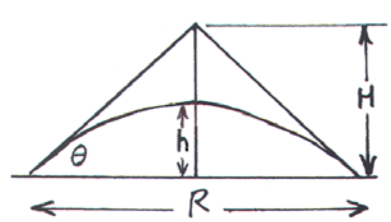
10 Projectile and Satellite Motion

My granddaughter Emily shares good information in opening photo 1. Photos 2 and 3 are of Tenny Lim. As teachers we are rewarded by the success that some of our students achieve after leaving our tutelage. In my career, Tenny Lim is the most outstanding of these. It is with great pride that she is featured in the photo opener to this chapter and the personal profile as well. Photo 3 is of CCSF physics instructor Shruti Kumar projecting a ball after students have made predictions of the landing point. Photo 5 is Peter Rea, whose company Arbor Scientific supplies teaching materials to schools. Arbor is the primary supplier of materials that complement Conceptual Physics. He is also the main supplier of my classroom videos, both on DVDs and more recently via streaming from the Arbor Scientific website.

In editions previous to the ninth edition, projectile motion was treated with linear motion. Kinematics began the sequence of mechanics chapters. Since then I've postponed projectile motion until after Newton's laws and energy, and just before satellite motion. When projectiles move fast enough for the Earth's curvature to make a difference in range, you're at the doorstep to satellite motion.

Regarding 45° as the maximum range for projectiles, keep in mind that this is only true when air resistance can be neglected, and most important and often overlooked, when the launching speed is the same at all angles concerned. Tilt a water hose up 45° and sure enough, for short distances where air resistance is nil, it attains maximum range. The same is true for a slowly-bunted baseball. But for a high-speed ball, air resistance is a factor and maximum range occurs for angles between 39° and 42°. For very high speeds where the lesser air resistance of high altitudes is a consideration, angles greater than 45° produce maximum range. During World War I, for example, the German cannon "Big Bertha" fired shells 11.5 km high and attained maximum range at 52°. Air resistance is one factor; launching speed is another. When one throws a heavy object, like a shot put, its launching speed is less for higher angles simply because some of the launching force must be used to overcome the force due to gravity. (You can throw a heavy boulder a lot faster horizontally than you can straight up.) Shot puts are usually launched at angles slightly less than 40°. The fact that they are launched higher than ground level decreases the angle as well. Screencast *Ball Toss* covers much of this.

Interestingly, the maximum height of a projectile following a parabolic path is nicely given by sketching an isosceles triangle with the base equal to the range of the projectile. Let the two side angles be equal to the launch angle θ, as shown in the figure. The maximum height h reached by the projectile is equal to one-half H, the altitude of the triangle. This goodie from Jon Lamoreux and Luis Phillipe Tosi, of Culver Academies, Culver, IN.



The interesting fact that projectiles launched at a particular angle have the small range if launched at the complementary angle is stated without proof in the chapter, and is shown in Figure 10.11. This fact is shown by the range formula, $R = (2v \sin\theta \cos\theta)/g$. Because the sine of an angle is the cosine of the complement of that angle, replacing the angle with its complement results in the same range. So the range is the same whether aiming at θ or at $(90° - \theta)$. As said, maximum range occurs at a projection angle of 45°, where sine and cosine are equal.

The spin of the Earth is helpful in launching satellites, which gives advantage to launching cities closest to the equator. The launch site closest to the equator is Kaurou, French Guiana, in South America, 5° 08', used by the European Space Agency. The U.S. launches from Cape Canaveral, 28° 22', and Vandenberg, 34° 38'. Russia used to launch at Kapustin Yar, 48° 31', Plesetsk, 62° 42', and Tyuratam (Baikonur) 45° 38'. Is Hawaii, less than 20° in our space launching future?

If you haven't shown the 15-minute oldie but goodie NASA film, "Zero *g*," be sure to show it now. It is of footage taken aboard Skylab in 1978, narrated by astronaut Owen Garriott. Newton's laws of motion are reviewed with excellent and entertaining examples. (It would be a shame for this stimulating movie to fall through the cracks due to being "dated.")

Ask your students this question: An Earth satellite remains in orbit because it's above Earth's A. atmosphere. B. gravitational field. C. Both of these. D. Neither of these. Be prepared for most to answer C. That's because of the common misconception that no gravitational field exists in satellite territory. Of course it's the gravitational field that keeps a satellite from flying off in space, but this isn't immediately apparent to many students. Strictly speaking, there IS *some* atmosphere in satellite territory. That's why boosters on the ISS have to periodically fire to overcome the slight drag that exists. So perhaps in your discussion, qualify your question to "it's above <u>most</u> of Earth's".

Solar Photon Force: To a small extent, sunlight affects satellites, particularly the large disco-ball-like satellite LAGEOS, which wobbles slightly in its orbit because of unequal heating by sunlight. The side in the Sun radiates infrared photons, the energy of which provides a small, but persistent, rocket effect as the photons eject from the surface. So a net force some 100 billion times weaker than gravity pushes on the satellite in a direction away from its hot end. LAGEOS has 426 prism-shaped mirrors. By reflecting laser beams off its mirrored surface, geophysicists can make precise measurements of tiny displacements in the Earth's surface.

Asteroids: Of particular interest are asteroids that threaten Planet Earth. Asteroid 2004 MN4 is big enough to flatten Texas and a couple of European countries with an impact equivalent to 10,000 megatons of dynamite—more than the world's nuclear weapons. The asteroid is predicted to have a close encounter with Earth in 2029, which likely won't be the last of its close encounters. Space missions in the future may employ "tugboat" spacecraft to near-Earth objects, dock with them and gently alter their speeds to more favorable orbits.

Space Debris: More than 20,000 pieces of space trash larger than 10 cm are in low-Earth orbit, along with a half million bits of 1-to-2 cm bits of junk in between. Yuk!

Tunnel through Earth: Neil de Grasse Tyson does a nice job on NOVA describing what would happen if you fell into a tunnel that goes from one side of Earth, through its center, to the other side. I attempt the same in the screencast *Tunnel Through Earth*.

Practicing Physics Book:
- Independence of Horizontal and Vertical Components of Motion
- Tossed Ball
- Satellites in Circular Orbit
- Satellites in Elliptical Orbit
- Mechanics Overview

Problem Solving Book:
Many problems involve projectile motion and satellite motion

Laboratory Manual:
• The BB Race *Horizontal and Vertical Motion* (Demonstration)
• Bull's Eye *A Puzzle You CAN Solve* (Experiment)
• Blast Off! *Rockets Real and Virtual* (Experiment and Tech Lab)
• Worlds of Wonder *Orbital Mechanics Simulation* (Tech Lab)

Next-Time Questions:
• Ball Toss from Tower
• Monkey and Banana
• Elliptical Orbit
• Escape Velocity
• Satellite Speed
• Satellite Mass
• Earth Satellites
• Orbital Speed
• Escape Fuel
• Moon Face
• Dart Gun
• Bull's-Eye
• Projectile Speeds

Hewitt-Drew-It! Screencasts: •*Sideways Drop* •*Ball Toss* •*Tennis-Ball Problem* •*Satellite Speed* •*Circular/Eliptical Orbits*

SUGGESTED LECTURE PRESENTATION

Independence of Horizontal and Vertical Motion

Roll a ball off the edge of your lecture table and call attention to the curve it follows. The ball is a projectile. Discuss the idea of the "downwardness" of gravity, and how there is no "horizontalness" to it, and therefore no horizontal influence on the projectile. Draw a rendition of Figure 10.2 on the board, with vectors. You're going an extra step beyond the textbook treatment.

Pose the situation of the horizontally-held gun and the shooter who drops a bullet at the same time he pulls the trigger, and ask which bullet hits the ground first. (This is treated in screencast *Sideways Drop* and also in a video.)

> DEMONSTRATION: Show the independence of horizontal and vertical motion with a spring-gun apparatus that will shoot a ball horizontally while at the same time dropping another that falls vertically. Follow this up with the popular "monkey and hunter" demonstration.
>
> CHECK QUESTIONS: Point to some target at the far side of your classroom and ask your class to imagine you are going to project a rock to the target via a slingshot. Ask if you should aim at the target, above it, or below it. Easy stuff. Then ask your class to suppose it takes 1 second for the rock to reach the target. If you aim directly at the target, it will fall beneath and miss. How far beneath the target would the rock hit (if the floor weren't in the way)? Have your students check with their neighbors. Then ask how far above should you aim to hit the target. Do a neighbor check. Now you're ready to discuss Figure 10.6 (nicely developed in Practicing Physics Book pages 55 and 56).

My screencast *Tennis-Ball Problem* features an interesting case involving the independence of horizontal and vertical motion, highlighting a method for solving problems in general—which is to begin *with what is asked for*. This method is as simple and direct as can be, answering the student question, "How do I begin a problem solution?"

Air Resistance

Acknowledge the large effect of air resistance on fast-moving objects such as bullets and cannonballs. A batted baseball, for example, travels only about 60 percent as far in air as it would in a vacuum. Its curved path is no longer a parabola, as Figure 10.13 indicates. What makes its decent steeper than its ascent is the horizontal slowing due to air resistance. What makes it not as high is air resistance vertically, which diminishes with height. This is covered in the screencast *Ball Toss*.

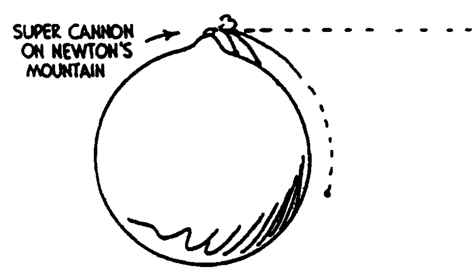
Hang Time Again
Ask if one could jump higher if on a moving skateboard or in a moving bus. It should be clear that the answer is no to both. But one can usually jump higher from a running jump. It is a mistake to assume that the horizontal motion is responsible for the higher jump and longer hang time. The action of running likely enables a greater force between the foot and floor, which gives a greater vertical lift-off component of velocity. This greater bound against the floor, and not any holiday by gravity on a horizontally moving body, is the explanation. Stress that the vertical component of velocity alone determines vertical height and hang time.

Projectiles
There are several ways to horizontally launch a projectile and have your class predict where it will strike the floor. Chuck Stone nicely shows one method in Figure 10.5. If this isn't a lab activity, consider it a classroom demonstration. If students know the speed at which the projectile is horizontally launched, and the height of launch, they can predict where the projectile will hit. It's a fun experience.

This is supported by the relationship of the curved path of Figure 10.6 and the vertical distance fallen, $d = 5t^2$, of Chapter 3. Stress that the projectile is falling beneath the straight line it would otherwise follow. This idea is important for later understanding of satellite motion. Continue with an explanation of Figure 10.7, and how the dangling beads of page 187 nicely summarizes projectile motion. A worthwhile class project can be fashioning such beads from points on a meterstick.

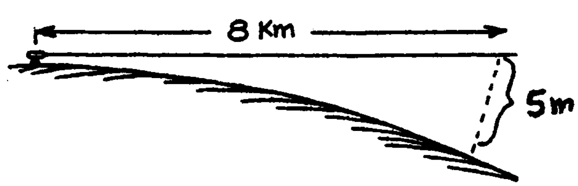
Discuss Figure 10.15 and ask for the pitching speed if the ball traveled 30 m instead of 20 m. Note the vertical height is 5 m. If you use any height that does not correspond to an integral number of seconds, you're diverting your focus from physics to algebra. This leads to what the screencast *Tennis-Ball Problem* that asks for the maximum speed of a tennis ball clearing the net. More interesting is considering greater horizontal distances—great enough for the curvature of the Earth to make a difference in arriving at the answer. It's easy to see that the time the projectile is in the air increases where the Earth curves beneath the trajectory.

Satellite Motion
Sketch "Newton's Mountain" and consider the longer time intervals for greater and greater horizontal speeds. Ask if there is a "pitching speed" or cannonball velocity large enough so the time in the air is forever. Not literally "in the air," which is why the cannon is atop a mountain that extends above the atmosphere. The answer of course is yes. Fired fast enough the cannonball will fall around the world rather than into it. You're into satellite motion.



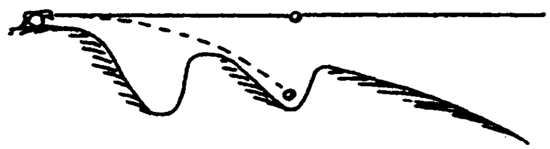
CHECK QUESTION: Why is it confusing to ask why a satellite doesn't fall? [All satellites are continuously falling, in the sense that they fall below the straight line they would travel if they weren't. Why they don't crash to Earth is a different question.]

Calculating Satellite Speed
An effective skit (covered in the screencast *Satellite Speed*) that can have your class calculating the speed necessary for close Earth orbit is as follows: Call attention to the curvature of the Earth, Figure 10.17. Consider a horizontal laser standing about a meter above the ground with its beam shining over a level desert. The beam is straight but the desert floor curves 5 m over an 8000 m or 8 km tangent, which you sketch on your chalkboard. Stress this is not to scale.

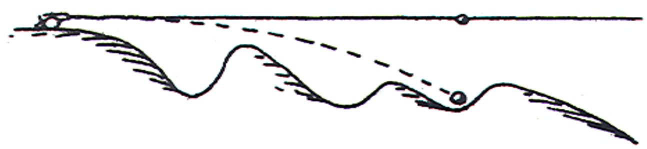


Now erase the laser and sketch in a super cannon positioned so it points along the laser line. Consider a cannonball fired at say, 2 km/s, and ask how far downrange will it be at the end of one second. A neighbor check should yield an answer of 2 km, which you indicate with an "X." But it doesn't really get to the "X," you say, for it falls beneath the "X" because of gravity. How far? 5 m if the sand weren't in the way. Ask if 2 km/s is sufficient for orbiting the Earth. Clearly not, for the cannonball strikes the ground. If the cannonball is not to hit the ground, we'd have to dig a trench first, as you show on your sketch, which now looks like this:

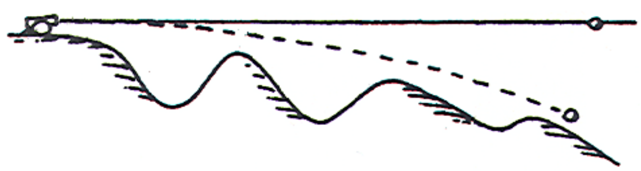
Continue by considering a greater muzzle velocity, say 4 km/s, so the cannonball travels 4 km in one second. Ask if this is fast enough to attain an Earth orbit. Student response should indicate that they realize that the cannonball will hit the ground before 1 second is up. Then repeat the previous line of reasoning, again having to dig a trench, and your sketch looks like this:



Continue by considering a greater muzzle velocity—great enough so the cannonball travels 6 km in 1 second. This is 6 km/s. Ask if this is fast enough not to hit the ground (or equivalently, if it is fast enough for Earth orbit). Then repeat the previous line of reasoning, again having to dig a trench. Now your sketch looks like this:



You're almost there. Continue by considering a muzzle velocity great enough so the cannonball travels 8 km in one second. (Don't state the velocity is 8 km/s here as you'll diminish your punch line.) Repeat your previous reasoning and note that this time you don't have to dig a trench! After a pause, and with a tone of importance, ask the class with what speed must the cannonball have to orbit the Earth. Done properly, you have led your class into a "derivation" of orbital speed about the Earth with no equations or algebra.



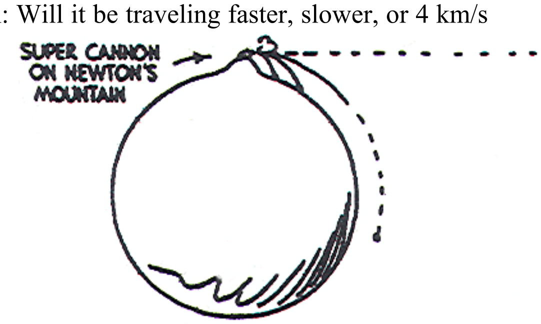
Acknowledge that the gravitational force is less on satellites in higher orbits so they do not need to go so fast. This is acknowledged later in the chapter in a footnote. (Since $v = \sqrt{GM/d}$, a satellite at 4 times the Earth's radius needs to travel only half as fast, 4 km/s.)

You can wind up your brief treatment of satellite motion and catch its essence via the following skit: Ask your students to pretend they are encountered by a bright youngster, too young to have much knowledge of physics and mathematics, but who nevertheless asks why satellites seem to defy gravity and stay in orbit. You ask what answer could correctly satisfy the curiosity of the kid, then pose the following dialogue between the kid and the students in your class (you're effectively suggesting how the student might interact with the bright kid). Ask the kid to observe and then describe what you do, as you hold a rock at arm's length and then simply drop it. The kid replies, "You dropped the rock and it fell to the ground below," to which you respond, "Very good—now what happens this time?", as you move your hand horizontally and again drop the rock. The kid observes and then says, "The rock dropped again, but because your hand was moving it followed a curved path and fell farther away." You continue, "Very good—now again—" as you throw the rock still farther. The kid replies, "I note that as your hand moves faster, the path follows a wider curve." You're elated at this response, and you ask the kid, "How far away will the rock hit the ground if its curved path matches the curved surface of the Earth?" The kid at first appears very puzzled, but then beams, "Oh—I get it! The stone doesn't hit at all—it's in Earth orbit." Then you interrupt your dialogue and ask the class, "Do YOU get it?" Then back to the kid who asks, "But isn't it really more complicated than that?", to which the answer is NO. The essential idea of satellite motion IS that simple.

Moving Perpendicular vs Moving Nonperpendicular to Gravity

Pose the case of rolling a ball along a bowling alley. Does gravity pull on the ball? [Yes.] Does gravity speed up or slow down the ball? [No.] Why? [Because all along the horizontal surface, gravity pulls in a direction downward, perpendicular to the surface. There is no component of gravity pulling horizontally, not forward and not backward.] This is the topic of Figure 10.22. Then ask if this fact relates to why a satellite in circular orbit similarly doesn't speed up or slow down due to gravity's persistent pull on it. [Aha! In both the ball on the alley and the satellite above, both "criss-cross" gravity, having no component of gravitational force in the direction of motion. No change in speed, no work, no change in KE, no change in PE. Aha! The cannonball and the bowling ball simply coast.]

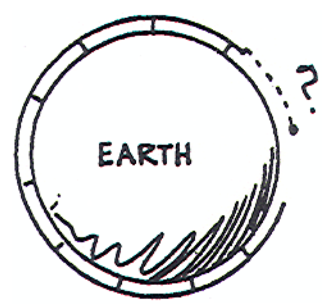
Discuss the motion of a cannonball fired horizontally from a mountain top. Suppose the cannonball leaves the cannon at a velocity of say 1 km/s. Ask your class whether the speed when it strikes the ground will be 1 km/s, more than 1 km/s, or less than 1 km/s (neglecting air resistance). The answer is that it strikes at *more* than 1 km/s because gravity speeds it up. (Toss your keys horizontally from a one-story window and catching them would pose no problem. But if you toss them horizontally from the top of a 20-story building, you wouldn't want to catch them!) That's because gravity plays a role on speed. Sketch "Newton's Mountain" on the whole world as shown, and sketch a trajectory that meets Earth's surface. Suppose the firing speed is now 4 km/s. Repeat your question: Will it be traveling faster, slower, or 4 km/s when it hits the ground? Again, faster, because it moves in the direction of gravity. Caution: Do not draw a trajectory that meets the Earth's surface at a point beyond the halfway mark. (Interestingly, the Zero-*g* film and other depictions show a complete orbit when past the half-way point, which is erroneous. Why? Because the parabolic path is actually a segment of a Keplerian ellipse, Figure 10.28. Halfway around puts it all around). Now draw the circular trajectory that occurs when the firing speed is 8 km/s. Ask if the speed increases, decreases, or remains the same after leaving the cannon. This time it remains the same. Why?



Neighbor checking time!

Circular Orbits

Erase the mountain from your sketch of the world and draw a huge elevated bowling alley that completely circles the world (Figure 10.23). You're extending Figure 10.22. Show how a bowling ball on such an alley would gain no speed because of gravity. But now cut part of the alley away, so the ball rolls off the edge and crashes to the ground below. Does it gain speed after falling in the gap? [Yes, because its circular path becomes a parabolic path, no longer moving perpendicular to gravity—having a component of velocity in the downward direction of the Earth's gravity.] Acknowledge that if the ball moves faster it will fall farther before crashing to the ground. Ask what speed would allow it to clear the gap (like a motorcyclist who drives off a ramp and clears a gap to meet a ramp on the other side). [8 km/s, of course.] Can the gap be bigger at this speed? Sketch a gap that nearly circles the world when you ask this question. Then ask, what happens with no alley? And your class sees that at 8 km/s no supporting alley is needed. The ball orbits the Earth.



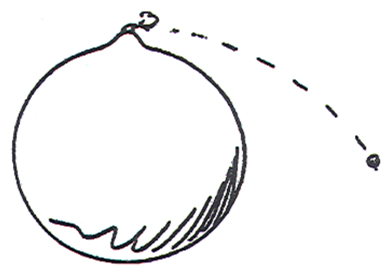
CHECK QUESTION: We say that satellites are falling around the Earth. But communication satellites remain at one place overhead. Isn't this contradictory? [Communication satellites fall in a wider circle than closer satellites. Their periods are 24 hours, which coincides with the period of the spinning Earth. So from Earth they appear to be motionless.]

Ask your class if they are familiar with an Earth satellite that has an average period of one month. There certainly is—it's the Moon, which has been falling around Earth for billions of years! Go further and ask about stars in the sky that appear motionless. Are they motionless, just hovering in space? The answer is NO. Stars in our galaxy, the Milky Way, are falling around the center of the galaxy. How intriguing that *everything is falling*! (This information should elicit interest even in the dullest of your students :-)

CHECK QUESTION: Why is it advantageous to launch rockets close to the equator? [The tangential speed at the equator is 1000 miles per hour, which can be subtracted from the speed needed to put a satellite in orbit. The closer the launch site to the equator, the closer it is to the 1000 mph free ride.]

Elliptical Orbits

Back to Newton's Mountain. Fire the cannonball at 9 km/s. It overshoots a circular path. Your sketch looks like this. Ask, at the position shown, is the cannonball moving at 9 km/s, more than 9 km/s, or less than 9 km/s. And why? After a neighbor check, toss a piece of chalk upward and say you toss it upward with an initial speed of 9 m/s. When it's halfway to the top of its path, is it moving 9 m/s, more than 9 m/s, or less than 9 m/s? Equate the two situations. [In both cases the projectile slows because it is going against gravity.]



Continue your sketch and show a closed path—an ellipse. As you draw the elliptical path, show with a sweeping motion of your arm how the satellite slows in receding from the Earth, moving slowest at its farthermost point, then how it speeds in falling towards the Earth, whipping around the Earth and repeating the cycle over and over again. Move to a fresh part of the chalkboard and redraw with the mountain at the bottom, so your sketch is more like Figure 10.27. (It is more comfortable seeing your chalk moving slowest when farthest coincides with the direction "up" in the classroom. I quip that Australians have no trouble seeing it the first way.)

Sketch in larger ellipses for still greater cannon speeds, with the limit being 11.2 km/s, beyond which the path does not close—escape speed.

State that Newton's equation was deducted from Kepler's laws.

Kepler's Laws

Briefly discuss Kepler's laws. Sketch an elliptical path of a planet about the Sun as in Figure 10.29. Show how the equal areas law means that the planet travels slowest when farthest from the Sun, and fastest when closest. State that Kepler had no idea why this was so. Walk to the side of your room and toss a piece of chalk upward at a slight angle so the class can see the parabolic path it traces. Ask where the chalk is moving slowest? Fastest? Why is it moving slowest at the top? [Because it has been traveling against gravity all the way up!] Why is it moving fastest when it is thrown and when it is caught? [It's moving fastest when it is caught because it has been traveling in the direction of gravity all the way down!] Speculate how amazed Kepler would have been if the same questions were asked of him, and relate this to the speeds of the planets around the Sun—slowest where they have been traveling against the gravity of the Sun, and fastest where they have been falling back toward the Sun. Kepler would have been amazed to see the physics of a body tossed upward is essentially the physics of satellite motion! Kepler lacked this simple model to guide his thinking. What simple models of tomorrow do we lack today, that finds us presently blind to the common sense of tomorrow?

Work-Energy Relationship for Satellites

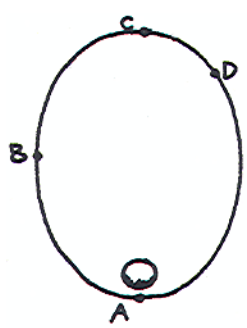
You already have sketches on the board of circular and elliptical orbits. Draw sample satellites and then sketch in force vectors. Ask the class to do likewise, and then draw component vectors parallel and perpendicular to instantaneous directions of motion. Then show how the changes in speed are consistent with the work-energy relationship.

Draw a large ellipse on the board with a planet in various positions and ask your class for a comparison of the relative magnitudes of KE and PE along the orbit. You can do this with different size symbols for KE and PE. Stress that the two add up to be the same. (This is treated in the screencast *Circular/Elliptical* Orbit.)

Escape Speed
Distinguish between ballistic speed and sustained speed, and that the value 11.2 km/s refers to ballistic speed. (One could go to the Moon at 1 km/s, given a means of sustaining that speed and enough time to make the trip!) Compare the escape speeds from different bodies via Table 10-1.

Maximum Falling Speed
The idea of maximum falling speed, footnoted on page 199, is sufficiently interesting for elaboration. Pretend you throw your car keys from ground level to your friend at the top of a building. Throw them too fast and they pass beyond your friend; throw them too slow and they never reach your friend. But if you throw them just right, say 11 m/s, they just barely reach her so she has only to grab them at their point of zero speed. Question: It took a speed of 11 m/s to get the keys up to her—if she simply drops them, how fast will they fall into your hands? Aha! If it takes a speed of 11.2 km/s to throw them to her if she is somewhat beyond Pluto, and she similarly drops them, how fast will they fall into your hands? Now your students understand maximum falling speed.

CHECK QUESTIONS: This reviews several chapters of mechanics; draw an elliptical orbit about a planet as shown on the board. Pose the following questions (from the *Practicing Physics Book*): At which position does the satellite experience the maximum



(a) gravitational force on it?
(b) speed?
(c) momentum?
(d) kinetic energy?
(e) gravitational potential energy?
(f) total energy (KE + PE)?
(g) acceleration?
(h) angular momentum?

Don't be surprised to find many of your students miss (g), acceleration, even though they answer the first about force correctly. If they use either equation for acceleration as their "guide," the answer is at hand; that is, from a - F/m, the acceleration is seen to be maximum where the force is maximum—at A. Or from a = (change in v)/t, acceleration is seen to be greatest where most of the change occurs—where the satellite whips around A. This Check Question summarizes important ideas in four chapters. Go over the answers carefully.

Answers and Solutions for Chapter 10

Reading Check Questions

1. A projectile is any object that is projected by some means and continues in motion by its own inertia.
2. The vertical component moves with or against gravity, while the horizontal component moves with no horizontal force acting.
3. With no air resistance the horizontal component of velocity remains constant, both in rising and falling.
4. Neglecting air resistance, the vertical component of velocity decreases as the stone rises, and increases as it descends, the same as with any freely-falling object.
5. In 1 second it falls 5 m beneath the line; For 2 seconds, 20 m beneath.
6. No, the falling distance beneath the line makes no difference whether or not the line is at an angle.
7. An angle of 15° would produce the same range, in accord with Figure 4.19.
8. The projectile would return at the same speed of 100 m/s, as indicated in Figure 4.22.
9. A projectile can fall around the Earth if it has sufficient tangential speed so that its curve downward is no sharper than that of Earth's curvature.
10. The speed must be enough so that the path of the projectile matches Earth's curvature.
11. A satellite must remain above the atmosphere because air resistance would not only slow it down, but incinerate it at its high speed. A satellite must not have to contend with either of these.
12. Speed doesn't change because there is no component of gravitational force along the ball's direction of motion when the bowling ball is moving horizontally.
13. As with the previous question, speed doesn't change when there's no component of gravitational force in the direction of its motion.
14. The time for a complete close orbit is about 90 minutes.
15. The period for satellites at higher altitudes is more than 90 minutes.
16. In an elliptical orbit there *is* a component of force in the direction of motion.
17. A satellite has the greatest speed when nearest Earth, and least when farthest away.
18. Tycho Brahe gathered the data, Kepler discovered elliptical orbits, and Newton explained them.
19. Kepler discovered the period squared was proportional to the radial distance cubed.
20. Kepler thought the planets were being pulled along their orbits. Newton realized they were being pulled toward the Sun.
21. KE is constant because no work is done by gravity on the satellite.
22. The sum of KE and PE is constant for all orbits.
23. Yes, escape speed can be at speeds less than 11.2 km/s if that speed is *sustained*.

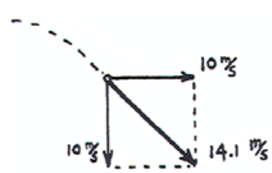
Think and Do

24. A worthwhile activity, and holding the stick at different angles nicely illustrates that distance of "fall" doesn't depend on angle of launch. If using a meterstick, at the 25 cm mark a 5-cm string can be attached; at the 50-cm mark, a 20 cm string; at the 75-cm mark, a 45 cm string; and at the end of the stick, the 100-cm mark, an 80 cm string. (Consider this as a classroom activity.)

25. Physics is about connections in nature. Discovering the connection between falling water in a swung bucket and falling satellites was an "aha" moment for PGH while whirling a water-filled bucket during a rotational-motion classroom demonstration—on a day when a much-publicized satellite launch was being discussed. How exhilarating to discover connections in nature!)

Think and Solve

26. One second after being thrown, its horizontal component of velocity is 10 m/s, and its vertical component is also 10 m/s. By the Pythagorean theorem, $V = \sqrt{(10^2 + 10^2)} = 14.1$ m/s. (It is moving at a 45° angle.)



27. (a) From $y = 5t^2 = 5(30)^2 = 4{,}500$ m, or 4.5 km high (4.4 km if we use $g = 9.8$ m/s^2).
(b) In 30 seconds; $d = vt = 280$ m/s $\times$ 30 s = 8400 m.

(c) The engine is directly below the airplane. (In a more practical case, air resistance is overcome for the plane by its engines, but not for the falling engine. The engine's speed is reduced by air resistance, covering less than 8400 horizontal m, landing behind the plane.)

28. Time during which the bullet travels is 200 m/400 m/s = 0.5 s. (a) So distance fallen is = ½ gt^2 = ½ (10 m/s^2)(0.5 s)^2 = 1.25 m. (b) The barrel must be aimed 1.25 m above the bullseye to match the falling distance.

29. At the top of its trajectory, the vertical component of velocity is zero, leaving only the horizontal component. The horizontal component at the top or anywhere along the path is the same as the initial horizontal component, **100 m/s** (the side of a square where the diagonal is 141).

30. The distance wanted is horizontal velocity × time. We find the time from the vertical distance the ball falls to the top of the can. This distance *y* is 1.0 m – 0.2 m = 0.8 m. The time is found using *g* = 10 m/s^2 and *y* = 0.8 m = ½ gt^2. Solving for *t* we get *t* = √2*y*/*g* = √[2(0.8m)/10 m/s^2] =0.4 s. Horizontal travel is then *d* = *vt* = (8.0 m/s)(0.4 s) = 3.2 m. (If the height of the can is *not* subtracted from the 1.0-m vertical distance between floor and tabletop, the calculated *d* will equal 3.6 m, the can will be too far away, and the ball will miss!)

31. Total energy = 5000 MJ + 4500 MJ = 9500 MJ. Subtract 6000 MJ and KE = 3500 MJ.

32. In accord with the work-energy theorem (Chapter 7) W = ΔKE the work done equals energy gained. The KE gain is 8 - 5 billion joules = 3 billion joules. The potential energy decreases by the same amount that the kinetic energy increases, 3 billion joules.

33. Hang time depends only on the vertical component of initial velocity and the corresponding vertical distance attained. From *d* = 5t^2 a vertical 1.25 m drop corresponds to 0.5 s (*t* = √2*d*/*g* = √2(1.25)/10 = 0.5 s). Double this (time up and time down) for a hang time of 1 s. Hang time is the same whatever the horizontal distance traveled.

34. (a) We're asked for horizontal speed, so we write, $v_x = \frac{d}{t}$, where *d* is horizontal distance traveled in time *t*. The time *t* of the ball in flight is as if we drop it from rest a vertical distance *y* from the top of the net. At highest point in its path, its vertical component of velocity is zero.

From $y = 1/2gt^2 \Rightarrow t^2 = \frac{2y}{g} \Rightarrow t = \sqrt{\frac{2y}{g}}$. So $v = \frac{d}{\sqrt{\frac{2y}{g}}}$.

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

(c) Note mass of the ball doesn't show in the equation, so mass is irrelevant.

Think and Rank

35. a. B, C, A, D b. B, D, A, C c. A=B=C=D (10 m/s^2)
36. a. A=B=C b. A=B=C c. A=B=C d. B, A, C
37. a. A, B, C b. C, B, A
38. a. A, B, C, D b. A, B, C, D c. A, B, C, D d. A, B, C, D e. D, C, B, A f. A=B=C=D g. A, B, C, D

Think and Explain

39. Divers can orient their bodies to change the force of air resistance so that the ratio of *net* force to mass is nearly the same for each.

40. In accord with the principle of horizontal and vertical projectile motion, the time to hit the floor is independent of the ball's speed.

41. Yes, it will hit with a higher speed in the same time because the horizontal (not the vertical) component of motion is greater.

42. No, because while the ball is in the air its horizontal speed doesn't change, but the train's speed does.

43. The crate will not hit the Porsche, but will crash a distance beyond it determined by the height and speed of the plane.

44. The path of the falling object will be a parabola as seen by an observer off to the side on the ground. You, however, will see the object fall straight down along a vertical path beneath you. You'll be directly above the point of impact. In the case of air resistance, where the airplane maintains constant velocity via its engines while air resistance decreases the horizontal component of velocity for the falling object, impact will be somewhere behind the airplane.

45. (a) The paths are parabolas. (b) The paths would be straight lines.

46. There are no forces horizontally (neglecting air resistance) so there is no horizontal acceleration, hence the horizontal component of velocity doesn't change. Gravitation acts vertically, which is why the vertical component of velocity changes.

47. Minimum speed occurs at the top, which is the same as the horizontal component of velocity anywhere along the path.

48. The bullet falls beneath the projected line of the barrel. To compensate for the bullet's fall, the barrel is elevated. How much elevation depends on the velocity and distance to the target. Correspondingly, the gunsight is raised so the line of sight from the gunsight to the end of the barrel extends to the target. If a scope is used, it is tilted downward to accomplish the same line of sight.

49. Both balls have the same range (see Figure 10.9). The ball with the initial projection angle of 30°, however, is in the air for a shorter time and hits the ground first.

50. The monkey is hit as the dart and monkey meet in midair. For a fast-moving dart, their meeting place is closer to the monkey's starting point than for a slower-moving dart. The dart and monkey fall equal vertical distances—the monkey below the tree, and the dart below the line of sight—because they both fall with equal accelerations for equal times.

51. Any vertically projected object has zero speed at the top of its trajectory. But if it is fired at an angle, only its vertical component of velocity is zero and the velocity of the projectile at the top is equal to its horizontal component of velocity. This would be 100 m/s when the 141-m/s projectile is fired at 45°.

52. Hang time depends only on the vertical component of your lift-off velocity. If you can increase this vertical component from a running position rather than from a dead stop, perhaps by bounding harder against the ground, then hang time is also increased. In any case, hang time depends *only* on the vertical component of your lift-off velocity.

53. The hang time will be the same, in accord with the answer to the preceding exercise. Hang time is related to the vertical height attained in a jump, not on horizontal distance moved across a level floor.

54. The Moon's tangential velocity is what keeps the Moon coasting around the Earth rather than crashing into it. If its tangential velocity were reduced to zero, then it would fall straight into the Earth!

55. From Kepler's third law, $T^2 \sim R^3$, the period is greater when the distance is greater. So the periods of planets farther from the Sun are longer than our year.

56. Yes, the satellite is accelerating, as evidenced by its continual change of direction. It accelerates due to the gravitational force between it and the Earth. The acceleration is toward the Earth's center.

57. Speed does not depend on the mass of the satellite (just as free-fall speed doesn't).

58. Neither the speed of a falling object (without air resistance) nor the speed of a satellite in orbit depends on its mass. In both cases, a greater mass (greater inertia) is balanced by a correspondingly greater gravitational force, so the acceleration remains the same ($a = F/m$, Newton's 2nd law).

59. Gravitation supplies the centripetal force on satellites.

60. The initial vertical climb lets the rocket get through the denser, retarding part of the atmosphere most quickly, and is also the best direction at low initial speed, when a large part of the rocket's thrust is needed just to support the rocket's weight. But eventually the rocket must acquire enough tangential speed to remain in orbit without thrust, so it must tilt until finally its path is horizontal.

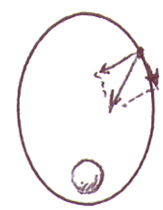
61. Gravity changes the speed of a cannonball when the cannonball moves in the direction of Earth gravity. At low speeds, the cannonball curves downward and gains speed because there is a component of the force of gravity along its direction of motion. Fired fast enough, however, the curvature matches the curvature of the Earth so the cannonball moves at right angles to the force of gravity. With no component of force along its direction of motion, its speed remains constant.

62. Upon slowing it spirals in toward the Earth and in so doing has a component of gravitational force in its direction of motion which causes it to gain speed. Or put another way, in circular orbit the perpendicular component of force does no work on the satellite and it maintains constant speed. But when it slows and spirals toward Earth there is a component of gravitational force that does work to increase the KE of the satellite.

63. A satellite travels faster when closest to the body it orbits. Therefore Earth travels faster about the Sun in December than in June.

64. Yes, a satellite needn't be above the surface of the orbiting body. It could orbit at any distance from the Earth's center of mass. Its orbital speed would be less because the effective mass of the Earth would be that of the mass below the tunnel radius. So interestingly, a satellite in circular orbit has its greatest speed near the surface of the Earth, and decreases with both decreasing and increasing distances.

65. The component along the direction of motion does work on the satellite to change its speed. The component perpendicular to the direction of motion changes its direction of motion.



66. In circular orbit there is no component of force along the direction of the satellite's motion so no work is done. In elliptical orbit, there is always a component of force along the direction of the satellite's motion (except at the apogee and perigee) so work is done on the satellite.

67. When the velocity of a satellite is everywhere perpendicular to the force of gravity, the orbital path is a circle (see Figure 10.20).

68. The period of any satellite at the same distance from Earth as the Moon would be the same as the Moon's, 27.3 days.

69. No way, for the Earth's center is a focus of the elliptical path (including the special case of a circle), so an Earth satellite orbits the center of the Earth. The plane of a satellite coasting in orbit always intersects the Earth's center.

70. Period is greater for satellites farther from Earth.

71. If a box of tools or anything else is "dropped" from an orbiting space vehicle, it has the same tangential speed as the vehicle and remains in orbit. If a box of tools is dropped from a high-flying jumbo jet, it too has the tangential speed of the jet. But this speed is insufficient for the box to fall around and around the Earth. Instead it soon falls into the Earth.

72. It could be dropped by firing it straight backward at the same speed of the satellite. Then its speed relative to Earth would be zero, and it would fall straight downward.

73. When a capsule is projected rearward at 7 km/s with respect to the spaceship, which is itself moving forward at 7 km/s with respect to the Earth, the speed of the capsule with respect to the Earth will be zero. It will have no tangential speed for orbit. What will happen? It will simply drop vertically to Earth and crash.

74. If the speed of the probe relative to the satellite is the same as the speed of the satellite relative to the Moon, then, like the projected capsule that fell to Earth in the previous question, it will drop vertically to the Moon. If fired at twice the speed, it and the satellite would have the same speed relative to the Moon, but in the opposite direction, and might collide with the satellite after half an orbit.

75. The tangential velocity of the Earth about the Sun is 30 km/s. If a rocket carrying the radioactive wastes were fired at 30 km/s from the Earth in the direction opposite to the Earth's orbital motion about the Sun, the wastes would have no tangential velocity with respect to the Sun. They would simply fall into the Sun.

76. Communication satellites only appear motionless because their orbital period coincides with the daily rotation of the Earth.

77. There are several potential advantages. A principal one is bypassing expensive first-stage rockets. Also, the plane, by flying eastward, can impart added initial speed to the spacecraft. And the spacecraft has less air resistance to overcome and somewhat less PE to surmount.

78. Since Moon's surface gravity is much less than Earth's, less thrust and less fuel is required to launch it to escape speed from the Moon.

79. Maximum falling speed by virtue only of the Earth's gravity is 11.2 km/s (see the Table 10.1 or the footnote on page 199).

80. Gravitation may "seem" to cancel, but it doesn't. The airplane is simply in a state of free fall and occupants inside experience no support force. No support force means no sensation of weight.

81. The satellite experiences the greatest gravitational force at A, where it is closest to the Earth, the perigee; and the greatest speed and the greatest velocity at A, and by the same token the greatest momentum and greatest kinetic energy at A, and the greatest gravitational potential energy at the farthest point C. It would have the same total energy (KE + PE) at all parts of its orbit, likewise the same angular momentum because it's conserved. It would have the greatest acceleration at A, where F/m is greatest.

82. Acceleration is maximum where gravitational force is maximum, and that's when Earth is closest to the Sun, at the perigee. At the apogee, force and acceleration are minimum.

Think and Discuss

83. Kicking the ball at angles greater than 45° sacrifices some distance to gain extra time. A kick greater than 45° doesn't go as far, but stays in the air longer, giving players on the kicker's team a chance to run down field and be close to the player on the other team who catches the ball.

84. For very slow-moving bullets, the dropping distance is comparable to the horizontal range, and the resulting parabola is easily noticed (the curved path of a bullet tossed sideways by hand, for example). For high speed bullets, the same drop occurs in the same time, but the horizontal distance traveled is so large that the trajectory is "stretched out" and hardly seems to curve at all. But it does curve. All bullets will drop equal distances in equal times, whatever their speed. (It is interesting to note that air resistance plays only a small role, since the air resistance acting *downward* is practically the same for a slow-moving or fast-moving bullet.)

85. Mars or any body in Earth's orbit would take the same time to orbit. The motion of a satellite, like that of a freely-falling object, does not depend on mass.

86. Consider "Newton's cannon" fired from a tall mountain on Jupiter. To match the wider curvature of much larger Jupiter, and to contend with Jupiter's greater gravitational pull, the cannonball would have to be fired significantly faster. (Orbital speed about Jupiter is about 5 times that for Earth.)

87. Rockets for launching satellites into orbit are fired easterly to take advantage of the spin of the Earth. Any point on the equator of the Earth moves at nearly 0.5 km/s with respect to the center of the Earth or the Earth's polar axis. This extra speed does not have to be provided by the rocket engines. At higher latitudes, this "extra free ride" is less.

88. Hawaii is closer to the equator, and therefore has a greater tangential speed about the polar axis. This speed could be added to the launch speed of a satellite and thereby save fuel. As seen from the North Star, Hawaii is closer to the edge of “turntable Earth” than other locations in the United States.

89. The Moon has no atmosphere (because escape velocity at the Moon’s surface is less than the speeds of any atmospheric gases). A satellite 5 km above the Earth’s surface is still in considerable atmosphere, as well as in range of some mountain peaks. Atmospheric drag is the factor that most determines orbiting altitude.

90. The satellite circles at the same rate as Earth rotates, which is why it appears motionless to Earth observers. But to remain above a certain location, both the location and satellite need to be in the same line between Earth’s center and the satellite. This can only occur above Earth’s equator. Above any other location, the “ring” of satellite motion would be out of synch.

91. Singapore lies on the Earth’s equator. The plane of the satellite’s equatorial orbit includes Singapore, so a satellite can be located directly above Singapore. But in San Francisco, a geosynchronous satellite over the equator is seen at an angle with the vertical—not directly overhead.

92. Considerably less than 8 km/s. To see why, think of “Newton’s cannon” fired from a hilltop on tiny Eros, with its small gravity. If the speed of the cannonball were 8 km/s, it would fall far less than 5 m in its first second of travel (as it would on Earth), and would not curve enough to follow the round surface of the asteroid. It would shoot off into space. To follow the curvature of the asteroid, it must be launched with a much smaller speed.

93. At midnight you face away from the Sun, and therefore cannot see the planets closest to the Sun—Mercury and Venus (which lie inside the Earth’s orbit).

94. When descending, a satellite meets the atmosphere at almost orbital speed. When ascending, its speed through the air is considerably less and it attains orbital speed well above air drag.

95. No, for an orbit in the plane of the Arctic Circle does not intersect the Earth’s center. All Earth satellites orbit in a plane that intersects the center of the Earth. A satellite may pass over the Arctic Circle, but cannot remain above it indefinitely, as a satellite can over the equator.

96. The inverse-square law of gravity finds gravity a mere 62 miles high very nearly as strong as it is on Earth’s surface. Gravity is an inverse-square law phenomenon that has nothing to do with being above the atmosphere. Also, there is still some atmosphere, although very thin, above 62 miles in altitude.

97. The GPS system “triangulates” to show locations. One satellite can tell distance between the satellite and the receiver, and two perhaps longitude, but three are needed for altitude, longitude, and latitude. Four confirms the results of three.

98. The half brought to rest will fall vertically to Earth. The other half, in accord with the conservation of linear momentum will have twice the satellite's original velocity, and will move farther from Earth (actually, it will have enough speed to escape Earth and fly into space).

99. The design is a good one. Rotation would provide a centripetal force on the occupants. Watch for this design in future space habitats.

100. In accord with the work-energy relationship, $Fd = \Delta\text{KE}$, for a constant thrust F, the maximum change in KE will occur when d is maximum. The rocket will travel the greatest distance d during the brief firing time when it is traveling fastest—at the perigee.