraic reasoning, show that your gravitational acceleration toward any planet of mass M a distance d from its center is $a = \frac{GM}{d^2}$.

(b) How does this equation tell you whether or not your gravitational acceleration depends on your mass?

49. An airplane is flying horizontally with speed 1000 km/h (280 m/s) when an engine falls off. Neglecting air resistance, assume that it takes 30 s for the engine to hit the ground.
(a) Show that the altitude of the airplane is 4.4 km. (Use $g = 9.8\ \text{m/s}^2$.)
(b) Show that the horizontal distance that the airplane engine travels during its fall is 8.4 km.
(c) If the airplane somehow continues to fly as though nothing had happened, where is the engine relative to the airplane at the moment the engine hits the ground?

50. A ball is thrown horizontally from a cliff at a speed of 10 m/s. Show that its speed one second later is about 14 m/s.

51. A satellite at a particular point along an elliptical orbit has a gravitational potential energy of 5000 MJ with respect to Earth's surface and a kinetic energy of 4500 MJ. Later in its orbit the satellite's potential energy is 6000 MJ. Use the conservation of energy to find its kinetic energy at that point.

52. A rock thrown horizontally from a bridge hits the water below. The rock travels a smooth parabolic path in time t.
(a) Show that the height of the bridge is $\frac{1}{2}gt^2$.
(b) What is the height of the bridge if the time the rock is airborne is 2 s?
(c) To solve this problem, what information is assumed here that wasn't in Chapter 2?

53. A baseball is tossed at a steep angle into the air and makes a smooth parabolic path. Its time in the air is t, and it reaches a maximum height h. Assume that air resistance is negligible.
(a) Show that the height reached by the ball is $\frac{gt^2}{8}$.
(b) Show that if the ball is in the air for 4 s, it reaches a height of nearly 20 m.
(c) If the ball reached the same height as it did when it was tossed at some other angle, would the time of flight be the same?

54. A penny on its side moving at speed v slides off the horizontal surface of a table a vertical distance y from the floor.
(a) Show that the penny lands a distance $v\sqrt{\frac{2y}{g}}$ from the base of the coffee table.
(b) Show that if the speed is 3.5 m/s and the coffee table is 0.4 m tall, the distance the coin lands from the base of the table is 1.0 m. (Use $g = 9.8\ \text{m/s}^2$.)

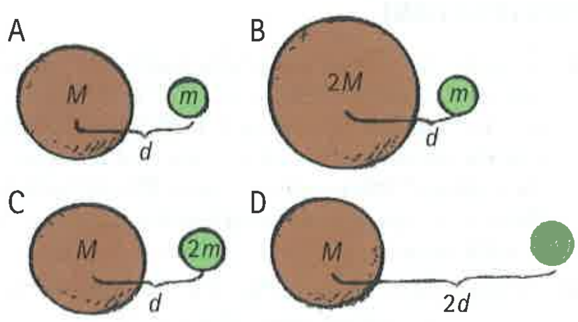
55. Students in a lab measure the speed of a steel ball launched horizontally from a tabletop to be v. The tabletop is distance y above the floor. They place a tin coffee can of height $0.1y$ on the floor to catch the ball.
(a) Show that the can should be placed a horizontal distance from the base of the table of

$$v\sqrt{\frac{2(0.9)y}{g}}$$

(b) Show that if the ball leaves the tabletop at a speed of 4.0 m/s, the tabletop is 1.5 m above the floor, and the can is 0.15 m tall, then the center of the can should be placed a horizontal distance of 2.1 m from the base of the table.

THINK AND RANK (ANALYSIS)

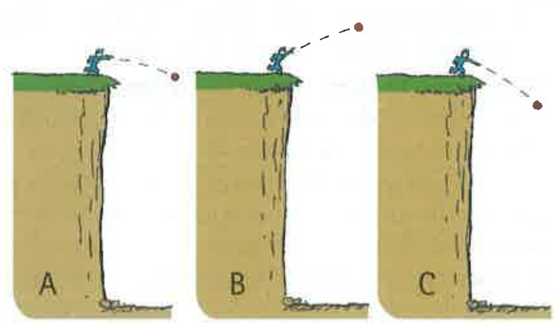
56. The planet and its moon gravitationally attract each other. Rank, from greatest to least, the force of attraction between the members of each pair.



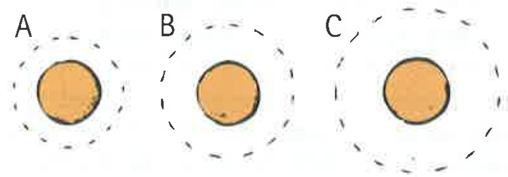
57. Consider the light of multiple candle flames, each of the same brightness. Rank, from brightest to dimmest, the light that enters your eye for the following situations. (a) 3 candles seen from a distance of 3 m. (b) 2 candles seen from a distance of 2 m. (c) 1 candle seen from a distance of 1 m.

58. Rank, from greatest to least, the average gravitational forces between: (a) The Sun and Mars. (b) The Sun and the Moon. (c) The Sun and Earth.

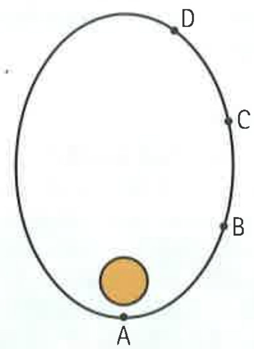
59. A ball is tossed off the edge of a cliff with the same speed, but at different angles as shown. Rank, from greatest to least: (a) The initial PEs of the balls relative to the ground below. (b) The initial KEs of the balls when tossed. (c) The KEs of the balls when hitting the ground below. (d) The times of flight while airborne.



60. The dashed lines show three circular orbits about Earth. Rank the following quantities from greatest to least: (a) Their orbital speed. (b) Their time to orbit Earth.



61. The positions of a satellite in elliptical orbit are indicated. Rank the following quantities from greatest to least: (a) Gravitational force. (b) Speed. (c) Momentum. (d) KE. (e) PE. (f) Total energy (KE + PE). (g)Acceleration.



EXERCISES (SYNTHESIS)

4.1 The Universal Law of Gravity

62. What would be the path of the Moon if somehow all gravitational acting forces on it sank to zero?
63. Is the gravitational force greater on a 1-kg piece of iron or on a 1-kg piece of glass? Defend your answer.
64. Consider a space pod somewhere between Earth and the Moon, at just the right distance so that gravitational attraction to Earth and gravitational attraction to the Moon are equal. Is this location nearer Earth or nearer the Moon?
65. An astronaut lands on a planet that has the same mass as Earth but half the diameter. How does the astronaut's weight differ from that on Earth?
66. An astronaut lands on a planet that has the same mass as Earth and twice the diameter. How does the astronaut's weight differ from her or his weight on Earth?
67. If Earth somehow expanded to a larger radius, with no change in mass, how would your weight be affected? How would it be affected if Earth instead shrunk? (Hint: Let the equation for gravitational force guide your thinking.)

4.2 Gravity and Distance: The Inverse-Square Law

68. How would the force between a planet and its moon change if its moon were boosted to twice its distance from the center of the planet? If it were instead brought to half its distance from the center of the planet?
69. Phil works on the 15th floor of an office building, and his wife Jean works on the 30th floor, which is twice as high as Phil's workplace. Is the force of gravity half as much in Jean's workspace as in Phil's? Explain why or why not.
70. In 2013, Curiosity landed on the surface of Mars. Does the weight of Curiosity vary if it makes its way from a valley floor to the top of a tall hill? Explain.
71. Earth is not exactly a sphere but, rather, bulges outward at the equator. How does this bulge affect the relationship between a person's weight in Singapore and his or her weight in Hong Kong?
72. A small light source located 1 m in front of a 1-m^2 opening illuminates a wall behind. If the wall is 1 m behind the opening (2 m from the light source), the illuminated area covers 4 m^2. How many square meters are illuminated if the wall is 3 m from the light source? 5 m from the light source? 10 m from the light source?
73. The intensity of light from a central source varies inversely as the square of the distance. If you lived on a planet only half as far from the Sun as our Earth, how would the light intensity compare with that on Earth? How about a planet five times as far away as Earth?

4.3 Weight and Weightlessness

74. Why do the passengers in high-altitude jet planes feel the sensation of weight, while passengers in the International Space Station do not?
75. To begin your wingsuit flight, you step off the edge of a high cliff. Why are you then momentarily weightless? At that point, is gravity acting on you?
76. In synchronized diving, divers remain in the air for the same time. With no air resistance, they would fall exactly together. But air resistance is appreciable, so how do they remain together in fall?
77. What two forces act on you while you are in a moving elevator? When are these forces of equal magnitude and when are they not?
78. If you were in a freely falling elevator and you dropped a pencil, it would hover in front of you. Is there a force of gravity acting on the pencil? Defend your answer.

4.4 Universal Gravitation

79. In the 2014 Rosetta mission, a probe from Earth landed on a comet of very low mass. If the probe had been twice as massive, how would its weight on the comet surface have been affected?
80. How does the size of Pluto compare with that of planets in the solar system?
81. Elements beyond the naturally occurring elements that have been discovered that are named Neptunium and Plutonium. How was the naming process related to discovery of new planets?

82. Earth and the Moon are gravitationally attracted to the Sun, but they don't crash into the Sun. A friend says that is because Earth and the Moon are beyond the Sun's main gravitational influence. Other friends look to you for a response. What is your response?

4.5 Projectile Motion

83. Chuck Stone releases a ball near the top of a track and measures the ball's speed as it rolls horizontally off the end of the table. Students make measurements to predict where a can must be placed to catch the ball. How will the ball's speed affect the time it takes to reach the can once the ball leaves the end of the table? (Does a faster ball take a longer time to hit the floor?) Defend your answer.

84. In the absence of air resistance, why does the horizontal component of a projectile's motion not change, while the vertical component does?
85. At what point in its trajectory does a batted baseball have its minimum speed? If air resistance can be neglected, how does this compare with the horizontal component of its velocity at other points?
86. A heavy crate accidentally falls from a high-flying airplane just as it flies directly above Mike's shiny red Corvette defensively parked in a car lot. Relative to the Corvette, where does the crate crash?

87. Two golfers each hit a ball at the same speed, but one hits it at 60° with the horizontal and the other at 30°. Which ball goes farther? Which hits the ground first? (Ignore air resistance.)
88. When you jump upward, your hang time is the time your feet are off the ground. Does hang time depend on the vertical component of your velocity when you jump, on your the horizontal component of your velocity, or on both? Defend your answer.
89. The hang time of a basketball player who jumps a vertical distance of 2 feet (0.6 m) is about 0.6 s. What is the hang time if the player reaches the same height while jumping 4 ft (1.2 m) horizontally?

4.6 Fast-Moving Projectiles—Satellites

90. If you've had the good fortune to witness the launching of an Earth satellite, you may have noticed that the rocket starts vertically upward, then departs from a vertical course and continues its climb at an angle. Why does it start vertically? Why does it not continue vertically?
91. Newton knew that if a cannonball were fired from a tall mountain, gravity would change its speed all along its trajectory (Figure 4.29). But if it is fired fast enough to attain circular orbit, gravity does not change its speed at all. Explain.
92. Satellites are normally sent into orbit by firing them in an easterly direction, the direction in which Earth spins. What is the advantage of this?
93. Hawaii presents the most efficient launching site in the United States for nonpolar satellites. Why is this so? (Hint: Look at the spinning Earth from above either pole, and compare it to a spinning turntable.)

4.7 Circular Satellite Orbits

94. Does the speed of a falling object depend on its mass? (Recall the answer to this question in earlier chapters.) Does the speed of a satellite in orbit depend on its mass? Defend your answers.
95. If a space vehicle circled Earth at a distance equal to the Earth–Moon distance, how long would it take for it to make a complete orbit? In other words, what would be its period?
96. What is the shape of the orbit when the velocity of the satellite is everywhere perpendicular to the force of gravity?
97. If a flight mechanic drops a box of tools from a high-flying jumbo jet, it crashes to Earth. If an astronaut in an orbiting space vehicle drops a box of tools, does it crash to Earth also? Defend your answer.
98. How could an astronaut in a space vehicle "drop" an object vertically to Earth?
99. If you stopped an Earth satellite dead in its tracks—that is, if you reduced its tangential velocity to zero—it would simply crash into Earth. Why, then, don't the communications satellites that "hover motionless" above the same spot on Earth crash into Earth?
100. The orbital velocity of Earth about the Sun is 30 km/s. If Earth were suddenly stopped in its tracks, it would simply fall radially into the Sun. Devise a plan whereby a rocket loaded with radioactive wastes could be fired into the Sun for permanent disposal. How fast and in what direction with respect to Earth's orbit should the rocket be fired?

4.8 Elliptical Orbits

101. At what point in Earth's elliptical orbit about the Sun is the acceleration of Earth toward the Sun a maximum? At what point is it a minimum? Defend your answers.
102. The force of gravity on an Earth satellite in circular orbit remains constant at all points along the orbit. Why is this not the case for a satellite in an elliptical orbit?
103. Earth is farthest away from the Sun in July and closest in January. In which of these two months is Earth moving faster around the Sun?

4.9 Escape Speed

104. In the 2014 Rosetta mission, when a probe from Earth landed on the low-mass comet, the probe bounced. Why were scientists overseeing the mission concerned about the comet's escape speed?

105. An object tossed vertically will reach a maximum height. An object dropped from that same height would land with the same speed at which the first object was thrown. How fast would an object hit Earth if it were dropped from a distance beyond Neptune, falling only because of Earth gravity?

DISCUSSION QUESTIONS (EVALUATION)

106. Comment on whether or not the following label on a consumer product should be cause for concern.

CAUTION: The mass of this product pulls on every other mass in the universe, with an attracting force that is proportional to the product of the masses and inversely proportional to the square of the distance between them.

107. Newton tells us that gravitational force acts on all bodies in proportion to their masses. Why, then, doesn't a heavy body fall faster than a light body?

108. "Okay," a friend says, "gravitational force is proportional to mass. Is gravitation then stronger on a crumpled piece of aluminum foil than on an identical piece of foil that has not been crumpled? Isn't that why the crumpled one falls faster when they are dropped together?" Defend your answer and explain why the two fall differently.

109. An apple falls because of its gravitational attraction to Earth. How does the gravitational attraction of Earth to the apple compare? (Does force change when you interchange m_1 and m_2 in the equation for gravity—$m_2 m_1$ instead of $m_1 m_2$?)

110. Jupiter is more than 300 times as massive as Earth, so it might seem that a body on the surface of Jupiter would weigh 300 times as much as it would weigh on Earth. But it so happens that a body would weigh scarcely three times as much on the surface of Jupiter as it would on the surface of Earth. Discuss why this is so. (Hint: Let the terms in the equation for gravitational force guide your thinking.)

111. When will the gravitational force between you and the Sun be greater: today at noon or tomorrow at midnight? Defend your answer.

112. Explain why the following reasoning is wrong. "The Sun attracts all bodies on Earth. At midnight, when the Sun is directly below, it pulls on you in the same direction as Earth pulls on you; at noon, when the Sun is directly overhead, it pulls on you in a direction opposite to Earth's pull on you. Therefore, you should be somewhat heavier at midnight and somewhat lighter at noon."

113. Some people dismiss the validity of scientific theories by saying they are "only" theories. The law of universal gravitation is a theory. Does this mean that scientists still doubt its validity? Explain.

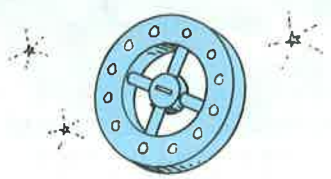
114. Shruti Kumar projects a ball at an angle of 30° above the horizontal. Which component of initial velocity is larger: the vertical or the horizontal? Which of these components undergoes the least change while the ball is airborne? Defend your answer.

115. A friend claims that bullets fired by some high-powered rifles travel for many meters in a straight-line path before they start to fall. Another friend disputes this claim and states that all bullets from any rifle drop beneath a straight-line path a vertical distance given by $\frac{1}{2}gt^2$ as soon as they leave the barrel and that the curved path is apparent for low velocities and less apparent for high velocities. Now it's your turn: Do all bullets drop the same vertical distance in equal times? Explain.

116. A park ranger shoots a monkey hanging from a branch of a tree with a tranquilizing dart. The ranger aims directly at the monkey, not realizing that the dart will follow a parabolic path and thus will fall below the monkey. The monkey, however, sees the dart leave the gun and lets go of the branch to avoid being hit. Will the monkey be hit anyway? Does the velocity of the dart affect your answer, assuming that it is great enough to travel the horizontal distance to the tree before hitting the ground? Defend your answer.

117. Which requires more fuel: a rocket going from Earth to the Moon or a rocket returning from the Moon to Earth? Why?

118. Two facts: A freely falling object at Earth's surface drops vertically 5 m in 1 s. Earth's curvature "drops" 5 m for each 8-km tangent. Discuss how these two facts are related to the 8-km/s orbital speed necessary to orbit Earth.
119. A new member of your discussion group says that, because Earth's gravity is so much stronger than the Moon's gravity, rocks on the Moon could be dropped to Earth. What is wrong with this assumption?
120. A friend says that astronauts inside the International Space Station (ISS) are weightless because they're beyond the pull of Earth's gravity. Correct your friend's reasoning.
121. Another new member of your discussion group says the primary reason why astronauts in orbit feel weightless is that they are being pulled by other planets and stars. Why do you agree or disagree?
122. Occupants inside future donut-shaped rotating habitats in space will be pressed to their floors by rotational effects. Their sensation of weight feels as real as that due to gravity. Does this indicate that weight need not be related to gravity?



123. A satellite can orbit at 5 km above the Moon's surface, but not at 5 km above Earth's surface. Why?
124. As part of their training before going into orbit, astronauts experience weightlessness when riding in an airplane that is flown along the same parabolic trajectory as a freely falling projectile. A classmate says that gravitational forces on everything inside the plane during this maneuver cancel to zero. Another classmate looks to you for confirmation. What is your response?
125. Would the speed of a satellite in close circular orbit about Jupiter be greater than, equal to, or less than 8 km/s?
126. A communications satellite with a 24-h period hovers over a fixed point on Earth. Why is it placed in orbit only in the plane of Earth's equator? (Hint: Think of the satellite's orbit as a ring around Earth.)
127. This situation should elicit good discussion: In an accidental explosion, a satellite breaks in half while in circular orbit about Earth. One half is brought momentarily to rest. What is the fate of the half brought to rest? What happens to the other half? (Hint: Think momentum conservation.)
128. (Here's a Chapter 2-type question): When the brakes are applied on a vehicle moving to the right, the horizontal net force on the vehicle is to the left. A friend says that the velocity and acceleration of the vehicle are in opposite directions. Do you agree or disagree? Defend your answer.
129. (Here's a Chapter 4-type question): The first stage of each SpaceX rocket that services the ISS no longer is dumped into the sea, but is returned for recycling (when all goes well). As the empty first stage falls back to Earth, one of its main engines slows its descent velocity to zero at the moment of touchdown. Is it correct to say that during this maneuver, the velocity and the acceleration of the first stage are in opposite directions? Defend your answer.
130. Here's a situation to challenge you and your friends: A rocket coasts in an elliptical orbit around Earth. To attain the greatest amount of KE for escape using a given amount of fuel, should it fire its engines at the apogee (the point at which it is farthest from Earth) or at the perigee (the point at which it is closest to Earth)? (Hint: Let the formula $Fd = \Delta\text{KE}$ guide your thinking. Suppose the thrust F is brief and of the same duration in either case. Then consider the distance d that the rocket would travel during this brief burst at the apogee and at the perigee.)