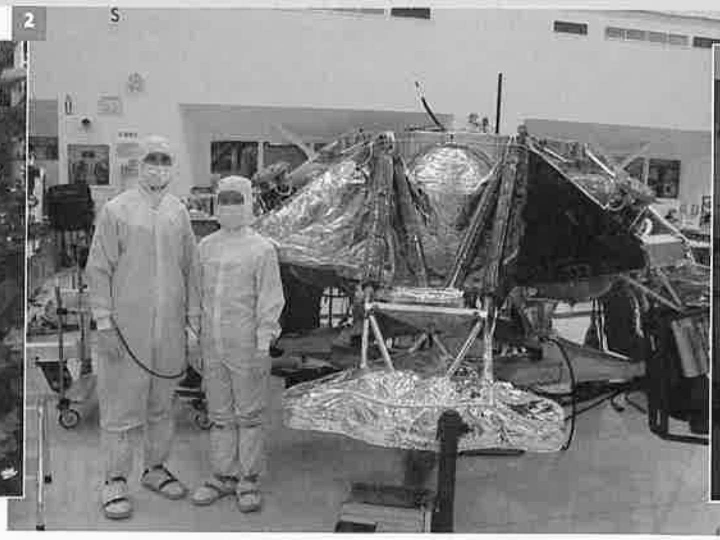
10 Projectile and Satellite Motion



1 Topographic globes that show the relative heights of mountains and valleys are greatly exaggerated. Truly scaled, the surface of Earth is as smooth as the globe that Emily Abrams holds. And Earth's atmosphere is a small fraction of the width of her fingers, with space shuttles orbiting about the distance to her smallest fingernail! 2 In the dust-free "clean room" of the Jet Propulsion Laboratory, Ben Thoma and Tenny Lim stand beside the Mars Science Laboratory Descent Stage that is scheduled for a 2011 launch to Mars. 3 Tenny with a scale model of her design.

A teacher's influence knows no bounds. Our influence on students goes beyond what feedback makes its way to us. When I'm asked about which of my many students I take most pride in, and whom I most influenced, my answer is quick: Tenny Lim. In addition to being bright, she is artistic and very dexterous with her hands. She was the top-scoring student in my Conceptual Physics class in 1980 and earned an AS degree in Dental Laboratory Technology. With my encouragement and support, she continued at City College with courses in math and science and decided to pursue an engineering career. Two years later, she transferred to California Polytechnic Institute in San Luis Obispo. While earning her BS degree in mechanical engineering, a recruiter from the Jet Propulsion Laboratory in Pasadena was impressed that she concurrently took art classes to balance her technical studies. When asked about this, she replied that art was one of her passions. What the recruiter was looking for was someone talented in both art and engineering for JPL's design team. Tenny was hired and became part of the space program. Her current project is the Mars Science Laboratory, where she is the lead designer for the Descent Stage (see photo above). She also continues to pursue her art and has her work shown in local galleries.

Tenny's story exemplifies my advice to young people: Excel at more than one thing.

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Without gravity, you could toss a rock at an angle skyward and it would follow a straight-line path. Because of gravity, however, the path curves. A tossed rock, a cannonball, or any object that is projected by some means and continues in motion by its own inertia is called a **projectile.** To the cannoneers of earlier centuries, the curved paths of projectiles seemed very complex. Today these paths are surprisingly simple when we look at the horizontal and vertical components of velocity separately.

The horizontal component of velocity for a projectile is no more complicated than the horizontal velocity of a bowling ball rolling freely on the lane of a bowling alley. If the retarding effect of friction can be ignored, there is no horizontal force on the ball and its velocity is constant. It rolls of its own inertia and covers equal distances in equal intervals of time (Figure 10.1, above right). The horizontal component of a projectile's motion is just like the bowling ball's motion along the lane.

The vertical component of motion for a projectile following a curved path is just like the motion described in Chapter 3 for a freely falling object. The vertical component is exactly the same as for an object falling freely straight down, as shown at the left in Figure 10.1. The faster the object falls, the greater the distance covered in each successive second. Or, if the object is projected upward, the vertical distances of travel decrease with time on the way up.

The curved path of a projectile is a combination of horizontal and vertical motion (Figure 10.2). The horizontal component of velocity for a projectile is completely independent of the vertical component of velocity when air resistance is small enough to ignore. Then the constant horizontal-velocity component is not affected by the vertical force of gravity. Each component is independent of the other. Their combined effects produce the trajectories of projectiles.

FIGURE 10.1

(Above right) Roll a ball along a level surface, and its velocity is constant because no component of gravitational force acts horizontally. (Above) Drop it, and it accelerates downward and covers a greater vertical distance each second.

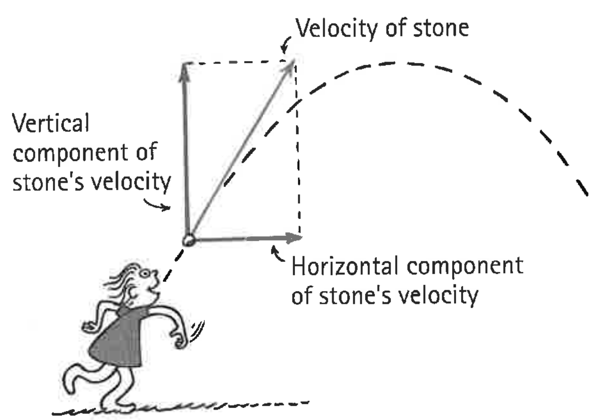
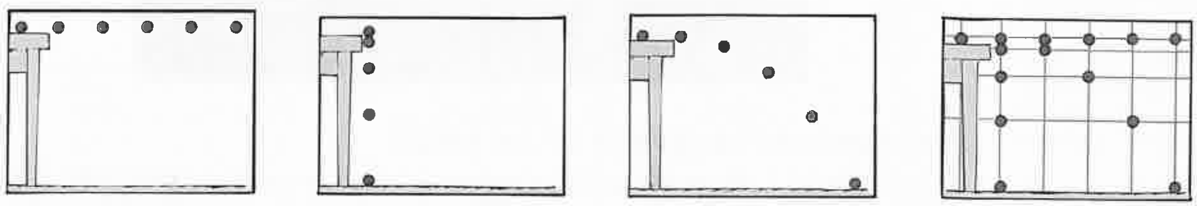


FIGURE 10.2

Vertical and horizontal components of a stone's velocity.

PROJECTILES LAUNCHED HORIZONTALLY

Projectile motion is nicely analyzed in Figure 10.3, 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. At 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. Notice two important things. 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. Notice the curvature of the ball's path is the combination of constant horizontal motion, and accelerated vertical motion.



Horizontal motion with no gravity

Vertical motion only with gravity

Combined horizontal and vertical motion

Superposition of the preceding cases

FIGURE 10.3

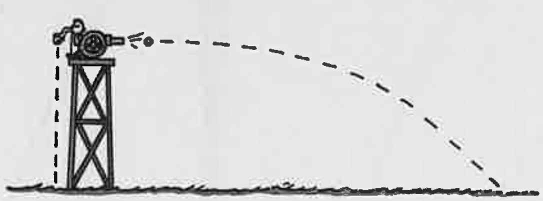
INTERACTIVE FIGURE

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.

CHECK POINT

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?



Check Your Answer

Both cannonballs hit the ground at the same time, for both fall *the same vertical distance.* Notice that the physics is the same as shown in Figures 10.3 and 10.4. 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 remains 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?

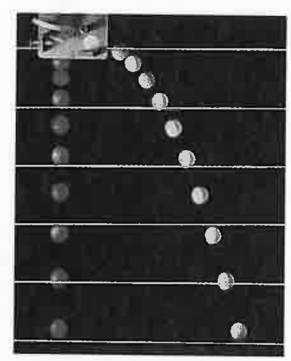


FIGURE 10.4

INTERACTIVE FIGURE

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.

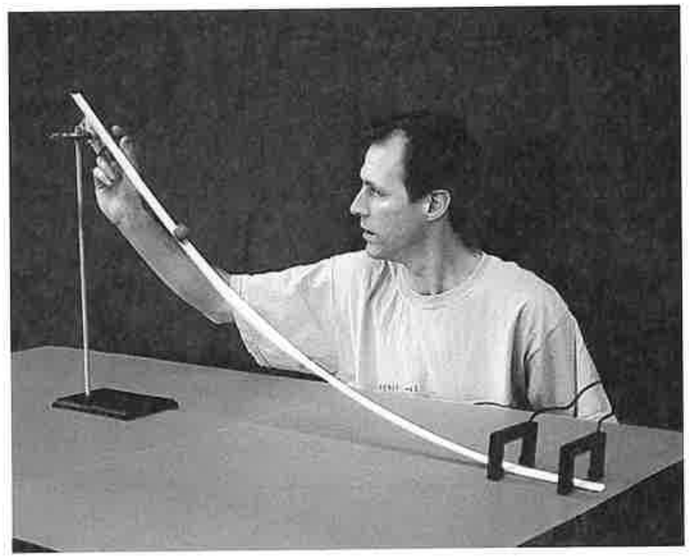


FIGURE 10.5
Chuck Stone releases a ball near the top of a track. His students make measurements to predict where a can on the floor should be placed to catch the ball after it rolls off the table.

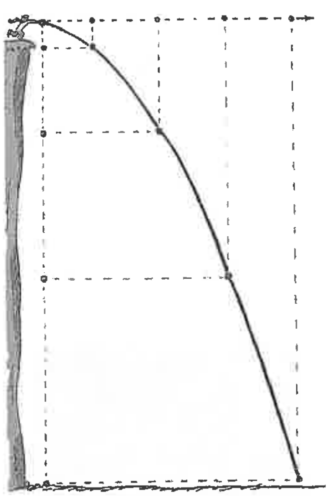


FIGURE 10.6
The vertical dashed line is the path of a stone dropped from rest. The horizontal dashed line would be its path if there were no gravity. The curved solid line shows the resulting trajectory that combines horizontal and vertical motion.

PROJECTILES LAUNCHED AT AN ANGLE

In Figure 10.7, we see the paths of stones thrown at an angle upward (left) and downward (right). The dashed straight lines show the ideal trajectories of the stones if there were no gravity. Notice that the vertical distance beneath the idealized straight-line paths is the same for equal times. This vertical distance is independent of what's happening horizontally.

Figure 10.8 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 really happens is that the cannonball continuously falls beneath the imaginary line until it finally strikes the ground. Note that the vertical distance it falls beneath any point on the dashed line is the same vertical distance it would fall if it were dropped from rest and had been falling for the same amount of time. This distance, as introduced in Chapter 3, is given by $d = \frac{1}{2}gt^2$, where t is the elapsed time.

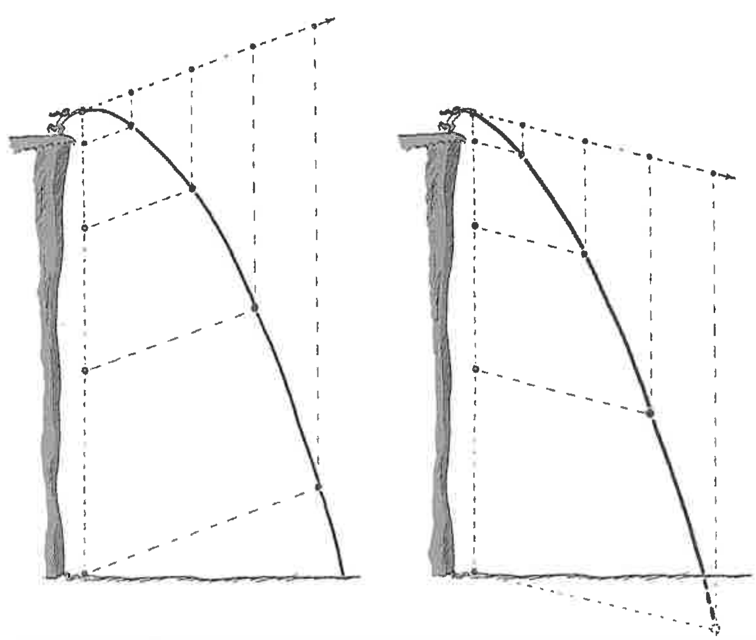


FIGURE 10.7
Whether launched at an angle upward or downward, the vertical distance of fall beneath the idealized straight-line path is the same for equal times.

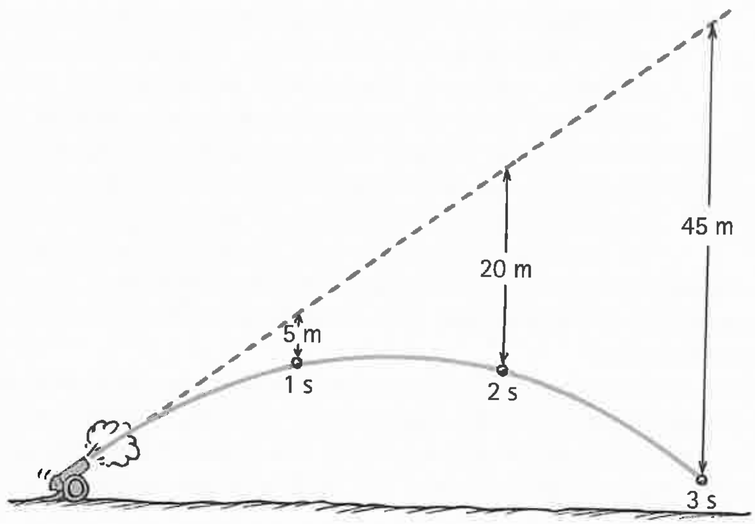


FIGURE 10.8
With no gravity, the projectile would follow a straight-line path (dashed line). But, because of gravity, the projectile falls beneath this line the same vertical distance it would fall if it were released from rest. Compare the distances fallen with those given in Table 3.3 in Chapter 3. (With $g = 9.8\ \text{m/s}^2$, these distances are more precisely 4.9 m, 19.6 m, and 44.1 m.)

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!

Note another thing from Figure 10.8 and previous figures. The ball moves equal horizontal distances in equal time intervals. That's because no acceleration takes place horizontally. The only acceleration is vertical, in the direction of Earth's gravity.

CHECK POINT

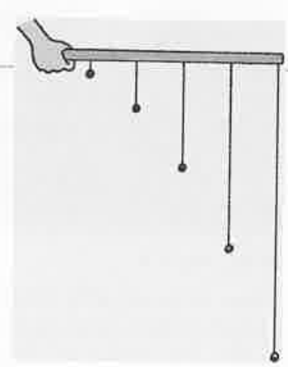
1. Suppose the cannonball in Figure 10.8 were fired faster. How many meters below the dashed line would it be at the end of the 5 s?
2. If the horizontal component of the cannonball's velocity is 20 m/s, how far downrange will the cannonball be in 5 s?

Check Your Answers

1. The vertical distance beneath the dashed line at the end of 5 s is 125 m $[d = 5t^2 = 5(5)^2 = 5(25) = 125\ \text{m}]$. Interestingly enough, this distance doesn't depend on the angle of the cannon. If air drag is neglected, any projectile will fall $5t^2$ m below where it would have reached if there were no gravity.
2. With no air drag, the cannonball will travel a horizontal distance of 100 m $[d = \bar{v}t = (20\ \text{m/s})(5\ \text{s}) = 100\ \text{m}]$. Note that, since 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).

Practicing Physics: 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 10.6. Hold it at a slight upward angle to show a version of Figure 10.7, left. Hold it at a downward angle to show a version of Figure 10.7, right.



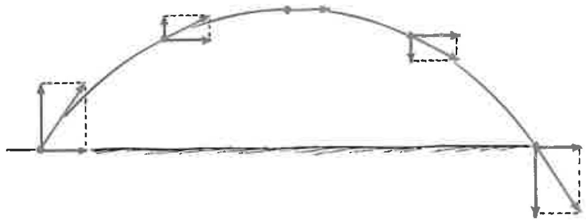


FIGURE 10.9

INTERACTIVE FIGURE

The velocity of a projectile at various points along its trajectory. Note that the vertical component changes and that the horizontal component is the same everywhere.

In Figure 10.9, we see vectors representing both horizontal and vertical components of velocity for a projectile following a parabolic trajectory. Notice that the horizontal component everywhere along the trajectory is the same, and only the vertical component changes. Note also that the actual velocity is represented by the vector that forms the diagonal of the rectangle formed by the vector components. At the top of the trajectory, the vertical component is zero, so the velocity at the zenith is only the horizontal component of velocity. Everywhere else along the trajectory, the magnitude of velocity is greater (just as the diagonal of a rectangle is greater than either of its sides).

Figure 10.10 shows the trajectory traced by a projectile launched with the same speed at a steeper angle. Notice the initial velocity vector has a greater vertical component than when the launch angle is smaller. This greater component results in a trajectory that reaches a greater height. But the horizontal component is less, and the range is less.

Figure 10.11 shows the paths of several projectiles, all with the same initial speed but different launching angles. The figure neglects the effects of air drag, 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 10.11 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, will have 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°—when air drag is negligible.

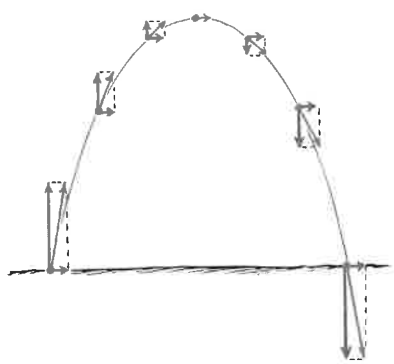


FIGURE 10.10

Trajectory for a steeper projection angle.

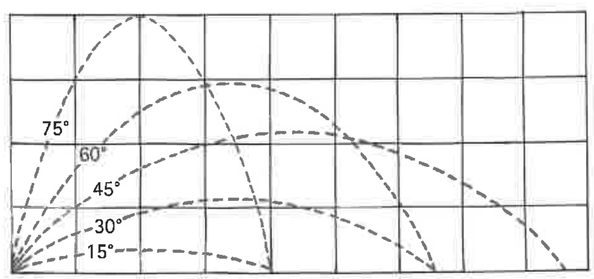


FIGURE 10.11

INTERACTIVE FIGURE

Ranges of a projectile shot at the same speed at different projection angles.

FIGURE 10.12

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

CHECK POINT

1. A baseball is batted at an angle into the air. Once airborne, and neglecting air drag, 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?

Check 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!

Without the effects of air, the maximum range for a baseball would occur when it is batted 45° above the horizontal. Without air drag, the ball rises just like it falls, covering the same amount of ground while rising as while falling. But not so when air drag slows the ball. Its horizontal speed at the top of its path is less than its horizontal speed when leaving the bat, so it covers less ground while falling than when 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 14 will show, spin of the ball also affects range.) For heavy projectiles like javelins and the shot, air has less effect on range. A javelin, being heavy and presenting a very small cross section to the air, follows an almost perfect parabola when thrown. So does a shot. Aha, but *launching speeds* are not equal for heavy projectiles thrown at different angles. In throwing a javelin or putting a shot, a significant part of the launching *force* goes into lifting—combating gravity—so launching at 45° means less 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 maximum range for heavy projectiles thrown by humans is attained for angles of less than 45°—and not because of air drag.

When air resistance is small enough to be negligible, a projectile will rise to its maximum height in the same time it takes to fall from that height to its initial level (Figure 10.14). 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.

Baseball games normally take place on level ground. For the short-range projectile motion on the playing field, Earth can be considered to be 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 will fall all the way around Earth and become an Earth satellite.

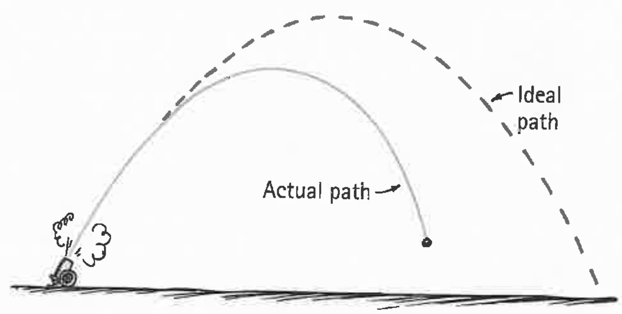


FIGURE 10.13

INTERACTIVE FIGURE

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

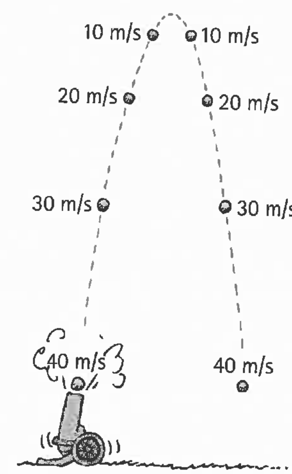


FIGURE 10.14

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

CHECK POINT

The boy on the tower throws a ball 20 m downrange, as shown in Figure 10.15. What is his pitching speed?

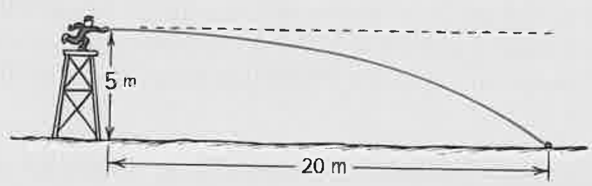


FIGURE 10.15

Check 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*.

Hang Time Revisited

In Chapter 3, 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 lift-off velocity. It so happens, however, that the action of running can make a difference. When running, the lift-off force during jumping can be appreciably increased by 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 exceed hang time for a standing jump. But again for emphasis: Once the runner's feet are off the ground, only the vertical component of lift-off velocity determines hang time.

Fast-Moving Projectiles—Satellites

Consider the baseball pitcher on the tower in Figure 10.15. 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 will have 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.

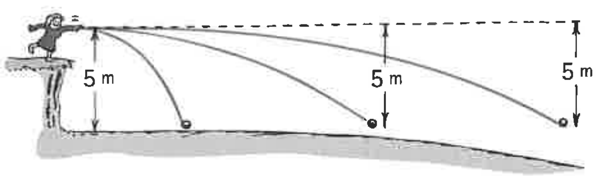


FIGURE 10.16
If you throw a ball at any speed, 1 s later it will have fallen 5 m below where it would have been without gravity.

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.

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 tangent to the surface (Figure 10.17). 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)!

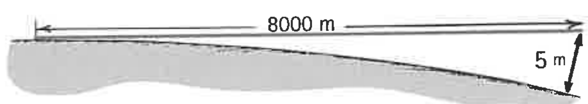


FIGURE 10.17
Earth's curvature—not to scale!

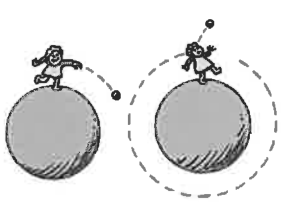


FIGURE 10.18
If the speed of the stone is great enough, the stone may become a satellite.

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 km 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 km above

Earth's surface is nearly as strong as it is at the surface. The high altitude is to position the satellite beyond Earth's atmosphere, where air resistance is almost totally absent, but not beyond Earth's gravity.

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 10.19). He compared the motion of the Moon to 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 cannonball and Moon have tangential velocity (parallel to Earth's surface) sufficient to ensure motion *around* the Earth rather than *into* it. If there is no resistance to reduce its speed, the Moon or any Earth satellite "falls" around and around the 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 their 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.

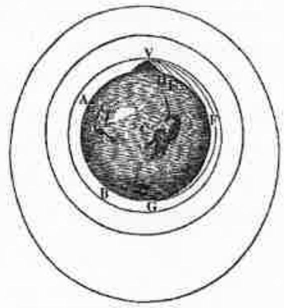


FIGURE 10.19

"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.*

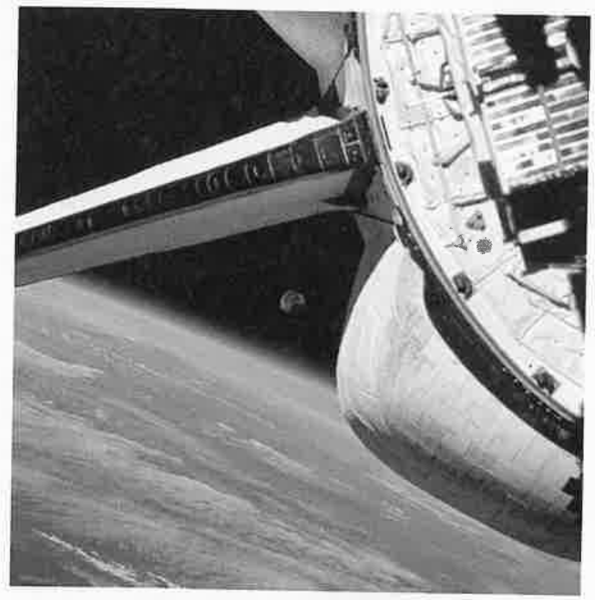


FIGURE 10.20

A space shuttle is a projectile in a constant state of free fall. Because of its tangential velocity, it falls around the Earth rather than vertically into it.

CHECK POINT

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.

Check 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 field is only a few percent weaker than it is at Earth's surface.

Circular Satellite Orbits

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

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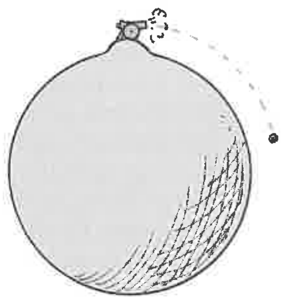


FIGURE 10.21

INTERACTIVE FIGURE

Fired fast enough, the cannonball will go into orbit.

foresee the possibility of humans launching satellites (and likely didn't consider multistage rockets).

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.

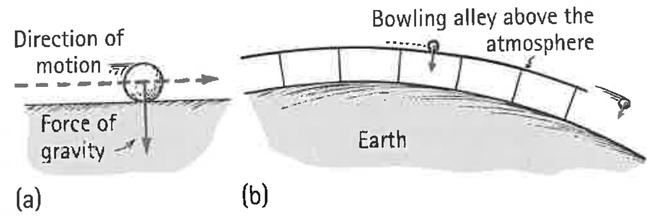


FIGURE 10.22

(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.

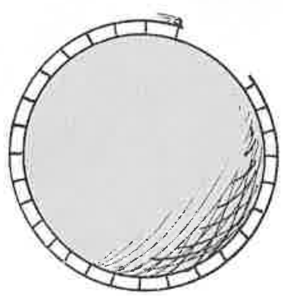


FIGURE 10.23

What speed will allow the ball to clear the gap?

Consider a bowling lane that completely surrounds the Earth, elevated high enough to be above the atmosphere and air resistance. The bowling ball will roll at constant speed along the lane. If a part of the lane were cut away, 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 any gap—even a 360° gap. The ball would be in circular orbit.

Note that a satellite in circular orbit is always moving in a direction perpendicular to the force of gravity that acts upon it. The satellite does not move in the direction of the force, which would increase its speed, nor does it move in a direction against the force, which would decrease its speed. Instead, the satellite moves at right angles to the gravitational force that acts upon it. No change in speed occurs—only a change in direction. So we see why a satellite in circular orbit sails parallel to the surface of the 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 minutes. For higher altitudes, the orbital speed is less, 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 hours. This period matches the period of daily Earth rotation. For an orbit around the equator, these satellites always 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 less its speed, the longer its path, and the longer its period.[1]

> The initial vertical climb gets a rocket quickly through the denser part of the atmosphere. Eventually, the rocket must acquire enough tangential speed to remain in orbit without thrust, so it must tilt until its path is parallel to Earth's surface.

Putting a satellite 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 resistance of the atmosphere, it is aimed horizontally, whereupon the satellite is given a final thrust to orbital speed. We see this in Figure 10.24, where, for the sake of simplicity, the

[1]The speed of a satellite in circular orbit is given by $v = \sqrt{\frac{GM}{d}}$ and the period of satellite motion is given by $T = 2\pi\sqrt{\frac{d^3}{GM}}$, where G is the universal gravitational constant (see previous Chapter 9), 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.

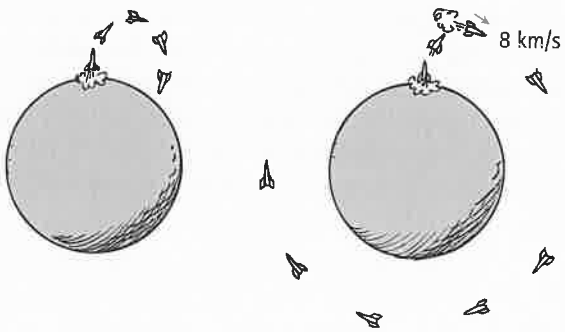


FIGURE 10.24
The initial thrust of the rocket pushes it up above the atmosphere. Another thrust to a tangential speed of at least 8 km/s is required if the rocket is to fall around rather than into Earth.

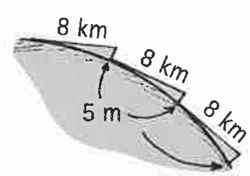
satellite is the entire single-stage rocket. With the proper tangential velocity, it falls around Earth, rather than into it, and becomes an Earth satellite.

CHECK POINT

1. True or false: The space shuttle orbits at altitudes in excess of 150 km to be above both gravity and Earth's atmosphere.
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?

Check Your Answers

1. False. What satellites are above is 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 the planet. 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.



Elliptical Orbits

If a projectile just above the resistance of the atmosphere is given a horizontal speed somewhat greater than 8 km/s, it will overshoot a circular path and trace 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 pencil (Figure 10.25). 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.

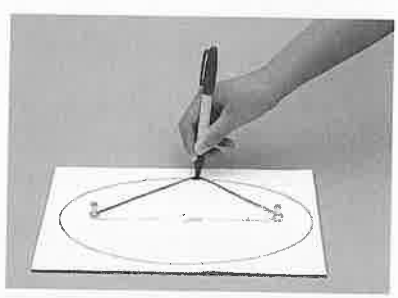


FIGURE 10.25
INTERACTIVE FIGURE
A simple method for constructing an ellipse.

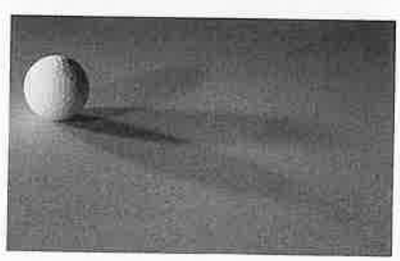


FIGURE 10.26
The shadows cast by the ball from each lamp in the room are all ellipses. The point at which the ball makes contact with the table is the common focus of all three ellipses.

Whereas the speed of a satellite is constant in a circular orbit, speed varies in an elliptical orbit. For an initial speed greater than 8 km/s, the satellite 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 10.27). The procedure repeats over and over, and an ellipse is traced each cycle.

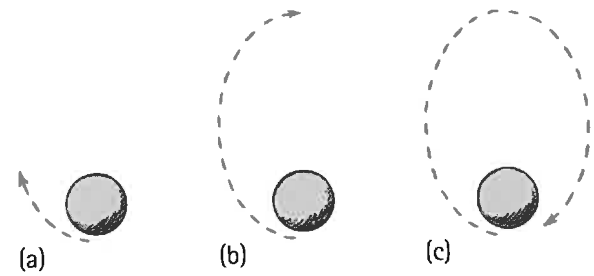


FIGURE 10.27

Elliptical orbit. An Earth satellite that has a speed somewhat greater than 8 km/s overshoots a circular orbit (a) and travels away from Earth. Gravitation slows it to a point where it no longer moves farther from Earth (b). It falls toward Earth, gaining the speed it lost in receding (c), and follows the same path as before in a repetitious 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 10.28a). In Figure 10.28b, 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.

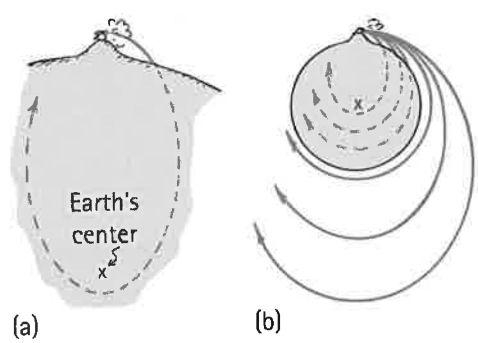
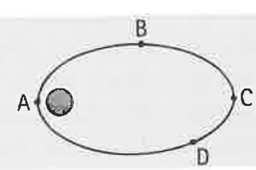


FIGURE 10.28

(a) The parabolic path of the cannonball is 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.

CHECK POINT

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



Check Your Answer

The satellite has its greatest speed as it whips around position 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.

World Monitoring by Satellite

Satellites are useful in monitoring our planet. Figure A shows the path traced in one period by a satellite in circular orbit launched in a northeasterly direction from Cape Canaveral, Florida. The path is curved only because the map is flat. Note that the path crosses the equator twice in one period, for the path describes a circle whose plane passes through Earth's center. Note also that the path does not terminate where it begins. This is because Earth rotates beneath the satellite while it orbits. During the 90-minute period, Earth turns 22.5°, so, when the satellite makes a complete orbit it begins its new sweep many kilometers to the west (about 2500 km at the equator). This is quite advantageous for Earth-monitoring satellites. Figure B shows the area monitored over 10 days by successive sweeps for a typical satellite.

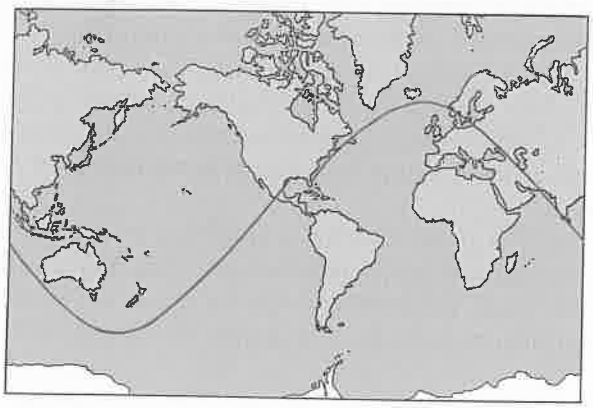


FIGURE A

The path of a typical satellite launched in a northeasterly direction from Cape Canaveral. Because Earth rotates while the satellite orbits, each sweep passes overhead some 2100 km farther west at the latitude of Cape Canaveral.

A dramatic but typical example of such monitoring is the 3-year worldwide watch of the distribution of ocean phytoplankton (Figure C). Such extensive information would have been impossible to acquire before the advent of satellites.

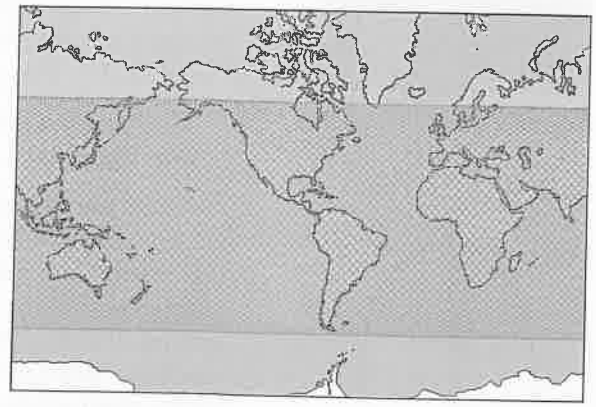


FIGURE B

Typical sweep pattern for a satellite over the period of a week.

FIGURE C

Phytoplankton production in Earth's oceans over a 3-year period. Magenta and yellow show the highest concentrations, while blue shows moderately high concentrations.

Kepler's Laws of Planetary Motion

Newton's law of gravitation was preceded by three important discoveries about planetary motion by the German astronomer Johannes Kepler, who started as a junior assistant to the famed Danish astronomer Tycho Brahe. Brahe directed the world's first great observatory, in Denmark, just before the advent of the telescope. Using huge, brass, protractor-like instruments called *quadrants,* Brahe measured the positions of planets over 20 years so accurately that his measurements are still valid today. Brahe entrusted his data to Kepler. After Brahe's death, Kepler converted Brahe's measurements to values that would be obtained by a stationary observer outside the solar system. Kepler's expectation that the planets would move in perfect circles around the Sun was shattered after years of effort. He discovered the paths to be ellipses. This is Kepler's first law of planetary motion:

Tycho Brahe (1546–1601)

Johannes Kepler (1571–1630)

The path of each planet around the Sun is an ellipse with the Sun at one focus.

Kepler also found that the planets do not revolve around the Sun at a uniform speed but move faster when they are nearer the Sun and slower when they are farther from the Sun. They do this in such a way that an imaginary line or spoke joining the Sun and the planet sweeps out equal areas of space in equal times. The triangular-shaped area swept out during a month when a planet is orbiting far from the Sun (triangle ASB in Figure 10.29) is equal to the triangular area swept out during a month when the planet is orbiting closer to the Sun (triangle CSD in Figure 10.29). This is Kepler's second law:

The line from the Sun to any planet sweeps out equal areas of space in equal time intervals.

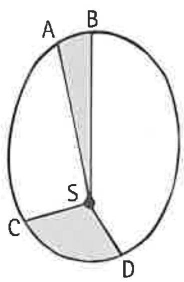


FIGURE 10.29

Equal areas are swept out in equal intervals of time.

Kepler was the first to coin the word *satellite.* He had no clear idea as to *why* the planets moved as he discovered. He lacked a conceptual model. Kepler didn't see that a satellite is simply a projectile under the influence of a gravitational force directed toward the body that the satellite orbits. You know that if you toss a rock upward, it goes slower the higher it rises because it's moving against gravity. And you know that when it returns, it's moving with gravity and its speed increases. Kepler didn't see that a satellite behaves in the same way. Going away from the Sun, it slows. Going toward the Sun, it speeds up. A satellite, whether a planet orbiting the Sun or one of today's satellites orbiting Earth, moves slower against the gravitational field and faster with the field. Kepler didn't see this simplicity and instead fabricated complex systems of geometrical figures to find sense in his discoveries. These systems proved to be futile.

After 10 years of searching by trial and error for a connection between the time it takes a planet to orbit the Sun and its distance from the Sun, Kepler discovered a third law. From Brahe's data, Kepler found that the square of any planet's period (T) is directly proportional to the cube of its average orbital radius (r). Law three is:

The square of the orbital period of a planet is directly proportional to the cube of the average distance of the planet from the Sun ($T^2 \sim r^3$ for all planets).

With Kepler's third law, you can calculate the radius of a planet's orbit from its orbital period.

This means that the ratio T^2/r^3 is the same for all planets. So, if a planet's period is known, its average orbital radial distance is easily calculated (or vice versa).

It is interesting to note that Kepler was familiar with Galileo's ideas about inertia and accelerated motion, but he failed to apply them to his own work. Like Aristotle, he thought that the force on a moving body would be in the same direction as the body's motion. Kepler never appreciated the concept of inertia. Galileo, on the other hand, never appreciated Kepler's work and held to his conviction that the planets move in circles.[2] Further understanding of planetary motion required someone who could integrate the findings of these two great scientists.[3] The rest is history, for this task fell to Isaac Newton.

fyi

- In 2009, 400 years after Galileo invented the telescope, the United States launched an orbiting telescope named Kepler, specifically to see Earth-like planets obscured by the light of their sun.

[2]It is not easy to look at familiar things through the new insights of others. We tend to see only what we have learned to see or wish to see. Galileo reported that many of his colleagues were unable or refused to see the moons of Jupiter when they peered skeptically through his telescopes. Galileo's telescopes were a boon to astronomy, but more important than an improved instrument to see things clearer was a new way of understanding what is seen. Is this still true today?

[3]Perhaps your instructor will show that Kepler's third law results when Newton's inverse-square formula for gravitational force is equated to centripetal force, and how T^2/r^3 equals a constant that depends only on G and M, the mass of the body about which orbiting occurs. Intriguing stuff!

Energy Conservation and Satellite Motion

Recall, from Chapter 7, that an object in motion possesses kinetic energy (KE) due to its motion. An object above Earth's surface possesses potential energy (PE) by virtue of its position. Everywhere in its orbit, a satellite has both KE and PE. The sum of the KE and PE is a constant all through the orbit. The simplest case occurs for a satellite in circular orbit.

In a circular orbit, the distance between the satellite and the center of the attracting body does not change, which means that the PE of the satellite is the same everywhere in its orbit. Then, by the conservation of energy, the KE must also be constant. So a satellite in circular orbit coasts at an unchanging PE, KE, and speed (Figure 10.30).

In an elliptical orbit, the situation is different. Both speed and distance vary. PE is greatest when the satellite is farthest away (at the *apogee*) and least when the satellite is closest (at the *perigee*). Note that the KE will be least when the PE is most, and the KE will be most when the PE is least. At every point in the orbit, the sum of KE and PE is the same (Figure 10.31).

At all points along the elliptical orbit, except at the apogee and the perigee, there is a component of gravitational force parallel to the direction of motion of the satellite. This component of force changes the speed of the satellite. Or we can say that (this component of force) × (distance moved) = ΔKE. Either way, when the satellite gains altitude and moves against this component, its speed and KE decrease. The decrease continues to the apogee. Once past the apogee, the satellite moves in the same direction as the component, and the speed and KE increase. The increase continues until the satellite whips past the perigee and repeats the cycle.

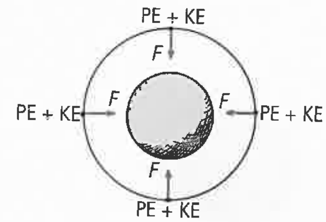


FIGURE 10.30

The force of gravity on the satellite is always toward the center of the body it orbits. For a satellite in circular orbit, no component of force acts along the direction of motion. The speed and thus the KE do not change.

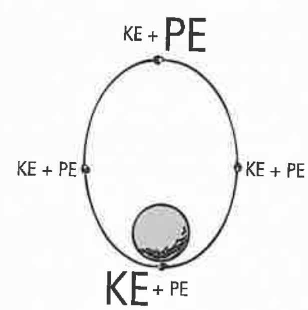
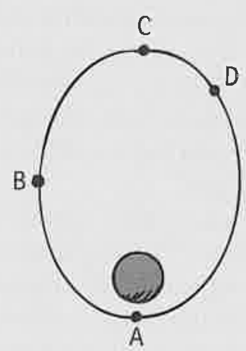


FIGURE 10.31

The sum of KE and PE for a satellite is a constant at all points along its orbit.

CHECK POINT

1. The orbital path of a satellite is shown in the sketch. In which marked positions A through D does the satellite have the greatest KE? The greatest PE? The greatest total energy?
2. Why does the force of gravity change the speed of a satellite when it is in an elliptical orbit but not when it is in a circular orbit?



Check Your Answers

1. KE is maximum at the perigee A; PE is maximum at the apogee C; the total energy is the same everywhere in the orbit.
2. In circular orbit, the gravitational force is always perpendicular to the orbital path. With no component of gravitational force along the path, only the direction of motion changes—not the speed. In elliptical orbit, however, the satellite moves in directions that are not perpendicular to the force of gravity. Then components of force do exist along the path, which change the speed of the satellite. A component of force along (parallel to) the direction the satellite moves does work to change its KE.

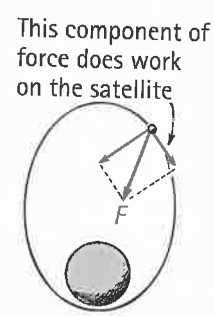


FIGURE 10.32

In elliptical orbit, a component of force exists along the direction of the satellite's motion. This component changes the speed and, thus, the KE. (The perpendicular component changes only the direction.)

Escape Speed

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 will be returned by gravity (unless, as we shall see, its speed is great enough).

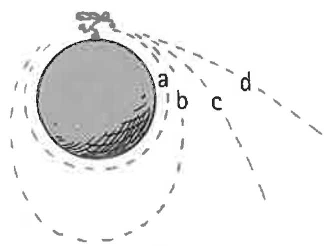


FIGURE 10.33

INTERACTIVE FIGURE

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 minutes later he can turn around and catch it (neglecting Earth's rotation). Tossed slightly faster (b), it will take an elliptical orbit and return in a slightly longer time. Tossed at more than 11.2 km/s (c), it will escape Earth. Tossed at more than 42.5 km/s (d), it will escape the solar system.

In today's spacefaring age, it is more accurate to say, "What goes up *may* come down," for there is a critical starting speed that permits a projectile to outrun gravity and 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 will leave Earth, traveling slower and slower, never stopping due to Earth's gravity.[4] 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 very, very far ("infinitely far") away? We might think that the change of PE 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 PE of a 1-kg body moved from the surface of Earth to an infinite distance is 62 million joules (62 MJ). So, to put a payload infinitely far from Earth's surface requires at least 62 MJ of energy per kilogram of load. We won't go through the calculation here, but 62 MJ per kilogram corresponds to a speed of 11.2 km/s, whatever the total mass involved. This is the escape speed from the surface of Earth.[5]

If we give a payload any more energy than 62 MJ per kilogram at the surface of Earth or, equivalently, any more speed than 11.2 km/s, then, neglecting air drag, the payload will escape from Earth, never to return. As it continues outward, its PE increases and its KE decreases. Its speed becomes less and less, though it is never reduced to zero. The payload outruns the gravity of Earth. It escapes.

Wouldn't Newton have relished seeing satellite motion in terms of *energy*—a concept that came much later?

The escape speeds from various bodies in the solar system are shown in Table 10.1. Note that the escape speed from the surface of the Sun is 620 km/s. Even at a 150,000,000-km distance 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 occupy an orbit around the Sun.

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 to pass just behind giant 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 (but without physical contact). 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 bottle cast into the sea with a note inside, *Pioneer 10* contains information about

[4]Escape speed from any planet or any body is given by $v = \sqrt{\frac{2GM}{d}}$, 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 footnote 1 a few pages back.

[5]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 10.1

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

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

Earth that might be of interest to extraterrestrials, in hopes that it will one day "wash up" and be found on some distant "seashore."

It is important to point out 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.

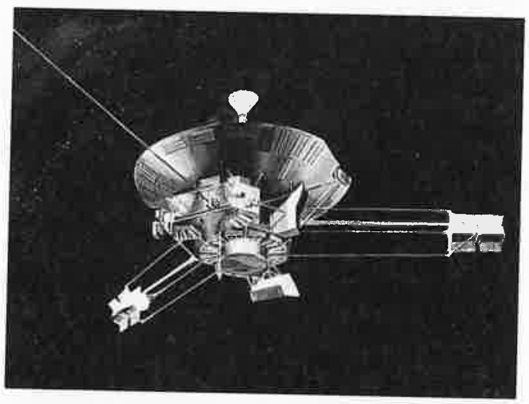


FIGURE 10.34

Historic *Pioneer 10*, launched from Earth in 1972, passed the outermost planet in 1984 and is now wandering in our galaxy.

It is interesting to note that the accuracy with which an unmanned rocket reaches its destination is not accomplished by staying on a preplanned 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 in finding a new path. Corrective thrusters direct the rocket to this new path. This process is repeated over and over again all the way to the goal.[6]

fyi

- 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.

FIGURE 10.35

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.

[6]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 and under, perhaps, different circumstances.

SUMMARY OF TERMS

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

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

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

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."

Kepler's laws Law 1: The path of each planet around the Sun is an ellipse with the Sun at one focus.
Law 2: The line from the Sun to any planet sweeps out equal areas of space in equal time intervals.
Law 3: The square of the orbital period of a planet is directly proportional to the cube of the average distance of the planet from the Sun ($T^2 \sim r^3$ for all planets).

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.

REVIEW QUESTIONS

1. Why must a horizontally moving projectile have a large speed to become an Earth satellite?

Projectile Motion

2. What exactly is a projectile?

Projectiles Launched Horizontally

3. Why does the vertical component of velocity for a projectile change with time, whereas the horizontal component of velocity doesn't?

Projectiles Launched at an Angle

4. A stone is thrown upward at an angle. What happens to the horizontal component of its velocity as it rises? As it falls?
5. A stone is thrown upward at an angle. What happens to the vertical component of its velocity as it rises? As it falls?
6. A projectile falls beneath the straight-line path it would follow if there were no gravity. How many meters does it fall below this line if it has been traveling for 1 s? For 2 s?
7. Do your answers to the previous question depend on the angle at which the projectile is launched?
8. 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?
9. A projectile is launched vertically at 100 m/s. If air resistance can be neglected, at what speed will it return to its initial level?

Fast-Moving Projectiles—Satellites

10. How can a projectile "fall around the Earth"?
11. Why will a projectile that moves horizontally at 8 km/s follow a curve that matches the curvature of the Earth?
12. Why is it important that the projectile in the previous question be above Earth's atmosphere?

Circular Satellite Orbits

13. Why doesn't the force of gravity change the speed of a satellite in circular orbit?
14. How much time is taken for a complete revolution of a satellite in close orbit about the Earth?
15. For orbits of greater altitude, is the period longer or shorter?

Elliptical Orbits

16. Why does the force of gravity change the speed of a satellite in an elliptical orbit?

Kepler's Laws of Planetary Motion

17. Who gathered the data that were used to show that the planets travel in elliptical paths around the Sun? Who discovered elliptical orbits? Who explained them?
18. What did Kepler discover about the periods of planets and their distances from the Sun? Was this discovery aided by thinking of satellites as projectiles moving under the influence of the Sun?
19. In Kepler's thinking, what was the direction of the force on a planet? In Newton's thinking, what was the direction of the force?

Energy Conservation and Satellite Motion

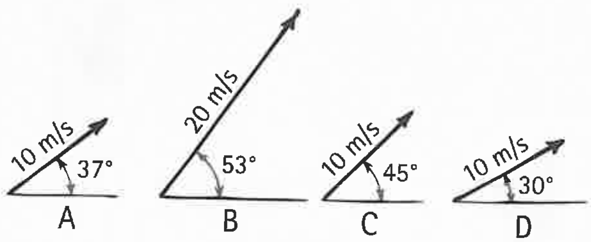
20. Why is kinetic energy a constant for a satellite in a circular orbit but not for a satellite in an elliptical orbit?
21. Is the sum of kinetic and potential energies a constant for satellites in circular orbits, in elliptical orbits, or in both?

Escape Speed

22. We talk of 11.2 km/s as the escape speed from Earth. Is it possible to escape from Earth at half this speed? At one-quarter this speed? If so, how?

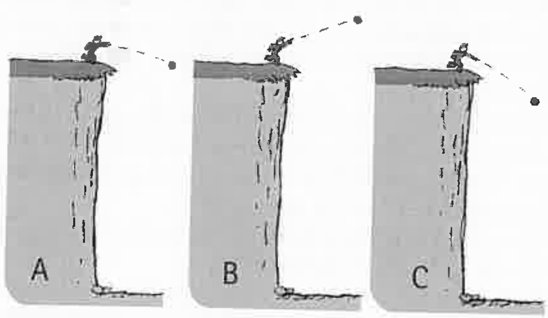
RANKING

1. A ball is thrown upward at velocities and angles shown. From greatest to least, rank them by their



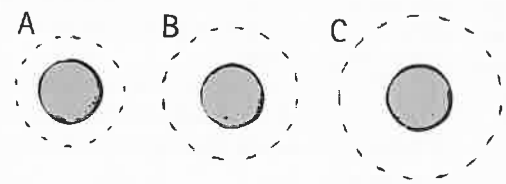
a. vertical components of velocity.
b. horizontal components of velocity.
c. accelerations when they reach the top of their paths.

2. A ball is tossed off the edge of a cliff with the same speed but at different angles, as shown. From greatest to least, rank the



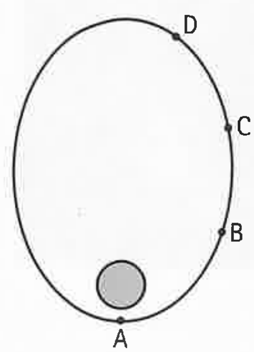
a. initial PEs of the balls relative to the ground below.
b. initial KEs of the balls when tossed.
c. KEs of the balls when hitting the ground below.
d. times of flight while airborne.

3. 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

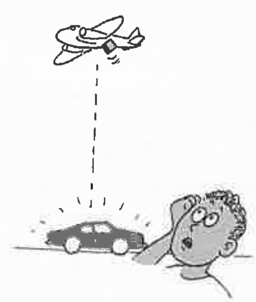
4. The positions of a satellite in elliptical orbit are indicated. Rank these quantities from greatest to least.



a. Gravitational force
b. Speed
c. Momentum
d. KE
e. PE
f. Total energy (KE + PE)
g. Acceleration

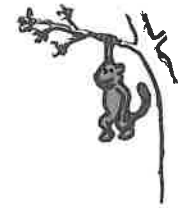
EXERCISES

1. In synchronized diving, divers remain in the air for the same time. With no air drag, they would fall together. But air drag is appreciable, so how do they remain together in fall?
2. Suppose you roll a ball off a tabletop. Will the time to hit the floor depend on the speed of the ball? (Will a fast ball take a longer time to hit the floor?) Defend your answer.
3. Suppose you roll a ball off a tabletop. Compared with a slow roll, will a faster-moving ball hit the floor with a higher *speed?* Defend your answer.
4. If you toss a ball vertically upward in a uniformly moving train, it returns to its starting place. Will it do the same if the train is accelerating? Explain.
5. A heavy crate accidentally falls from a high-flying airplane just as it flies directly above a shiny red Porsche smartly parked in a car lot. Relative to the Porsche, where will the crate crash?



6. Suppose you drop an object from an airplane traveling at constant velocity, and further suppose that air resistance doesn't affect the falling object. What will be its falling path as observed by someone at rest on the ground, not directly below but off to the side where there's a clear view? What will be the falling path as observed by you looking downward from the airplane? Where will the object strike the ground, relative to you in the airplane? Where will it strike in the more realistic case in which air resistance does affect the fall?
7. Fragments of fireworks beautifully illuminate the night sky. (a) What specific path is ideally traced by each fragment? (b) What paths would the fragments trace in a gravity-free region?

8. In the absence of air resistance, why does the horizontal component of a projectile's motion not change, while the vertical component does?
9. At what point in its trajectory does a batted baseball have its minimum speed? If air drag can be neglected, how does this compare with the horizontal component of its velocity at other points?
10. 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 $\frac{1}{2}gt^2$ and that the curved path is apparent for low velocities and less apparent for high velocities. Now it's your turn: Will all fired bullets drop the same vertical distance in equal times? Explain.
11. For maximum range, a football should be punted at about 45° to the horizontal—somewhat less due to air drag. But punts are often kicked at angles greater than 45°. Can you think of a reason why?
12. When a rifle is being fired at a distant target, why isn't the barrel aligned so that it points exactly at the target?
13. Two golfers each hit a ball at the same speed, but one at 60° with the horizontal and the other at 30°. Which ball goes farther? Which hits the ground first? (Ignore air resistance.)
14. 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.



15. A projectile is fired straight upward at 141 m/s. How fast is it moving at the instant it reaches the top of its trajectory? Suppose that it were fired upward at 45° instead. Then its horizontal component of velocity is 100 m/s. What would be the speed of the projectile at the top of its trajectory?
16. When you jump upward, your hang time is the time your feet are off the ground. Does hang time depend on your vertical component of velocity when you jump, your horizontal component of velocity, or both? Defend your answer.
17. The hang time of a basketball player who jumps a vertical distance of 2 feet (0.6 m) is about $\frac{2}{3}$ second. What will be the hang time if the player reaches the same height while jumping 4 feet (1.2 m) horizontally?
18. Since the Moon is gravitationally attracted to Earth, why doesn't it simply crash into Earth?
19. Which planets have a more-than-one-Earth-year period, planets nearer than Earth to the Sun, or planets farther from the Sun than Earth?
20. When the space shuttle coasts in a circular orbit at constant speed about Earth, is it accelerating? If so, in what direction? If not, why not?
21. Does the speed of a falling object depend on its mass? Does the speed of a satellite in orbit depend on its mass? Defend your answers.
22. On which does the speed of a circling satellite *not* depend: the mass of the satellite, the mass of Earth, or the distance of the satellite from Earth.
23. A circularly moving object requires a centripetal force. What supplies this force for satellites that orbit Earth?
24. If you have ever watched 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?
25. Mars has about $\frac{1}{9}$ the mass of Earth. If Mars were somehow positioned into the same orbit as Earth's, how would its time to circle the Sun compare with Earth's? (Longer, shorter, or the same?)
26. If a cannonball is fired from a tall mountain, gravity changes its speed all along its trajectory. But if it is fired fast enough to go into circular orbit, gravity does not change its speed at all. Explain.
27. A satellite can orbit at 5 km above the Moon, but not at 5 km above Earth. Why?

28. In 2000–2001, NASA's Near Earth Asteroid Rendezvous (NEAR) spacecraft orbited around the 20-mile-long asteroid Eros. Was the orbital speed of this spacecraft greater or less than 8 km/s? Defend your answer.

29. Would the speed of a satellite in close circular orbit about Jupiter be greater than, equal to, or less than 8 km/s?

30. Why are satellites normally sent into orbit by firing them in an easterly direction, the direction in which Earth spins?

31. When a satellite in circular orbit slows, perhaps due to the firing of a "retro rocket," it ends up gaining more speed than it had initially. Why?

32. Earth is closer to the Sun in December than in June. In which of these two months is Earth moving faster around the Sun?

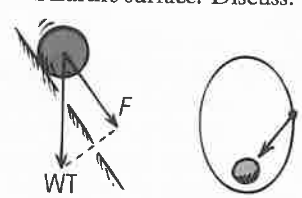
33. Of all the United States, why is Hawaii the most efficient launching site for nonpolar satellites? (*Hint:* Look at the spinning Earth from above either pole and compare it to a spinning turntable.)

34. Two planets are never seen at midnight. Which two, and why?

35. Why does a satellite burn up when it descends into the atmosphere when it doesn't burn up when it ascends through the atmosphere?

36. Neglecting air resistance, could a satellite be put into orbit in a circular tunnel beneath Earth's surface? Discuss.

37. In the sketch on the left, a ball gains KE when rolling down a hill because work is done by the component of weight (F) that acts in the direction of motion. Sketch in the similar component of gravitational force that does work to change the KE of the satellite on the right.



38. Why is work done by the force of gravity on a satellite when it moves from one part of an elliptical orbit to another, but not when it moves from one part of a circular orbit to another?

39. What is the shape of the orbit when the velocity of the satellite is everywhere perpendicular to the force of gravity?

40. If a space shuttle 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?

41. Can a satellite coast in a stable orbit in a plane that doesn't intersect the Earth's center? Defend your answer.

42. Can a satellite maintain an orbit in the plane of the Arctic Circle? Why or why not?

43. You read in an article about astronauts in a major magazine that "about 62 miles up, the atmosphere ends and gravity becomes very weak. . . ." What error is made here?

44. A "geosynchronous" Earth satellite can remain nearly directly overhead in Singapore, but not in San Francisco. Why?

45. When an Earth satellite is placed into a higher orbit, what happens to its period?

46. If a flight mechanic drops a box of tools from a high-flying jumbo jet, it crashes to Earth. In 2008 an astronaut on the orbiting space shuttle accidentally dropped a box of tools. Why did the tools not crash to Earth? Defend your answer.

47. How could an astronaut in a space shuttle "drop" an object vertically to Earth?

48. A high-orbiting spaceship travels at 7 km/s with respect to Earth. Suppose it projects a capsule rearward at 7 km/s with respect to the ship. Describe the path of the capsule with respect to Earth.

49. A satellite in circular orbit about the Moon fires a small probe in a direction opposite to the velocity of the satellite. If the speed of the probe relative to the satellite is the same as the satellite's speed relative to the Moon, describe the motion of the probe. If the probe's relative speed is twice the speed of the satellite, why would it pose a danger to the satellite?

50. 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?

51. If you stopped an Earth satellite dead in its tracks, 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?

52. 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?

53. A giant rotating wheel in space provides artificial gravity for its occupants, as discussed in Chapter 8. Instead of a full wheel, discuss the idea of a pair of capsules joined by a tether line and rotating about each other. Can such an arrangement provide artificial gravity for the occupants?

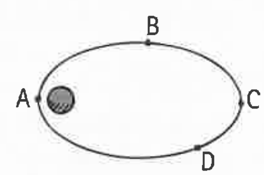
54. What is the advantage of launching space vehicles from high-flying aircraft instead of from the ground?

55. Which requires less fuel, launching a rocket to escape speed from the Moon or from Earth? Defend your answer.

56. What is the maximum possible speed of impact upon the surface of Earth for a faraway body initially at rest that falls to Earth by virtue of Earth's gravity only?

57. 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?

58. At which of the indicated positions does the satellite in elliptical orbit experience the greatest gravitational force? Have the greatest speed? The greatest velocity? The greatest momentum? The greatest kinetic energy? The greatest gravitational potential energy? The greatest total energy? The greatest angular momentum? The greatest acceleration?

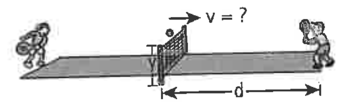


59. At what point in its elliptical orbit about the Sun is the acceleration of Earth toward the Sun at a maximum? At what point is it at a minimum? Defend your answers.

60. 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 to accelerate forward when it is at the apogee or at the perigee? (*Hint:* Let the formula $Fd = \Delta KE$be your guide to thinking. Suppose the thrust F is brief and of the same duration in either case. Then consider the distance d the rocket would travel during this brief burst at the apogee and at the perigee.)

PROBLEMS

1. A ball is thrown horizontally from a cliff at a speed of 10 m/s. You predict that its speed 1 s later will be slightly greater than 14 m/s. Your friend says it will be 10 m/s. Show who is correct.
2. You're in an airplane that flies horizontally with speed 1000 km/h (280 m/s) when an engine falls off. Neglecting air resistance, assume it takes 30 s for the engine to hit the ground.
   a. Show that the airplane is 4.5 km high.
   b. Show that the horizontal distance that the aircraft engine falls is 8400 m.
   c. If the airplane somehow continues to fly as if nothing had happened, where is the engine relative to the airplane at the moment the engine hits the ground?
3. A cannonball shot with an initial velocity of 141 m/s at an angle of 45° follows a parabolic path and hits a balloon at the top of its trajectory. Neglecting air resistance, show that the cannonball hits the balloon at a speed of 100 m/s.
4. Students in Chuck Stone's lab (Figure 10.5) measure the speed of a steel ball to be 8.0 m/s when launched horizontally from a 1.0-m high tabletop. Their objective is to place a 20-cm tall coffee can on the floor to catch the ball. Show that they score a bull's-eye when the can is placed 3.2 m from the base of the table.
5. At a particular point in orbit a satellite in 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. What is its kinetic energy at that point?
6. A certain satellite has a kinetic energy of 8 billion joules at perigee (the point at which it is closest to Earth) and 5 billion joules at apogee (the point at which it is farthest from Earth). As the satellite travels from apogee to perigee, how much work does the gravitational force do on it? Does its potential energy increase or decrease during this time, and by how much?
7. Calculate the hang time of a person who moves horizontally 3 m during a 1.25-m high jump. What is the hang time when moving 6 m horizontally during this jump?
8. • 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, 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.

CHAPTER 10 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 10.3, 10.4, 10.9, 10.11, 10.13, 10.21, 10.25, 10.33

Tutorials

- Projective Motion
- Orbital Motion

Videos

- Projectile Motion
- More Projectile Motion
- Circular Orbits

Quizzes

Flashcards

Links

PART ONE MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. The language of science is
   (a) mathematics.
   (b) Latin.
   (c) Chinese.
   (d) Arabic.
2. Somebody who says, "that's only a theory" likely doesn't know that a scientific theory is
   (a) an educated guess.
   (b) a hypothesis.
   (c) a vast synthesis of well-tested hypotheses and facts.
   (d) None of these.
3. The force needed to keep a ball rolling along a bowling alley is
   (a) due to gravity.
   (b) an inertial force.
   (c) a slight breeze.
   (d) None of these.
4. The equilibrium rule, $\Sigma F = 0$, applies to objects
   (a) at rest.
   (b) moving at constant velocity.
   (c) Both.
   (d) Neither.
5. If gravity between the Sun and Earth suddenly vanished, Earth would continue moving in
   (a) a curve.
   (b) a straight line.
   (c) an outward spiral.
   (d) an inward spiral.
6. The average speed of a gazelle traveling a distance of 2 km in a time of one-half hour is
   (a) 1 km/h.
   (b) 2 km/h.
   (c) 4 km/h.
   (d) more than 4 km/h.
7. An object in free fall undergoes an increase in
   (a) speed.
   (b) acceleration.
   (c) both speed and acceleration.
8. If a falling object gains 10 m/s each second it falls, its acceleration is
   (a) 10 m/s. (b) 10 m/s per second. (c) Both. (d) Neither.
9. An object with a huge mass also must have a huge
   (a) weight. (b) volume. (c) size. (d) surface area.
10. Why the acceleration of free fall is the same for all masses is explained by Newton's
    (a) first law. (b) second law. (c) third law. (d) law of gravity.
11. The amount of air drag on an 0.8-N flying squirrel dropping vertically at terminal velocity is
    (a) less than 0.8 N.
    (b) 0.8 N.
    (c) more than 0.8 N.
    (d) dependent on the orientation of its body.
12. When a cannonball is fired from a cannon, both the cannonball and the cannon experience equal
    (a) amounts of force. (b) accelerations. (c) Both. (d) Neither.
13. The team that wins in a tug-of-war is the team that
    (a) produces more tension in the rope than the opponent.
    (b) pushes hardest on the ground.
    (c) Both.
    (d) Neither.
14. An airplane with its nose pointing north with an airspeed of 40 km/h in a 30-km/h crosswind (at right angles) has a groundspeed of
    (a) 30 km/h. (b) 40 km/h. (c) 50 km/h. (d) 60 km/h.
15. The impulse-momentum relationship is a direct result of Newton's
    (a) first law. (b) second law. (c) third law. (d) law of gravity.
16. A big fish swims upon and swallows a small fish at rest. Right after lunch, the fattened big fish has a change in
    (a) speed. (b) momentum. (c) Both. (d) Neither.
17. The work done on a 100-kg crate that is hoisted 2 m in a time of 4 s is
    (a) 200 J. (b) 500 J. (c) 800 J. (d) 2000 J.
18. The power required to raise a 100-kg crate a vertical distance of 2 m in a time of 4 s is
    (a) 200 W. (b) 500 W. (c) 800 W. (d) 2000 W.
19. A model car with 3 times as much speed as another has a kinetic energy that is
    (a) the same. (b) twice. (c) 3 times. (d) None of these.
20. Lift a 100-N crate with an ideal pulley system by pulling a rope downward with 25 N of force. For every 1-m length of rope pulled down, the crate rises
    (a) 25 cm. (b) 25 m. (c) 50 cm. (d) None of these.
21. When 100 J are put into a device that puts out 40 J of useful work, the efficiency of the device is
    (a) 40%. (b) 50%. (c) 60%. (d) 140%.
22. A machine cannot multiply
    (a) forces. (b) distances. (c) energy. (d) None of these.
23. When a tin can is whirled in a horizontal circle, the net force on the can acts
    (a) inward. (b) outward. (c) upward. (d) None of these.
24. A torque is a force
    (a) like any other force.
    (b) multiplied by a lever arm.
    (c) that is fictitious.
    (d) that accelerates things.
25. The rotational inertial of an object is greater when most of the mass is located
    (a) near the rotational axis.
    (b) away from the axis.
    (c) on the rotational axis.
    (d) off center.
26. If the Sun were twice as massive, its pull on Mars would be
    (a) unchanged.
    (b) twice as much.
    (c) half as much.
    (d) 4 times as much.
27. The highest ocean tides occur when the Earth and Moon are
    (a) lined up with the Sun.
    (b) at right angles to the Sun.
    (c) at any angle to the Sun.
    (d) lined up during spring.
28. The component of velocity that can remain constant for a tossed baseball is
    (a) horizontal.
    (b) vertical.
    (c) Either of these.
    (d) None of these.
29. The magnitude of gravitational force on a satellite is constant if the orbit is
    (a) parabolic. (b) circular. (c) elliptical. (d) All of these.
30. A satellite in Earth orbit is above Earth's
    (a) atmosphere.
    (b) gravitational field.
    (c) Both.
    (d) Neither.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.