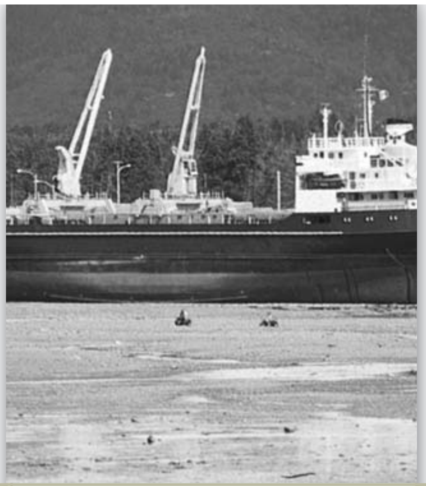
Extreme tidal variation.
High and low tides in a small harbor near Blomidon Provincial Park, Nova Scotia, Canada, demonstrate the dramatic change of sea level experienced daily in the Bay of Fundy, which has the world's largest tidal range.



> *"I derive from the celestial phenomena the forces of gravity with which bodies tend to the sun and several planets. Then from these forces, by other propositions which are also mathematical, I deduce the motions of the planets, the comets, the moon, and the sea."*
>
> *—Sir Isaac Newton,*
> *Philosophiae Naturalis Principia Mathematica*
> *(Philosophy of Natural Mathematical Principles) (1686)*

9

TIDES

CHAPTER AT A GLANCE

- The Moon and—to a lesser extent—the Sun create paired tidal bulges on Earth; as Earth rotates, it carries various locations into and out of these tidal bulges, causing alternating high and low tides.
- Spring tides have a large tidal range and are associated with full and new moon phases; neap tides have a small tidal range and are associated with quarter moon phases.
- The three types of tidal patterns include diurnal (one high/one low daily), semidiurnal (two highs/two lows of about equal heights) and mixed (like semidiurnal, but with different heights of high/low tides).

Tides are the periodic raising and lowering of sea level that occurs daily throughout the ocean. As sea level rises and falls, the edge of the sea slowly shifts landward and seaward each day; as it rises, it often destroys sand castles that were built during low tide. Knowledge of tides is important in many coastal activities, including tide pooling, shell collecting, surfing, fishing, navigation, and preparing for storms. Tides are so important that accurate records have been kept at nearly every port for several centuries and there are many examples of the term *tide* in everyday vocabulary (for instance, "to tide someone over," "to go against the tide," or to wish someone "good tidings").

There is no doubt that early coastal peoples noticed the tides yet the earliest written record of tides is in about 450 B.C. Even the earliest sailors knew the Moon had some connection with the tides because both followed a similar pattern. For example, high tides were associated with either a full or new moon. However, it wasn't until **Isaac Newton** (1642–1727) developed the universal law of gravitation that the tides could adequately be explained.

Although the study of the tides can be complex, tides are fundamentally very long and regular shallow-water waves. As we shall see, their wavelengths are measured in thousands of kilometers and their heights range to more than 15 meters (50 feet).

9.1 What Causes the Tides?

Simplistically, the gravitational attraction of the Sun and Moon on Earth creates ocean tides. In a more complete analysis, tides are generated by forces imposed on Earth that are caused by a combination of *gravity* and *motion* among Earth, the Moon, and the Sun.

Tide-Generating Forces

Newton's work on quantifying the forces involved in the Earth–Moon–Sun system led to the first understanding of the underlying forces that keep bodies in orbit around each other. It is well known that gravity is the force that interconnects the Sun, its planets, and their moons and keeps them in relatively fixed orbits. For example, most of us are taught that "the Moon orbits Earth," but it is not quite that simple. The two bodies actually rotate around a common center of mass called the **barycenter** (*barus* = heavy, *center* = center), which is the *balance point* of the system, located 1600 kilometers (1000 miles) beneath Earth's surface (Figure 9.1a). Why isn't the barycenter halfway in between the two bodies? It's because Earth's mass is so much greater than that of the Moon. This can be visualized by imagining Earth and its Moon as ends of an object that is much heavier on one end than the other. A good example of this is a sledgehammer, which has a lighter handle and a much heavier head, with its balance point within the head of the hammer. Now imagine that the

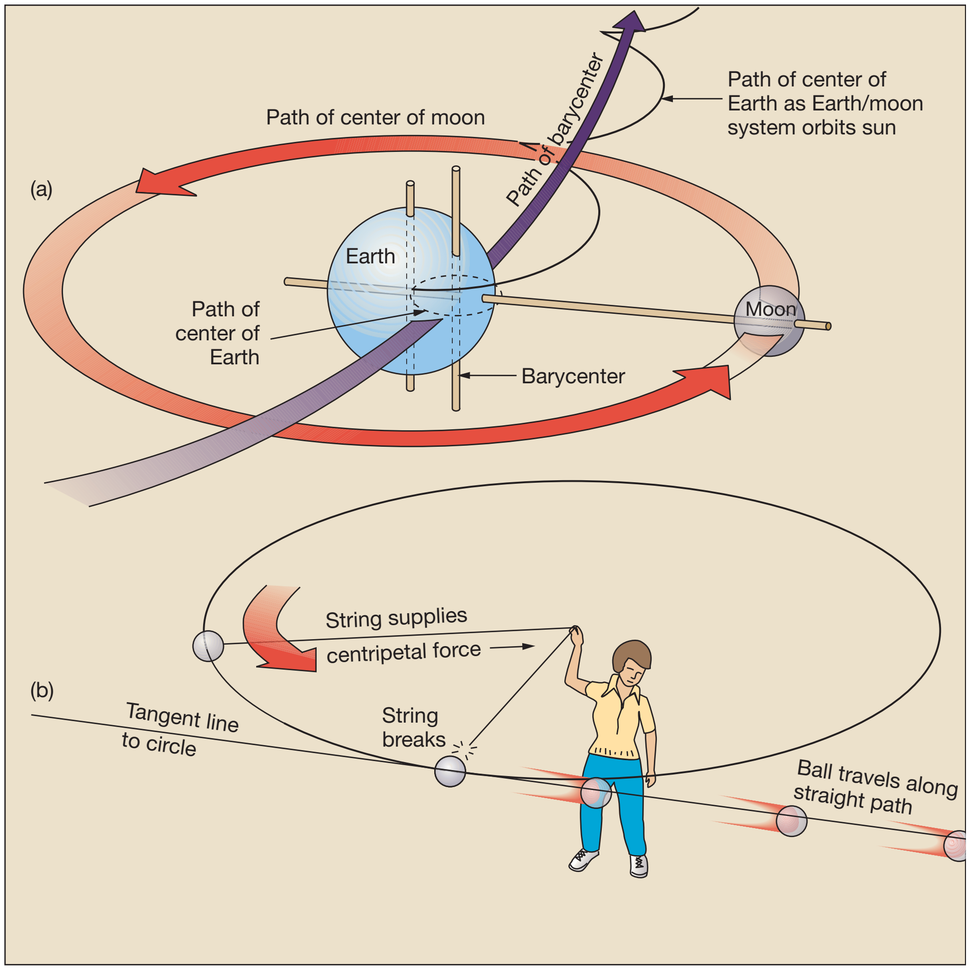


FIGURE 9.1 Earth–Moon system rotation. **(a)** The center of mass (*barycenter*) of the Earth–Moon system moves in a nearly circular orbit around the Sun. **(b)** If a ball with a string attached is swung overhead, it stays in a circular orbit because the string exerts a centripetal (center-seeking) force on the ball. If the string breaks, the ball will fly off along a straight path along a tangent to the circle.

WEB VIDEO
Tidal Change along a Coast (Time Lapse)

sledgehammer is flung into space, tumbling slowly end over end about its balance point. This is exactly the situation that describes the movement of the Earth–Moon system. The purple arrow in Figure 9.1a shows the smooth, nearly circular path of the Earth–Moon barycenter around the Sun.

If the Moon and Earth are attracted to one another, why don't the two collide? Moreover, the Earth–Moon system is involved in a mutual orbit held together by gravity and motion, which prevents the Moon and Earth from colliding. This is how orbits are established that keep objects at more or less fixed distances.

Newton's work also allowed an understanding of why the tides behave as they do. Just as gravity and motion serve to keep bodies in mutual orbits, they also exert an influence on every particle of water on Earth, thus creating the tides.

GRAVITATIONAL AND CENTRIPETAL FORCES IN THE EARTH–MOON SYSTEM To understand how *tide-generating forces* influence the oceans, let's examine how *gravitational forces* and *centripetal forces* affect objects on Earth within the Earth–Moon system. (We'll ignore the influence of the Sun for the moment.)

The **gravitational force** is derived from **Newton's law of universal gravitation**, which states that *every object that has mass in the universe is attracted to every other object*. An object can be as small as an individual atomic particle or as large as a sun. The basic equation for this relationship is:

$$F_g = \frac{Gm_1m_2}{r^2} \qquad (9.1)$$

What this equation states is that the gravitational force (F_g) is directly proportional to the product of the masses of the two bodies (m_1, m_2) and is inversely proportional to the square of the distance between the two masses (r^2). Note that G is the gravitational constant, so it does not change.

Let's simplify Newton's law of universal gravitation and examine the effect of both mass and distance on the gravitational force, which can be expressed with arrows (up arrow = increase, down arrow = decrease):

If mass increases (↑), then gravitational force increases (↑).

A practical example of this can be seen in an object with a large mass (such as the Sun), which produces a large gravitational attraction (Figure 9.2a).

Looking at how distance influences gravitational force, the relationship is:

If distance increases (↑), then gravitational force greatly decreases (↓↓).

Equation 9.1 shows that the gravitational attraction varies with the *square* of distance, so even a small *increase* in the distance between two objects significantly *decreases* the gravitational force between them, hence the double arrows in the distance relationship illustrated above. What this means is that when an object is twice as far away, the gravitational attraction is only one-quarter as strong. As a practical example, this is why astronauts experience weightlessness in space when they get far enough from Earth's gravitational pull (Figure 9.2b). In summary, then, the *greater* the mass of the objects and (especially) the *closer* they are together, the greater their gravitational attraction.

Figure 9.3 shows how gravitational forces for points on Earth (caused by the Moon) vary depending on their distances from the Moon. The greatest gravitational attraction (the longest arrow) is at *Z*, the **zenith** (*zenith* = a path over the head), which is the point closest to the Moon. The gravitational attraction is weakest at *N*, the **nadir** (*nadir* = opposite the zenith), which is the point farthest from the Moon. The direction of the gravitational attraction between most particles and the center of the Moon is at an angle relative to a line connecting the center of Earth and the Moon (Figure 9.3). This angle causes the force of gravitational attraction between each particle and the Moon to be slightly different.

The **centripetal** (*centri* = the center, *pet* = seeking) **force**[1] required to keep planets in their orbits is provided by the gravitational attraction between each of them and the Sun. Centripetal force connects an orbiting body to its parent, pulling the object *inward* toward the parent, "seeking the center" of its orbit. For example, if you tie a string to a ball and swing the ball around your head (Figure 9.1b), the string pulls the ball toward your hand. The string exerts a *centripetal force* on the ball, forcing the ball to *seek the center* of its orbit. If the string should break, the force is gone and the ball can no longer maintain its circular orbit. The ball flies off in a *straight* line,[2] *tangent* (*tangent* = touching) to the circle (Figure 9.1b).

The Earth and Moon are interconnected, too, not by strings but by gravity. Gravity provides the centripetal force that holds the Moon in its orbit around Earth. If all gravity in the solar system could be shut off, centripetal force would vanish, and the momentum of the celestial bodies would send them flying off into space along straight-line paths, tangent to their orbits.

RESULTANT FORCES Particles of identical mass rotate in identical-sized paths due to the Earth–Moon rotation system (Figure 9.4). Each particle requires an identical centripetal force to maintain it in its circular path. Gravitational

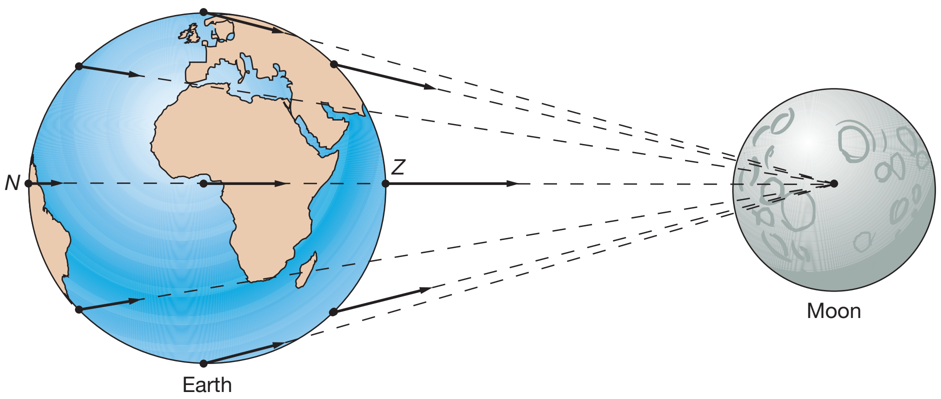
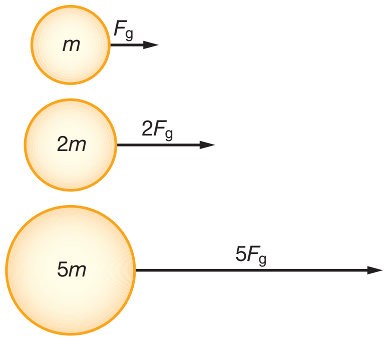
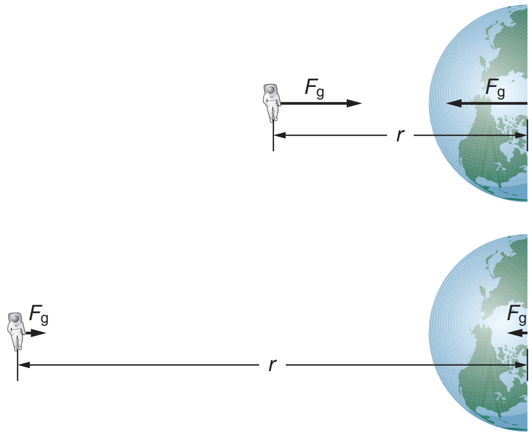


FIGURE 9.3 Gravitational forces on Earth due to the Moon. The gravitational forces on objects located at different places on Earth due to the Moon are shown by arrows. The length and orientation of the arrows indicate the strength and direction of the gravitational force. Notice the length and angular differences of the arrows for different points on Earth. The letter Z represents the zenith; N represents the nadir. Distance between Earth and Moon not shown to scale.



(a) The effect of mass on gravitational attraction



(b) The effect of distance on gravitational attraction

FIGURE 9.2 The relationship of gravitational force to mass and distance. **(a)** Gravitational force (F_g) is proportional to a body's mass; as mass increases, so does the gravitational force. **(b)** Gravitational forces between two bodies decrease rapidly as distance (r) increases.

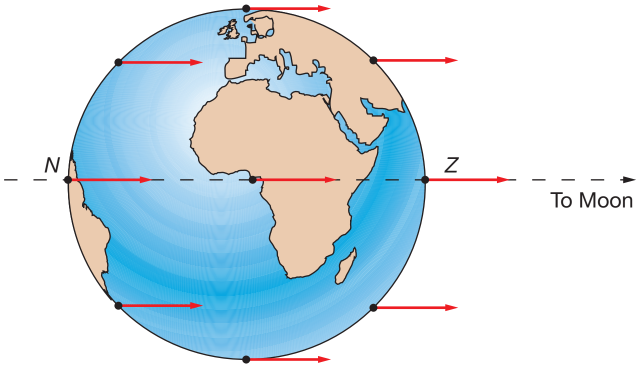


FIGURE 9.4 Required centripetal (center-seeking) forces. Centripetal forces required to keep identical-sized particles in identical-sized orbits as a result of the rotation of the Earth–Moon system around its barycenter. Notice that the arrows are all the same length and are oriented in the same direction for all points on Earth. Z = zenith; N = nadir.

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[1] This is not to be confused with the so-called *centrifugal* (*centri* = the center, *fug* = flee) *force*, an apparent or fictitious force that is oriented outward.

[2] At the moment that the string breaks, the ball will continue along a straight-line path, obeying Newton's first law of motion (the *law of inertia*), which states that moving objects follow straight-line paths until they are compelled to change that path by other forces.

attraction between the particle and the Moon supplies the centripetal force, but the *supplied* force is different than the *required* force (because gravitational attraction varies with distance from the Moon) except at the center of Earth. This difference creates tiny **resultant forces**, which are the mathematical difference between the two sets of arrows shown in Figures 9.3 and 9.4.

Figure 9.5 combines Figures 9.3 and Figure 9.4 to show that resultant forces are produced by the difference between the required centripetal (C) and supplied gravitational (G) forces. However, do not think that both of these forces are being applied to the points, because (C) is a force that would be required to keep the particles in a perfectly circular path, while (G) is the force actually provided for this purpose by gravitational attraction between the particles and the Moon. The resultant forces (*blue arrows*) are established by constructing an arrow from the tip of the centripetal (*red*) arrow to the tip of the gravity (*black*) arrow and located where the red and black arrows begin.

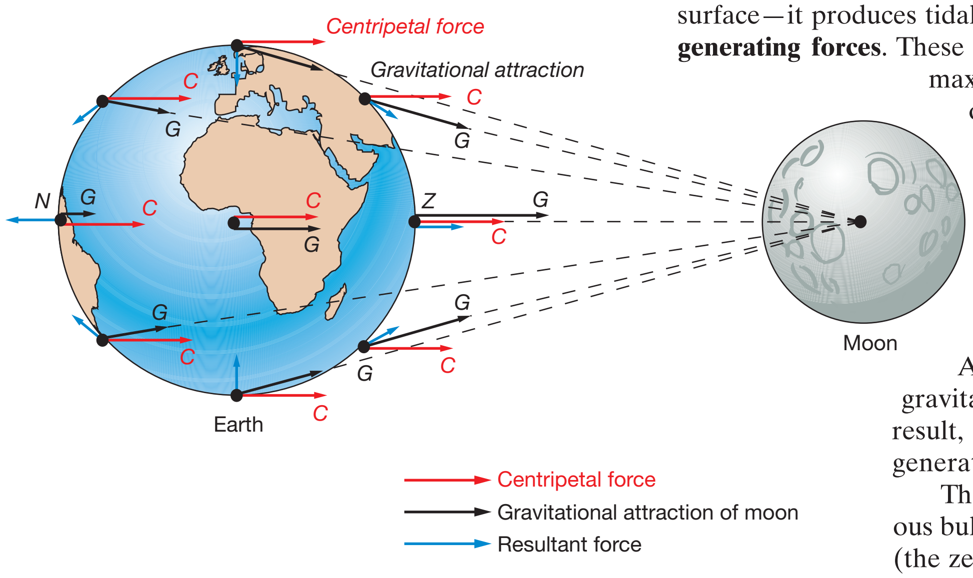

FIGURE 9.5 Resultant forces. Red arrows indicate centripetal forces (C), which are not equal to the black arrows that indicate gravitational attraction (G). The small blue arrows show resultant forces, which are established by constructing an arrow from the tip of the centripetal (*red*) arrow to the tip of the gravity (*black*) arrow and located where the red and black arrows begin. Z = zenith; N = nadir. Distance between Earth and Moon not shown to scale.

TIDE-GENERATING FORCES Resultant forces are small, averaging about one-millionth the magnitude of Earth's gravity. If the resultant force is vertical to Earth's surface, as it is at the zenith and nadir (oriented upward) and along an "equator" connecting all points halfway between the zenith and nadir (oriented downward), it has no tide-generating effect (Figure 9.6). However, if the resultant force has a significant *horizontal component*—that is, tangential to Earth's surface—it produces tidal bulges on Earth, creating what are known as the **tide-generating forces**. These tide-generating forces are quite small but reach their maximum value at points on Earth's surface at a "latitude" of 45 degrees relative to the "equator" between the zenith and nadir (Figure 9.6).

As previously discussed, gravitational attraction is inversely proportional to the *square* of the distance between two masses. The tide-generating force, however, is inversely proportional to the *cube* of the distance between each point on Earth and the *center* of the tide-generating body (Moon or Sun). Although the tide-generating force is derived from the gravitational force, it is not linearly proportional to it. As a result, distance is a more highly weighted variable for tide-generating forces.

The tide-generating forces push water into two simultaneous bulges: one on the side of Earth directed *toward* the Moon (the zenith) and the other on the side directed *away from* the Moon (the nadir) (Figure 9.7). On the side directly facing the Moon, the bulge is created because the provided gravitational force is greater than the required centripetal force. Conversely, on the side facing away from the Moon, the bulge is created because the required centripetal force is greater than the provided gravitational force. Although the forces are oriented in opposite directions on the two sides of Earth, the resultant forces are equal in magnitude, so the bulges are equal, too.

Tidal Bulges: The Moon's Effect

It is easier to understand how tides on Earth are created if we consider an ideal Earth and an ideal ocean. The ideal Earth has two tidal bulges, one toward the Moon and one away from the Moon (called the **lunar bulges**), as shown in Figure 9.7. The ideal ocean has a uniform depth, with no friction between the seawater and the sea floor. Newton made these same simplifications when he first explained Earth's tides.

STUDENTS SOMETIMES ASK . . .

Are there also tides in other objects, such as lakes and swimming pools?

The Moon and the Sun act on all objects that have the ability to flow, so there are tides in lakes, wells, and swimming pools. In fact, there are even extremely tiny tidal bulges in a glass of water! However, the tides in the atmosphere and the "solid" Earth have greater significance. Tides in the atmosphere—called *atmospheric tides*—can be miles high and are also affected by solar heating. The tides inside Earth's interior—called *solid-body tides*, or *Earth tides*—cause a slight but measurable stretching of Earth's crust, typically only a few centimeters high, that has recently been linked as a trigger mechanism for tremors along certain weak faults.

KEY CONCEPT

The tides are caused by an imbalance between the required centripetal and the provided gravitational forces acting on Earth. This difference produces residual forces, the horizontal component of which pushes ocean water into two equal tidal bulges on opposite sides of Earth.

If the Moon is stationary and aligned with the ideal Earth's equator, the maximum bulge will occur on the equator on opposite sides of Earth. If you were standing on the equator, you would experience two high tides each day. The time between high tides, which is the **tidal period**, would be 12 hours. If you moved to any latitude north or south of the equator, you would experience the same tidal period, but the high tides would be less high, because you would be at a lower point on the bulge.

In most places on Earth, however, high tides occur every 12 hours 25 minutes because tides depend on the lunar day, not the solar day. The **lunar day** (also called a *tidal day*) is measured from the time the Moon is on the meridian of an observer—that is, directly overhead—to the next time the Moon is on that meridian and is 24 hours 50 minutes.[3] The **solar day** is measured from the time the Sun is on the meridian of an observer to the next time the Sun is on that meridian and is 24 hours. Why is the lunar day 50 minutes longer than the solar day? During the 24 hours it takes Earth to make a full rotation, the Moon has continued moving another 12.2 degrees to the east in its orbit around Earth (Figure 9.8). Thus, Earth must rotate an additional 50 minutes to "catch up" to the Moon so that the Moon is again on the meridian (directly overhead) of our observer.

The difference between a solar day and a lunar day can be seen in some of the natural phenomena related to the tides. For example, alternating high tides are normally 50 minutes *later* each successive day and the Moon rises 50 minutes *later* each successive night.

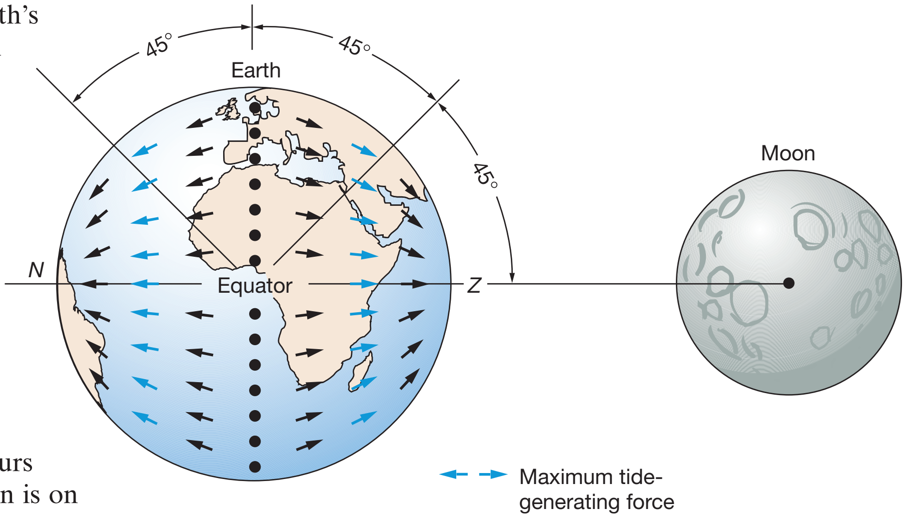

FIGURE 9.6 Tide-generating forces. Where the resultant force acts vertically relative to Earth's surface, the tide-generating force is zero. This occurs at the zenith (*Z*) and nadir (*N*), and along an "equator" connecting all points halfway between the zenith and nadir (*black dots*). However, where the resultant force has a significant *horizontal component*, it produces a tide-generating force on Earth. These tide-generating forces reach their maximum value at points on Earth's surface at a "latitude" of 45 degrees (*blue arrows*) relative to the "equator" mentioned here. Distance between Earth and Moon not shown to scale.

Tidal Bulges: The Sun's Effect

The Sun affects the tides, too. Like the Moon, the Sun produces tidal bulges on opposite sides of Earth, one oriented *toward* the Sun and one oriented *away from* the Sun. These **solar bulges**, however, are much smaller than the lunar bulges. Although the Sun is 27 million times more massive than the Moon, its tide-generating force is not 27 million times greater than the Moon's. This is because the Sun is 390 times farther from Earth than the Moon (Figure 9.9). Moreover, tide-generating forces vary inversely as the *cube* of the distance between objects. Thus, the tide-generating force is reduced by the cube of 390, or about 59 million times compared with that of the Moon. These conditions result in the Sun's tide-generating force being $^{27}/_{59}$ that of the Moon, or 46% (about one-half). Consequently, the solar bulges are only 46% the size of the lunar bulges and, as a result, the Moon exerts over two times the gravitational pull of the Sun on the tides.

Even though the Moon exerts over two times the gravitational pull of the Sun on Earth's tides, note that the Sun does not exert a smaller gravitational force on Earth as compared to the Moon. In fact, the Sun's total "pull" on all points on Earth is much greater than that of the Moon's, but the *difference* across Earth is small because the diameter of Earth is very small in relation to the distance from the Sun. In contrast, the diameter of Earth is quite large in relation to the distance to the center of the Moon. In summary, the reason why the Moon controls tides far more than the Sun is because the Moon is much closer to Earth, although it is much smaller in size and mass as compared to the Sun.

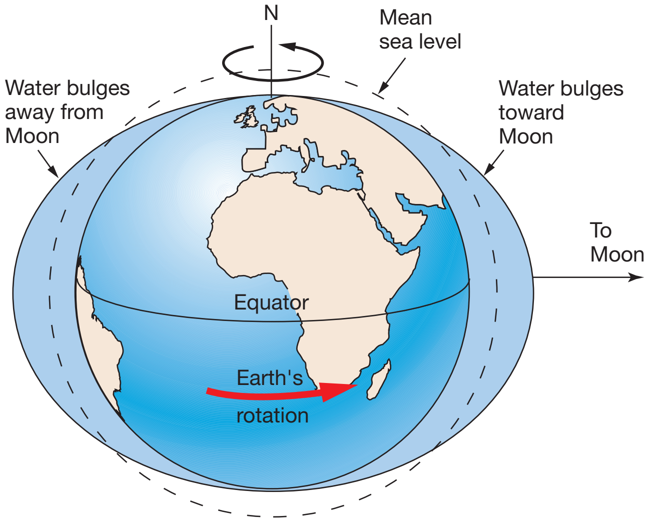

FIGURE 9.7 Idealized tidal bulges. In an idealized case, the Moon creates two bulges in the ocean surface: one that extends *toward* the Moon and the other *away from* the Moon. As Earth rotates, it carries various locations into and out of the two tidal bulges so that all points on its surface (except the poles) experience two high tides daily.

KEY CONCEPT

A solar day (24 hours) is shorter than a lunar day (24 hours and 50 minutes). The extra 50 minutes is caused by the Moon's movement in its orbit around Earth.

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[3] A lunar day is exactly 24 hours, 50 minutes, 28 seconds long.

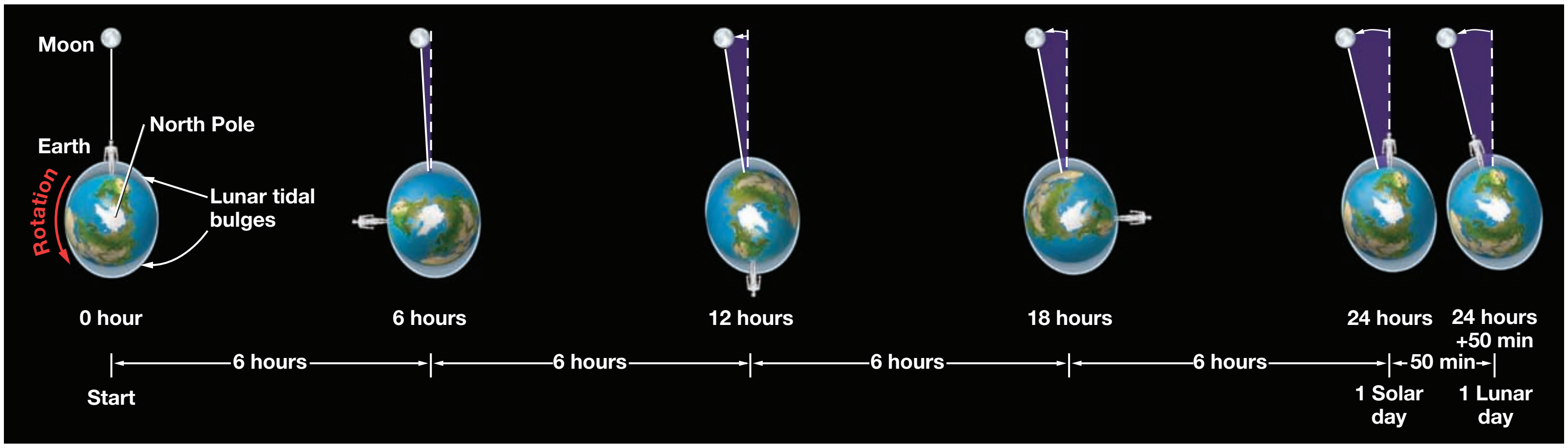

FIGURE 9.8 The lunar day. A lunar day is the time that elapses between when the Moon is directly overhead and the next time the Moon is directly overhead. During one complete rotation of Earth (the 24-hour solar day), the Moon moves eastward 12.2 degrees, and Earth must rotate an additional 50 minutes for the Moon to be in the exact same position overhead. Thus, a lunar day is 24 hours 50 minutes long.

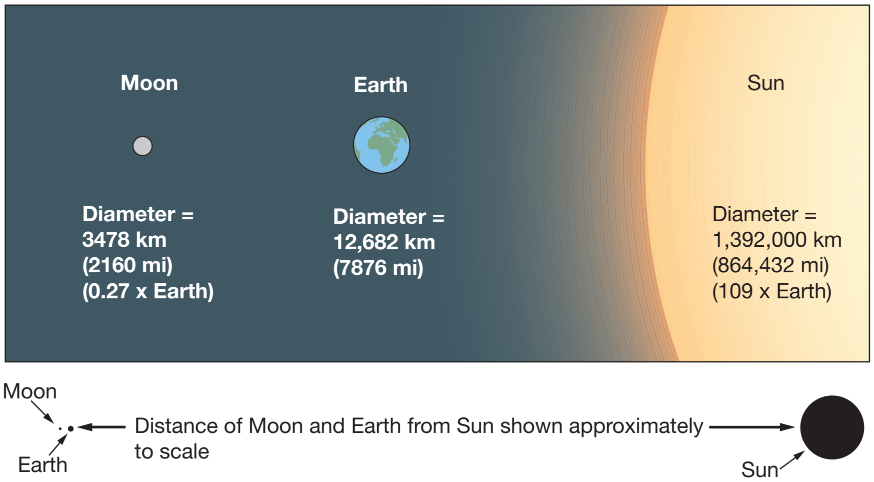

FIGURE 9.9 Relative sizes and distances of the Moon, Earth, and Sun. *Top:* The relative sizes of the Moon, Earth, and Sun, showing the diameter of the Moon is roughly one-fourth that of Earth, while the diameter of the Sun is 109 times the diameter of Earth. *Bottom:* The relative distances of the Moon, Earth, and Sun are shown to scale.

KEY CONCEPT

The lunar bulges are about twice the size of the solar bulges. In an idealized case, the rise and fall of the tides are caused by Earth's rotation carrying various locations into and out of the tidal bulges.

Earth's Rotation and the Tides

The tides appear to move water in toward shore (the **flood tide**) and to move water away from shore (the **ebb tide**). However, according to the nature of the idealized tides presented so far, *Earth's rotation carries various locations into and out of the tidal bulges*, which are in fixed positions relative to the Moon and the Sun. In essence, alternating high and low tides are created as Earth constantly rotates inside fluid bulges that are supported by the Moon and the Sun.

9.2 How Do Tides Vary During a Monthly Tidal Cycle?

The monthly tidal cycle is 29½ days because that's how long it takes the Moon to complete an orbit around Earth.[4] During its orbit around Earth, the Moon's changing position influences tidal conditions on Earth.

The Monthly Tidal Cycle

During the monthly tidal cycle, the phase of the Moon changes dramatically. When the Moon is between Earth and the Sun, it cannot be seen at night; this phase is called **new moon**. When the Moon is on the side of Earth opposite the Sun, its entire disk is brightly visible; this phase is called **full moon**. A **quarter moon**—a moon that is half lit and half dark as viewed from Earth—occurs when the Moon is at right angles to the Sun relative to Earth.

Figure 9.10 shows the positions of the Earth, Moon, and Sun at various points during the 29½-day lunar cycle. When the Sun and Moon are aligned, either with the Moon between Earth and the Sun (new moon; Moon in *conjunction*) or with the Moon on the side opposite the Sun (full moon; Moon in *opposition*), the tide-generating forces of the Sun and Moon combine (Figure 9.10, *top*). At this time, the **tidal range** (the vertical difference between high and low tides) is large (very *high* high tides and quite *low* low tides) because there is *constructive interference*[5] between the lunar and solar tidal bulges. The maximum tidal range is called

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[4] The 29½-day monthly tidal cycle is also called a *lunar cycle*, a *lunar month,* or a *synodic (synod* = meeting) *month.*

[5] As mentioned in Chapter 8, *constructive interference* occurs when two waves (or, in this case, two tidal bulges) overlap crest to crest and trough to trough.

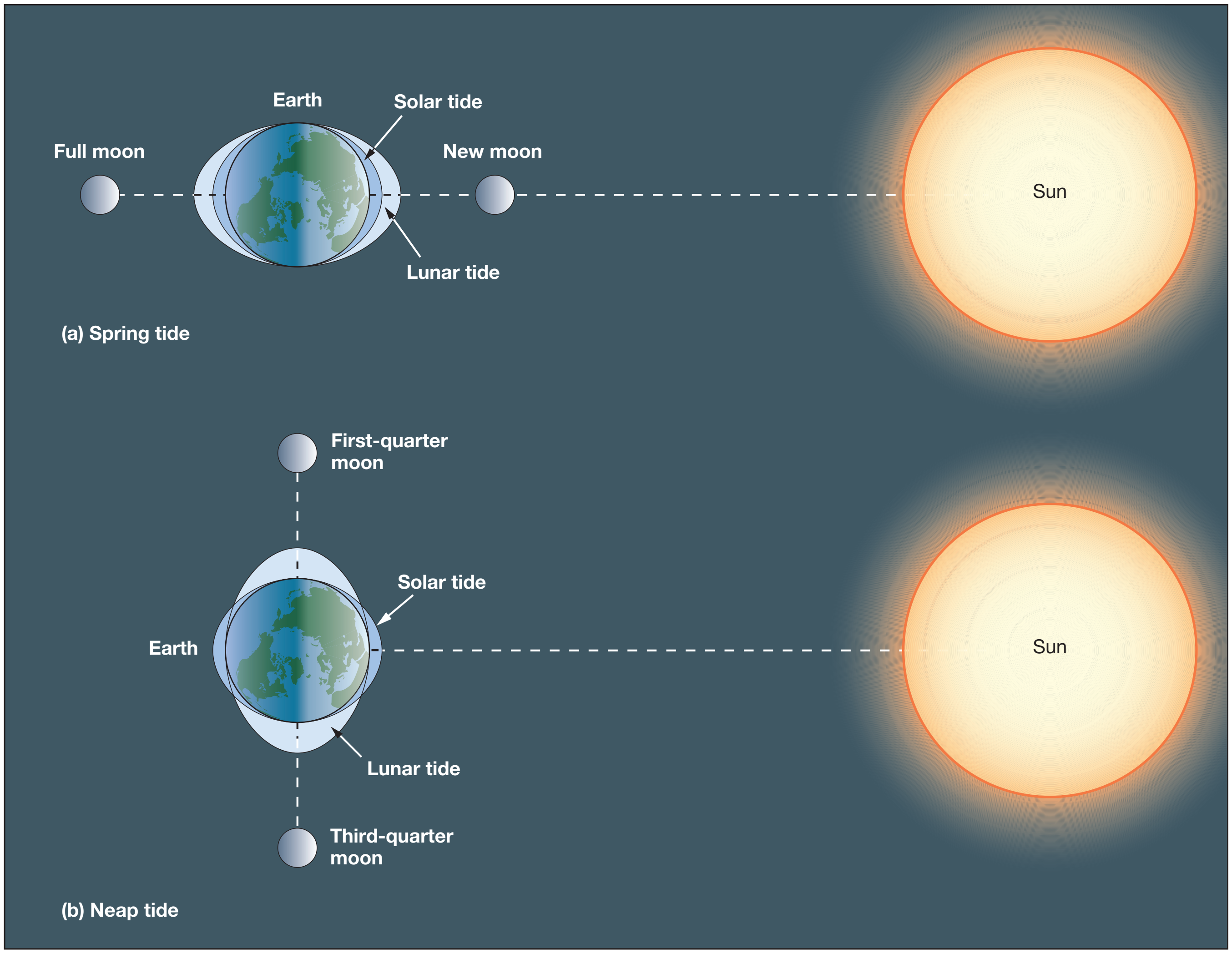

FIGURE 9.10 Earth–Moon–Sun positions and the tides. *Top*: When the Moon is in the new or full position, the tidal bulges created by the Sun and Moon are aligned, there is a large tidal range on Earth, and spring tides are experienced. *Bottom*: When the Moon is in the first- or third-quarter position, the tidal bulges produced by the Moon are at right angles to the bulges created by the Sun. Tidal ranges are smaller and neap tides are experienced. Note that there is only one moon in orbit around Earth.

a **spring** (*springen* = to rise up) **tide**,[6] because the tide is extremely large or "springs forth." When the Earth–Moon–Sun system is aligned, the Moon is said to be in **syzygy** (*syzygia* = union).

When the Moon is in either the first- or third-quarter[7] phase (Figure 9.10, *bottom*), the tide-generating force of the Sun is working at right angles to the tide-generating force of the Moon. The tidal range is small (*lower* high tides and *higher* low tides) because there is *destructive interference*[8] between the lunar and solar tidal bulges. This is called a **neap** (*nep* = scarcely or barely touching) **tide**,[9] and the Moon is said to be in **quadrature** (*quadra* = four).

The time between successive spring tides (full moon and new moon) or neap tides (first quarter and third quarter) is one-half the monthly lunar cycle, which is about two weeks. The time between a spring tide and a successive neap tide is one-quarter the monthly lunar cycle, which is about one week.

Monthly Tidal Cycle

KEY CONCEPT

Spring tides occur during the full and new moon, when the lunar and solar tidal bulges constructively interfere, producing a large tidal range. Neap tides occur during the quarter moon phases, when the lunar and solar tidal bulges destructively interfere, producing a small tidal range.

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[6] Spring tides have no connection with the spring season; they occur twice a month during the time when the Earth–Moon–Sun system is aligned.

[7] The third-quarter moon is often called the last-quarter moon, which is not to be confused with certain sports that have a fourth quarter.

[8] *Destructive interference* occurs when two waves (or, in this case, two tidal bulges) match up crest to trough and trough to crest.

[9] To help you remember a *neap tide,* think of it as one that has been *"nipped in the bud,"* indicating a small tidal range.

STUDENTS SOMETIMES ASK . . .

What would Earth be like if the Moon didn't exist?

For starters, Earth would spin faster, and days would be much shorter because the tidal forces that act as slow brakes on Earth's rotation wouldn't exist. In fact, geologists have evidence that an Earth day was originally five or six hours long in the distant geologic past; it might be just a little longer than that today if the Moon didn't exist. In the ocean, the tidal range would be much smaller because only the Sun would produce relatively small tidal bulges. Spring tides would not exist, and coastal erosion would be markedly reduced. There would be no moonlight, and nighttime would be much darker, which would affect nearly all life on Earth. There is even some speculation that life would not exist at all on Earth without the stabilizing effect of the Moon.

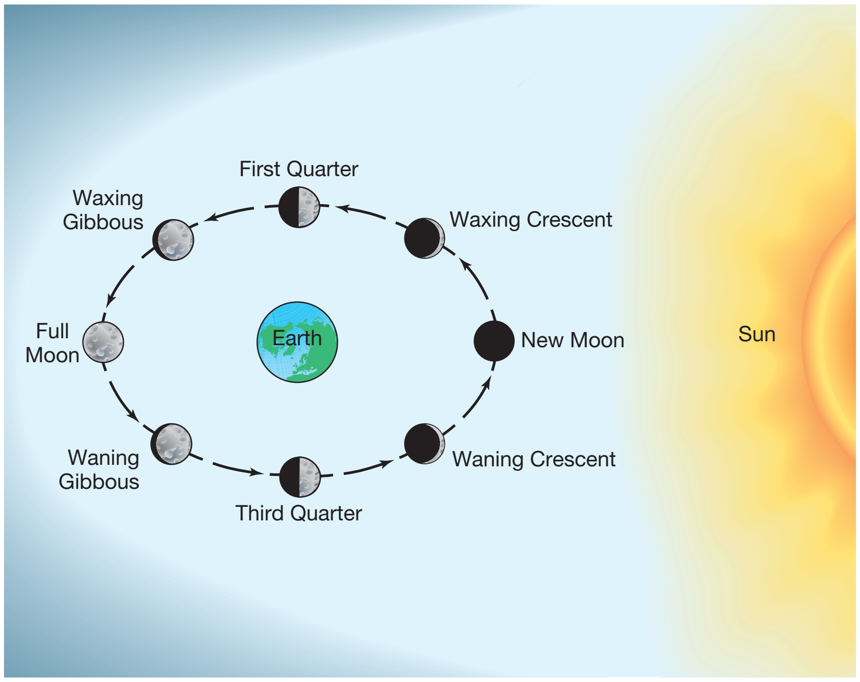

FIGURE 9.11 Phases of the Moon. As the Moon moves around Earth during its 29½-day lunar cycle, its phase changes depending on its position relative to the Sun and Earth. During a new moon, the dark side of the Moon faces Earth while during a full moon, the lit side of the Moon faces Earth. Moon phases are shown diagrammatically as seen from Earth.

Figure 9.11 shows the pattern that the Moon experiences as it moves through its monthly cycle. As the Moon progresses from new moon to first-quarter phase, the Moon is a **waxing crescent** (*waxen* = to increase; *crescere* = to grow). In between the first-quarter and full moon phase, the Moon is a **waxing gibbous** (*gibbus* = hump). Between the Moon's full and third-quarter phase, it is a **waning gibbous** (*wanen* = to decrease). And, in between the third-quarter and new moon phase, the Moon is a **waning crescent**. The Moon has identical periods of rotation on its axis and revolution around Earth (a property called *synchronous rotation*). As a result, the same side of the Moon always faces Earth.

Complicating Factors

Besides Earth's rotation and the relative positions of the Moon and the Sun, there are many other factors that influence tides on Earth. Two of the most prominent of these factors are the declination of the Moon and Sun and the elliptical shapes of Earth's and the Moon's orbits. Let's examine both of these factors.

DECLINATION OF THE MOON AND SUN Up to this point, we have assumed that the Moon and Sun have remained directly overhead at the equator, but this is not usually the case. Most of the year, in fact, they are either north or south of the equator. The angular distance of the Sun or Moon above or below Earth's equatorial plane is called **declination** (*declinare* = to turn away).

Earth revolves around the Sun along an invisible ellipse in space. The imaginary plane that contains this ellipse is called the **ecliptic** (*ekleipein* = to fail to appear). Recall from Chapter 6 that Earth's axis of rotation is tilted 23.5 degrees with respect to the ecliptic and that this tilt causes Earth's seasons. It also means the maximum declination of the Sun relative to Earth's equator is 23.5 degrees.

To complicate matters further, the plane of the Moon's orbit is tilted 5 degrees with respect to the ecliptic. Thus, the maximum declination of the Moon's orbit relative to Earth's equator is 28.5 degrees (5 degrees plus the 23.5 degrees of Earth's tilt). The declination changes from 28.5 degrees south to 28.5 degrees north and back to 28.5 degrees south of the equator during the multiple lunar cycles within one year. As a result, tidal bulges are rarely aligned with the equator. Instead, they occur mostly north and south of the equator. The Moon affects

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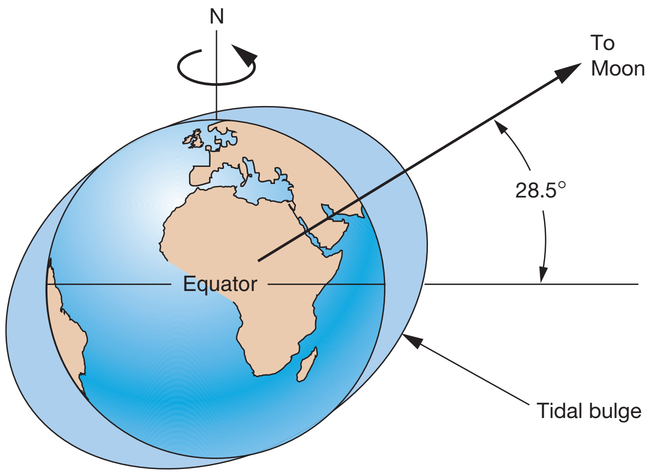

FIGURE 9.12 Maximum declination of tidal bulges from the equator. The center of the tidal bulges may lie at any latitude from the equator to a maximum of 28.5 degrees on either side of the equator, depending on the season of the year (solar angle) and the Moon's position.

STUDENTS SOMETIMES ASK ...

I've heard of a blue moon. Is the Moon really blue then?

No. "Once in a blue moon" is a phrase that has gained popularity and is synonymous with a rather infrequent occurrence. A blue moon is the second full moon of any calendar month, which occurs when the 29½-day lunar cycle falls entirely within a 30- or 31-day month. Because the divisions between our calendar months were determined arbitrarily, a blue moon has no special significance aside from the fact that it occurs only once every 2.72 years (about 33 months). At that rate, it's certainly less common than a month of Sundays!

The origin of the term *blue moon* is not exactly known, but it probably has nothing to do with color—although large forest fires or volcanic eruptions can put enough soot and ash particles in the atmosphere to cause the Moon to appear blue. One likely explanation involves the Old English word *belewe*, meaning "to betray." Thus, the Moon is *belewe* because it betrays the usual perception of one full moon per month. Another explanation links the term to a 1946 article in *Sky and Telescope* that tried to correct a misinterpretation of the term blue moon, but the article itself was misinterpreted to mean the second full moon in a given month. Apparently, the erroneous interpretation was repeated so often that it eventually stuck.

Earth's tides more than the Sun, so tidal bulges follow the Moon, ranging from a maximum of 28.5 degrees north to a maximum of 28.5 degrees south of the equator (Figure 9.12).

EFFECTS OF ELLIPTICAL ORBITS Earth revolves around the Sun in an elliptical orbit (Figure 9.13) such that Earth is 148.5 million kilometers (92.2 million miles) from the Sun during the Northern Hemisphere winter and 152.2 million kilometers (94.5 million miles) from the Sun during summer. Thus, the distance between Earth and the Sun varies by 2.5% over the course of a year. Tidal ranges are largest when Earth is near its closest point, called **perihelion** (*peri* = near, *helios* = Sun) and smallest near its most distant point, called **aphelion** (*apo* = away from, *helios* = Sun). Thus, the greatest tidal ranges typically occur in January each year.

The Moon revolves around Earth in an elliptical orbit, too. The Earth–Moon distance varies by 8% (between 375,000 kilometers [233,000 miles] and 405,800 kilometers [252,000 miles]). Tidal ranges are largest when the Moon is closest to Earth, called **perigee** (*peri* = near, *geo* = Earth), and smallest when most distant, called **apogee** (*apo* = away from, *geo* = Earth) (Figure 9.13, *top*). The Moon cycles between perigee, apogee, and back to perigee every 27½ days. Spring tides happen to coincide with perigee about every one and a half years, producing **proxigean** (*proximus* = nearest, *geo* = Earth) or "closest of the close moon" tides. During this time, the tidal range is especially large and often results in the flooding of low-lying coastal areas; if a storm occurs simultaneously, damage can be extreme. In 1962, for example, a winter storm that occurred at the same time as a proxigean tide caused widespread damage along the entire U.S. East Coast.

The elliptical orbits of Earth around the Sun and the Moon around Earth change the distances between Earth, the Moon, and

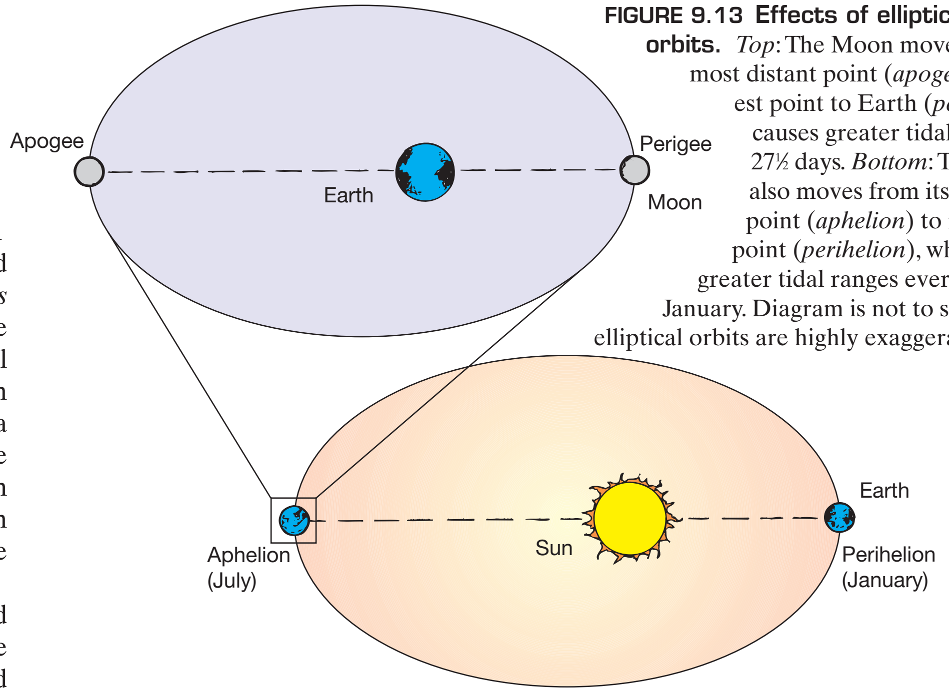

FIGURE 9.13 Effects of elliptical orbits. *Top*: The Moon moves from its most distant point (*apogee*) to its closest point to Earth (*perigee*), which causes greater tidal ranges every 27½ days. *Bottom*: The Earth also moves from its most distant point (*aphelion*) to its closest point (*perihelion*), which causes greater tidal ranges every year in January. Diagram is not to scale (the elliptical orbits are highly exaggerated).

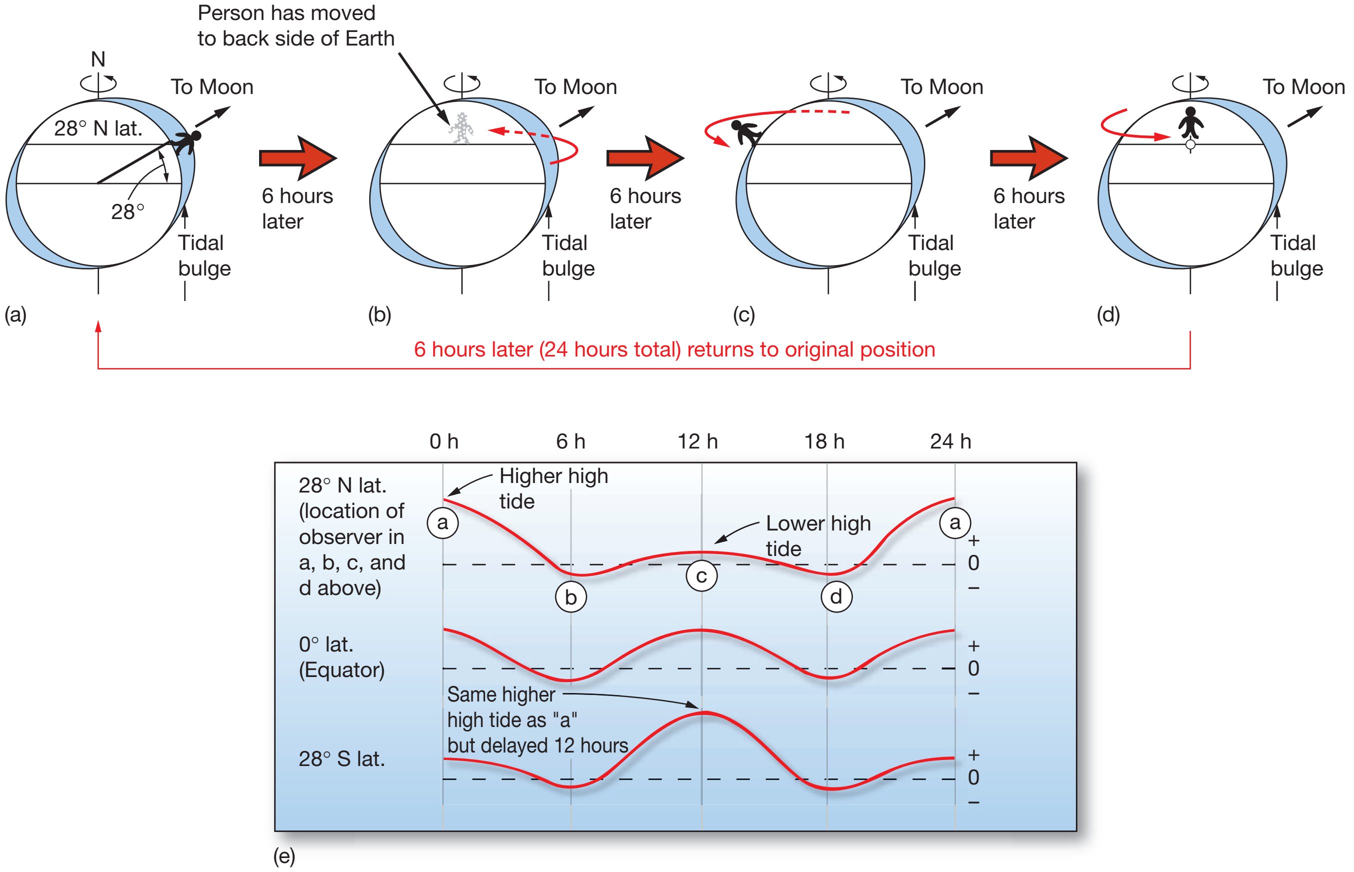

FIGURE 9.14 Predicted idealized tides. **(a)—(d)** Sequence showing the tide experienced every 6 lunar hours at 28 degrees north latitude when the declination of the Moon is 28 degrees north. **(e)** Tide curves for 28 degrees north, 0 degrees, and 28 degrees south latitudes during the lunar day shown in the sequence above. The tide curves for 28 degrees north and 28 degrees south latitude show that the higher high tides occur 12 hours later.

the Sun, thus affecting Earth's tides. The net result is that spring tides have greater ranges during the Northern Hemisphere winter than in the summer, and spring tides have greater ranges when they coincide with perigee.

Idealized Tide Prediction

The declination of the Moon determines the position of the tidal bulges. The example illustrated in Figure 9.14 shows that the Moon is directly overhead at 28 degrees north latitude when its declination is 28 degrees north of the equator. Imagine standing at 28 degrees north latitude and experiencing tidal conditions during a day, which is the sequence shown in Figure 9.14a-d:

- With the Moon directly overhead, the tidal conditions experienced will be high tide (Figure 9.14a).
- Low tide occurs 6 lunar hours later (6 hours 12½ minutes solar time) (Figure 9.14b).
- Another high tide, but one much lower than the first, occurs 6 lunar hours later (Figure 9.14c).
- Another low tide occurs 6 lunar hours later (Figure 9.14d).
- Six lunar hours later, at the end of a 24-lunar-hour period (24 hours 50 minutes solar time), you will have passed through a complete lunar-day cycle of two high tides and two low tides (returns to Figure 9.14a).

The graphs in Figure 9.14e show the heights of the tides observed during the same lunar day at 28 degrees north latitude, the equator, and 28 degrees south latitude when the declination of the Moon is 28 degrees north of the equator. Tide curves for 28 degrees north and 28 degrees south latitude have identically timed

STUDENTS SOMETIMES ASK . . .

What are tropical tides?
Differences between successive high tides and successive low tides occur each lunar day (see, for example, Figure 9.14e). Because these differences occur within a period of one day, they are called *diurnal* (*daily*) *inequalities*. These inequalities are at their greatest when the Moon is at its maximum declination, and such tides are called *tropical tides* because the Moon is over one of Earth's tropics. When the Moon is over the equator (*equatorial tides*), the difference between successive high tides and low tides is minimal.

highs and lows, but the *higher* high tides and *lower* low tides occur 12 hours later. The reason that they occur out of phase by 12 hours is because the bulges in the two hemispheres are on opposite sides of Earth in relation to the Moon. Web Table 9.1 summarizes the characteristics of the tides on the idealized Earth.

9.3 What Do Tides Really Look Like in the Ocean?

If tidal bulges are wave crests separated by a distance of one-half Earth's circumference—about 20,000 kilometers (12,420 miles)—one would expect the bulges to move across Earth at about 1600 kilometers (1000 miles) per hour. Tides, however, are an extreme example of shallow-water waves, so their speed is proportional to the water depth. For a tide wave to travel at 1600 kilometers (1000 miles) per hour, the ocean would have to be 22 kilometers (13.7 miles) deep! Instead, the average depth of the ocean is only 3.7 kilometers (2.3 miles), so tidal bulges move as *shallow-water waves*, with their speed determined by ocean depth.

Based on the average ocean depth, the average speed at which tide waves can travel across the open ocean is only about 700 kilometers (435 miles) per hour. Thus, the idealized bulges that are oriented toward and away from a tide-generating body cannot exist because they cannot keep up with the rotational speed of Earth. Instead, ocean tides break up into distinct large circulation units called *cells*.

Amphidromic Points and Cotidal Lines

In the open ocean, the crests and troughs of the tide wave rotate around an **amphidromic** (*amphi* = around, *dromus* = running) **point** near the center of each cell. There is essentially no tidal range at amphidromic points, but radiating from each point are **cotidal** (*co* = with, *tidal* = tide) **lines**, which connect all nearby locations where high tide occurs simultaneously. The labels on the cotidal lines in Figure 9.15 indicate the time of high tide in hours as they rotate around the cell.

The times in Figure 9.15 indicate that the tide wave rotates counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The wave must complete one rotation during the tidal period (usually 12 lunar hours), so this limits the size of the cells.

Low tide occurs 6 hours after high tide in an amphidromic cell. If high tide is occurring along the cotidal line labeled "10," for example, then low tide is occurring along the cotidal line labeled "4."

Effect of the Continents

The continents affect tides, too, because they interrupt the free movement of the tidal bulges across the ocean surface. Tides are expressed in each ocean basin as free-standing waves that are affected by the position and shape of the continents that ring the ocean basin. In fact, two of the most important factors that influence tidal conditions along a coast are coastline shape and offshore depth.

Just like surface waves that undergo physical changes as they move into shallow water (such as slowing down and increasing in height; see Chapter 8), tides experience similar physical changes as they enter the shallow water of continental shelves. These changes tend to amplify the tidal range as compared to the deep ocean, where the maximum tidal range is only about 45 centimeters (18 inches).

In addition, increased turbulent mixing rates in deep water over areas of rough bottom topography (as discussed in Chapter 7) are associated with internal waves created by tides breaking on this rough topography and against continental slopes. These tide-generated internal waves have recently been observed along

STUDENTS SOMETIMES ASK . . .

How often are conditions right to produce the maximum tide-generating force?

Maximum tides occur when Earth is closest to the Sun (at perihelion), the Moon is closest to Earth (at perigee), and the Earth–Moon–Sun system is aligned (at syzygy) with both the Sun and Moon at zero declination. This rare condition—which creates an absolute *maximum* spring tidal range—occurs once every 1600 years. Fortunately, the next occurrence is predicted for the year 3300.

However, there are other times when conditions produce large tide-generating forces. During early 1983, for example, large, slow-moving low-pressure cells developed in the North Pacific Ocean that caused strong northwest winds. In late January, the winds produced a near fully developed 3-meter (10-foot) swell that affected the West Coast from Oregon to Baja California. The large waves would have been trouble enough under normal conditions, but there were also unusually high spring tides of 2.25 meters (7.4 feet) because Earth was near perihelion at the same time that the Moon was at perigee. In addition, a strong El Niño had raised sea level by as much as 20 centimeters (8 inches). When the waves hit the coast during these unusual conditions, they caused more than $100 million in damage, including the destruction of 25 homes, damage to 3500 others, the collapse of several commercial and municipal piers, and at least a dozen deaths.

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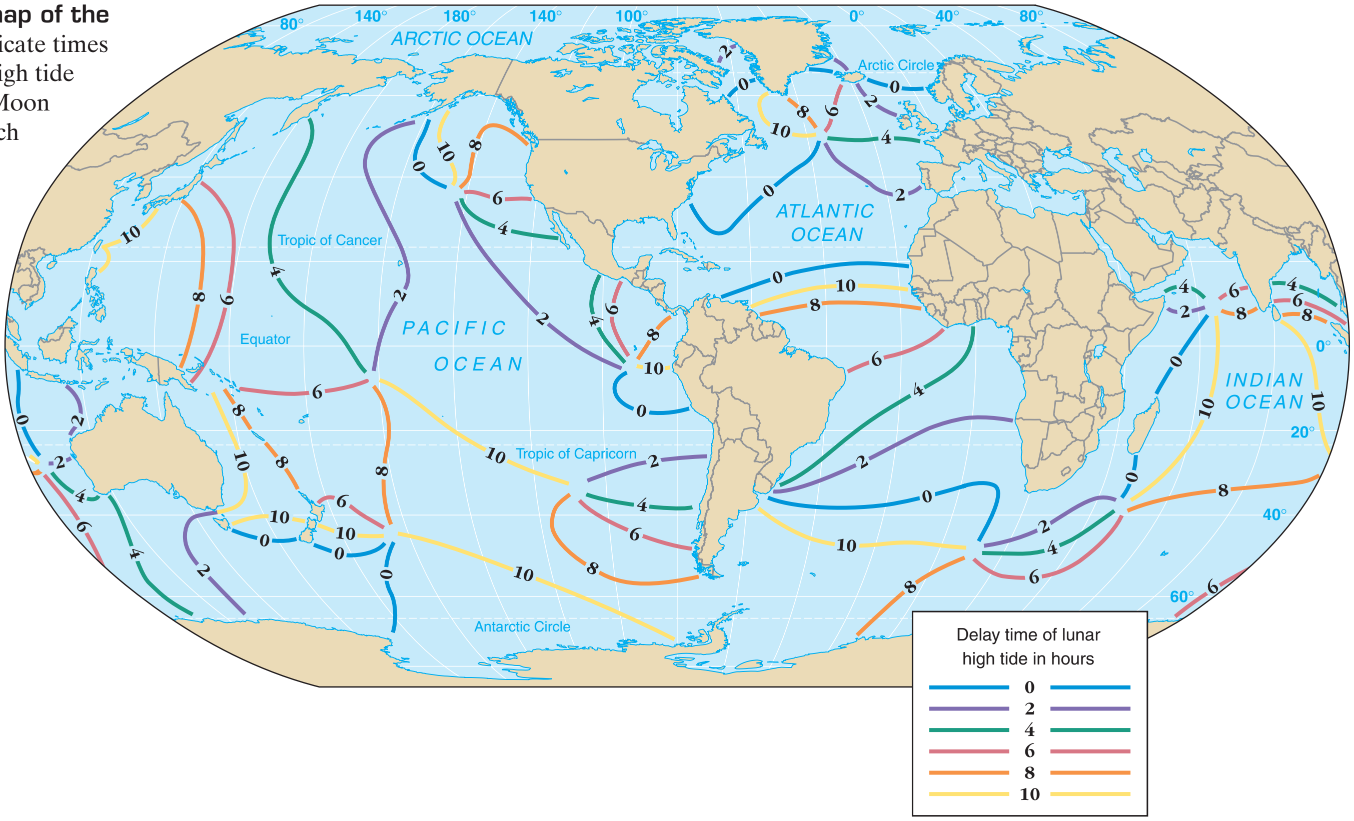
FIGURE 9.15 Cotidal map of the world. Cotidal lines indicate times of the main lunar daily high tide in lunar hours after the Moon has crossed the Greenwich Meridian (0 degrees longitude). Tidal ranges generally increase with increasing distance along cotidal lines away from the amphidromic points (center of the cell). Where cotidal lines terminate at both ends in amphidromic points, maximum tidal range will be near the midpoints of the lines.



the chain of Hawaiian Islands, have heights of up to 300 meters (1000 feet), and contribute to increased turbulence and mixing, which strongly affect the tides.

Other Considerations

A detailed analysis of all the variables that affect the tides at any particular coast reveals that nearly 400 factors are involved, which are far more than can adequately be addressed here. The combination of all these factors creates some conditions that are unexpected based on a simple tidal model. For example, high tide rarely occurs when the Moon is at its highest point in the sky. Instead, the time between the Moon crossing the meridian and a corresponding high tide varies from place to place.

Because of the complexity of the tides, a completely mathematical model of the tides is beyond the limits of marine science. Instead, a combination of mathematical analysis and observation is required to adequately model the tides. Moreover, successful models must take into account at least 37 independent factors related to tides (the two most important are the Moon and the Sun) and are usually quite successful in predicting future tides.

9.4 What Types of Tidal Patterns Exist?

In theory, most areas on Earth should experience two high tides and two low tides of unequal heights during a lunar day. In practice, however, the various depths, sizes, and shapes of ocean basins modify tides so they exhibit three different patterns in different parts of the world. The three tidal patterns, which are illustrated in

web animation

Tidal Patterns

STUDENTS SOMETIMES ASK . . .

I noticed that Figure 9.16 shows negative tides. How can there ever be a negative tide?

Negative tides occur because the *datum* (starting point or reference point from which tides are measured) is an average of the tides over many years. Along the West Coast of the United States, for instance, the datum is mean lower low water (MLLW), which is the average of the *lower* of the two low tides that occur daily in a mixed tidal pattern. Because the datum is an average, there will be some days when the tide is less than the average (similar to the distribution of exam scores, some of which will be below the average). These lower-than-average tides are given negative values, occur only during spring tides, and are often the best times to visit local tide pool areas.

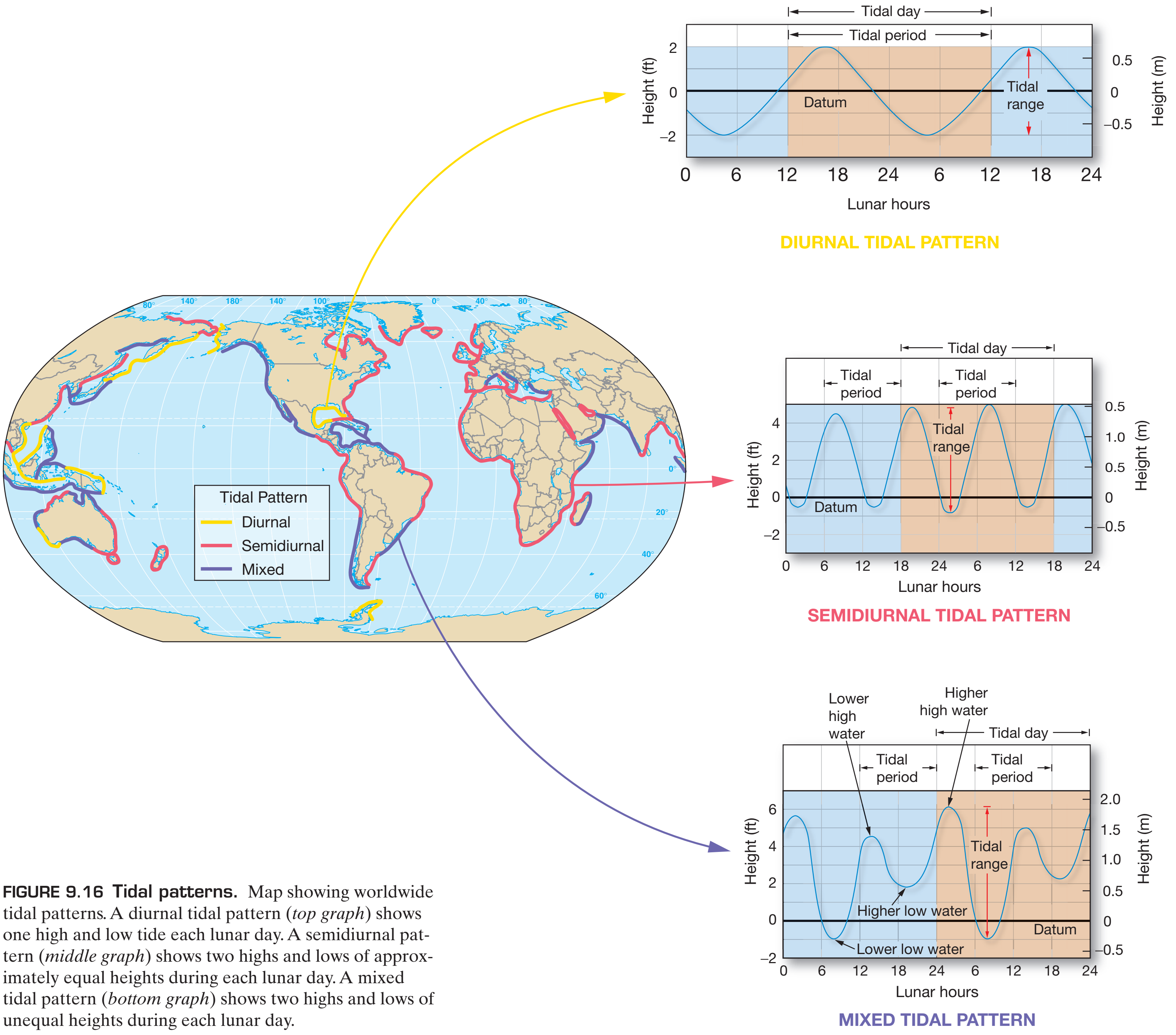


FIGURE 9.16 Tidal patterns. Map showing worldwide tidal patterns. A diurnal tidal pattern (*top graph*) shows one high and low tide each lunar day. A semidiurnal pattern (*middle graph*) shows two highs and lows of approximately equal heights during each lunar day. A mixed tidal pattern (*bottom graph*) shows two highs and lows of unequal heights during each lunar day.

Figure 9.16, are *diurnal* (*diurnal* = daily) *semidiurnal* (*semi* = twice, *diurnal* = daily) and *mixed*.[10]

Diurnal Tidal Pattern

A **diurnal tidal pattern** has one high tide and one low tide each lunar day. These tides are common in shallow inland seas such as the Gulf of Mexico and along the coast of Southeast Asia. Diurnal tides have a tidal period of 24 hours 50 minutes.

KEY CONCEPT

A diurnal tidal pattern exhibits one high and one low tide each lunar day; a semidiurnal tidal pattern exhibits two high and two low tides daily of about the same height; a mixed tidal pattern usually has two high and two low tides of different heights daily but may also exhibit diurnal characteristics.

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[10] Sometimes a *mixed* tidal pattern is referred to as *mixed semidiurnal*.

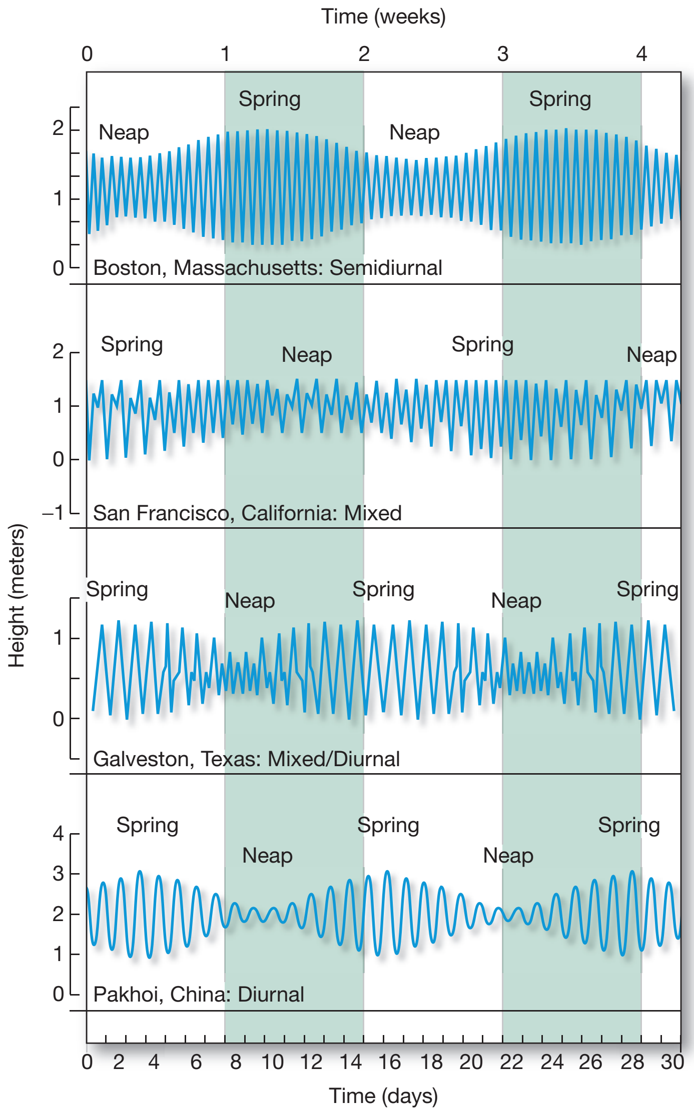

FIGURE 9.17 Monthly tidal curves. *Top*: Boston, Massachusetts, showing a semidiurnal tidal pattern. *Upper middle*: San Francisco, California, showing a mixed tidal pattern. *Lower middle*: Galveston, Texas, showing a mixed tidal pattern with strong diurnal tendencies. *Bottom*: Pakhoi, China, showing a diurnal tidal pattern.

STUDENTS SOMETIMES ASK . . .

Why don't all areas of the world experience the same type of tidal pattern?

If the Earth were a perfect sphere without large continents, all areas on the planet would experience two equally proportioned high and low tides every lunar day (a semidiurnal tidal pattern). The large continents on the planet, however, block the westward passage of the tidal bulges as the Earth rotates. Unable to move freely around the globe, the tides instead establish complex patterns within each ocean basin that often differ greatly from tidal patterns of adjacent ocean basins or other regions of the same ocean basin.

Semidiurnal Tidal Pattern

A **semidiurnal tidal pattern** has two high tides and two low tides each lunar day. The heights of successive high tides and successive low tides are approximately the same.[11] Semidiurnal tides are common along the Atlantic Coast of the United States. The tidal period is 12 hours 25 minutes.

Mixed Tidal Pattern

A **mixed tidal pattern** may have characteristics of both diurnal and semidiurnal tides. Successive high tides and/or low tides will have significantly different heights, a condition called *diurnal inequality*. Mixed tides commonly have a tidal period of 12 hours 25 minutes, but they may also exhibit diurnal periods. Mixed tides are the most common type in the world, including along the Pacific Coast of North America.

Figure 9.17 shows examples of monthly tidal curves for various coastal locations. Even though a tide at any particular location follows a single tidal pattern, it still may pass through stages of one or both of the other tidal patterns. Typically, however, the tidal pattern for a location remains the same throughout the year. Also, the tidal curves in Figure 9.17 clearly show the weekly switching of the spring tide-neap tide cycle.

9.5 What Tidal Phenomena Occur in Coastal Regions?

Remember that the tides are fundamentally a wave. When tide waves enter coastal waters, they are subject to reflection and amplification similar to what wind-generated waves experience. In certain locations, reflected wave energy causes water to slosh around in a bay, producing *standing waves*.[12] As a result, interesting tidal phenomena are sometimes experienced in coastal waters.

Large lakes and coastal rivers experience tidal phenomena, too. In some low-lying rivers, for instance, a *tidal bore* is produced by an incoming high tide (Box 9.1). Further, the tides profoundly affect the behavior of certain marine organisms (Box 9.2).

An Example of Tidal Extremes: The Bay of Fundy

The largest tidal range in the world is found in Nova Scotia's **Bay of Fundy**. With a length of 258 kilometers (160 miles), the Bay of Fundy has a wide opening into the Atlantic Ocean. At its northern end, however, it splits into two narrow basins, Chignecto Bay and Minas Basin (Figure 9.18). The period of free oscillation in the bay—the oscillation that occurs when a body is displaced and then released—is very nearly that of the tidal period. The resulting constructive interference—along with the narrowing and shoaling of the bay to the north—causes a buildup of tidal energy in the northern end of the bay. In addition, the bay curves to the right, so the Coriolis effect in the Northern Hemisphere adds to the extreme tidal range.

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[11] Because tides are always growing higher or lower at any location due to the spring tide-neap tide sequence, successive high tides and successive low tides can never be *exactly* the same at any location.

[12] See Chapter 8 for a discussion of standing waves, including the terms *node* and *antinode*.

9.1 OCEANS AND PEOPLE

TIDAL BORES: BORING WAVES THESE ARE NOT!

A **tidal bore** (*bore* = crest or wave) is a wall of water that moves up certain low-lying rivers due to an incoming tide. Because it is a wave created by the tides, it is a *true* tidal wave. When an incoming tide rushes up a river, it develops a steep forward slope because the flow of the river resists the advance of the tide (Figure 9A). This creates a tidal bore, which may reach heights of 5 meters (16.4 feet) or more and move at speeds up to 24 kilometers (15 miles) per hour.

Conditions necessary for the development of tidal bores include (1) a large spring tidal range of at least 6 meters (20 feet); (2) a tidal cycle that has a very abrupt rise of the flood tide phase and an elongated ebb tide phase; (3) a low-lying river with a persistent seaward current during the time when an incoming high tide begins; (4) a progressive shallowing of the sea floor as the basin progresses inland; and (5) a progressive narrowing of the basin toward its upper reaches. Because of these unique circumstances, only about 60 places on Earth experience tidal bores.

Although tidal bores do not commonly attain the size of waves in the surf zone, tidal bores have successfully been rafted, kayaked, and even surfed (Figure 9B). They can give a surfer a very long ride because the bore travels many kilometers upriver. If you miss the bore, though, you have to wait about half a day before the next one comes along because the incoming high tide occurs only twice a day.

The Amazon River is probably the longest estuary affected by oceanic tides: Tides can be measured as far as 800 kilometers (500 miles) from the river's mouth, although the effects are quite small at this distance. Tidal bores near the mouth of the Amazon River can reach heights up to 5 meters (16.4 feet) and are locally called *pororocas*—the name means "mighty noise." Other rivers that have notable tidal bores include the Qiantang River in China (which has the largest tidal bores in the world, often reaching 8 meters [26 feet] high); the Petitcodiac River in New Brunswick, Canada; the River Seine in France; the Trent and Severn Rivers in England; and Cook Inlet near Anchorage, Alaska (where the largest tidal bore in the United States can be found). Although the Bay of Fundy has the world's largest tidal range, its tidal bore rarely exceeds 1 meter (3.3 feet), mostly because the bay is so wide.

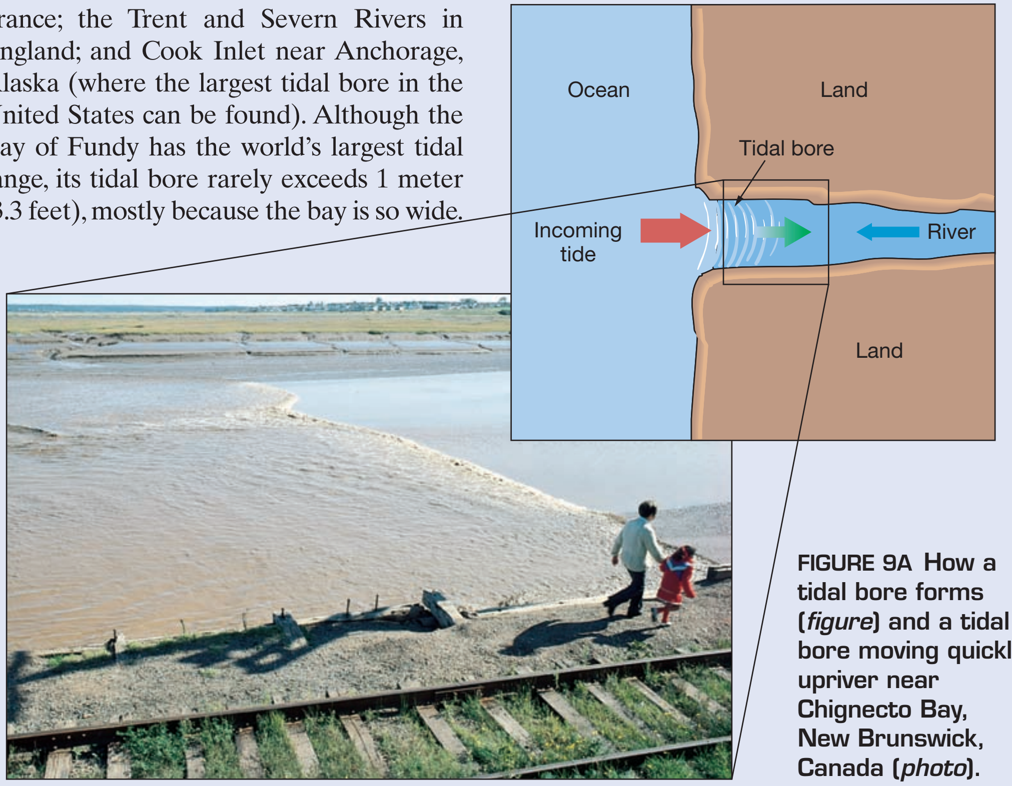

FIGURE 9A How a tidal bore forms (*figure*) and a tidal bore moving quickly upriver near Chignecto Bay, New Brunswick, Canada (*photo*).

FIGURE 9B Brazilian surf star Alex "Picuruta" Salazar tidal bore surfing on the Amazon River.

9.2 RESEARCH METHODS IN OCEANOGRAPHY

GRUNION: DOING WHAT COMES NATURALLY ON THE BEACH

From March through September, shortly after the maximum spring tide has occurred, **grunion (*Leuresthes tenuis*)** come ashore along sandy beaches of Southern California and Baja, California, to bury their eggs. Grunion—slender, silvery fish up to 15 centimeters (6 inches) long—are the only marine fish in the world that come completely out of water to spawn. The name *grunion* comes from the Spanish *gruñón*, which means "grunter" and refers to the faint noise they make during spawning.

A mixed tidal pattern occurs along Southern California and Baja, California, beaches. On most lunar days (24 hours and 50 minutes), there are two high and two low tides. There is usually a significant difference in the heights of the two high tides that occur each day. During the summer months, the higher high tide occurs at night. The night high tide becomes higher each night as the maximum spring tide range is approached, causing sand to be eroded from the beach (Figure 9C, *graph*). After the maximum spring tide has occurred, the night high tide diminishes each night. As neap tide is approached, sand is deposited on the beach.

Grunion spawn only after each night's higher high tide has peaked on the three or four nights following the night of the highest spring high tide. This assures that their eggs will be covered deeply in sand deposited by the receding higher high tides each succeeding night. The fertilized eggs buried in the sand are ready to hatch nine days after spawning. By this time, another spring tide is approaching, so the night high tide is getting progressively higher each night again. The beach sand is eroding again, too, which exposes the eggs to the waves that break ever higher on the beach. The eggs hatch about three minutes after being freed in the water. Tests done in laboratories have shown that the grunion eggs will not hatch until agitated in a manner that simulates that of the eroding waves.

The spawning begins as the grunion come ashore immediately following an appropriate high tide, and it may last from one to three hours. Spawning usually peaks about an hour after it starts and may last an additional 30 minutes to an hour. Thousands of fish may be on the beach at this time. During a run, the females, which are larger than the males, move high on the beach. If no males are near, a female may return to the water without depositing her eggs. In the presence of males, she drills her tail into the semifluid sand until only her head is visible. The female continues to twist, depositing her eggs 5 to 7 centimeters (2 to 3 inches) below the surface.

The male curls around the female's body and deposits his milt against it (Figure 9C, *photo*). The milt runs down the body of the female to fertilize the eggs. When the spawning is completed, both fish return to the water with the next wave.

Larger females are capable of producing up to 3000 eggs for each series of spawning runs, which are separated by the two-week period between spring tides. As soon as the eggs are deposited, another group of eggs begins to form within the female. These eggs will be deposited during the next spring tide run. Early in the season, only older fish spawn. By May, however, even the one-year-old females are in spawning condition.

Young grunion grow rapidly and are about 12 centimeters (5 inches) long when they are a year old and ready for their first spawning. They usually live two or three years, but four-year-olds have been recovered. The age of a grunion can be determined by its scales. After growing rapidly during the first year, they grow very slowly thereafter. There is no growth at all during the six-month spawning season, which causes marks to form on each scale that can be used to identify the grunion's age.

It is not known exactly how grunion are able to time their spawning behavior so precisely with the tides. Research suggests that grunion are somehow able to sense very small changes in hydrostatic pressure caused by rising and falling sea level due to changing tides. Certainly, a very dependable detection mechanism keeps the grunion accurately informed of the tidal conditions, because their survival depends on a spawning behavior precisely tuned to the tides.

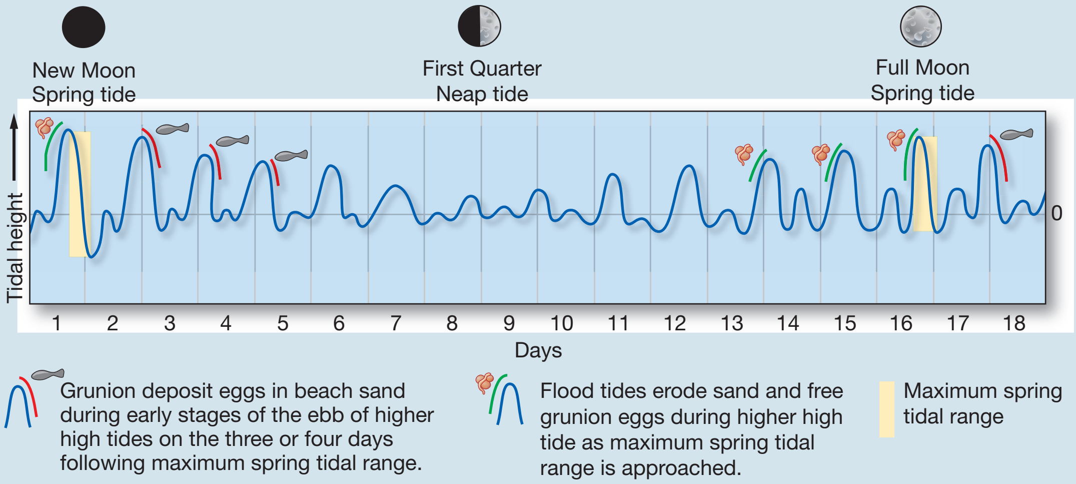

FIGURE 9C The tidal cycle and spawning grunion. During summer months and for 3 or 4 days after the highest spring tides (*graph*), grunion deposit their eggs on sandy beaches (*photo*). The successively lower high tides during the approaching neap tide conditions won't wash the eggs from the sand until they are ready to hatch about 10 days later. As the next spring tide is approached, successively higher high tides wash the eggs free and allow them to hatch. The spawning cycle begins a few days later after the peak of spring tide conditions with the next cycle of successively lower high tides.

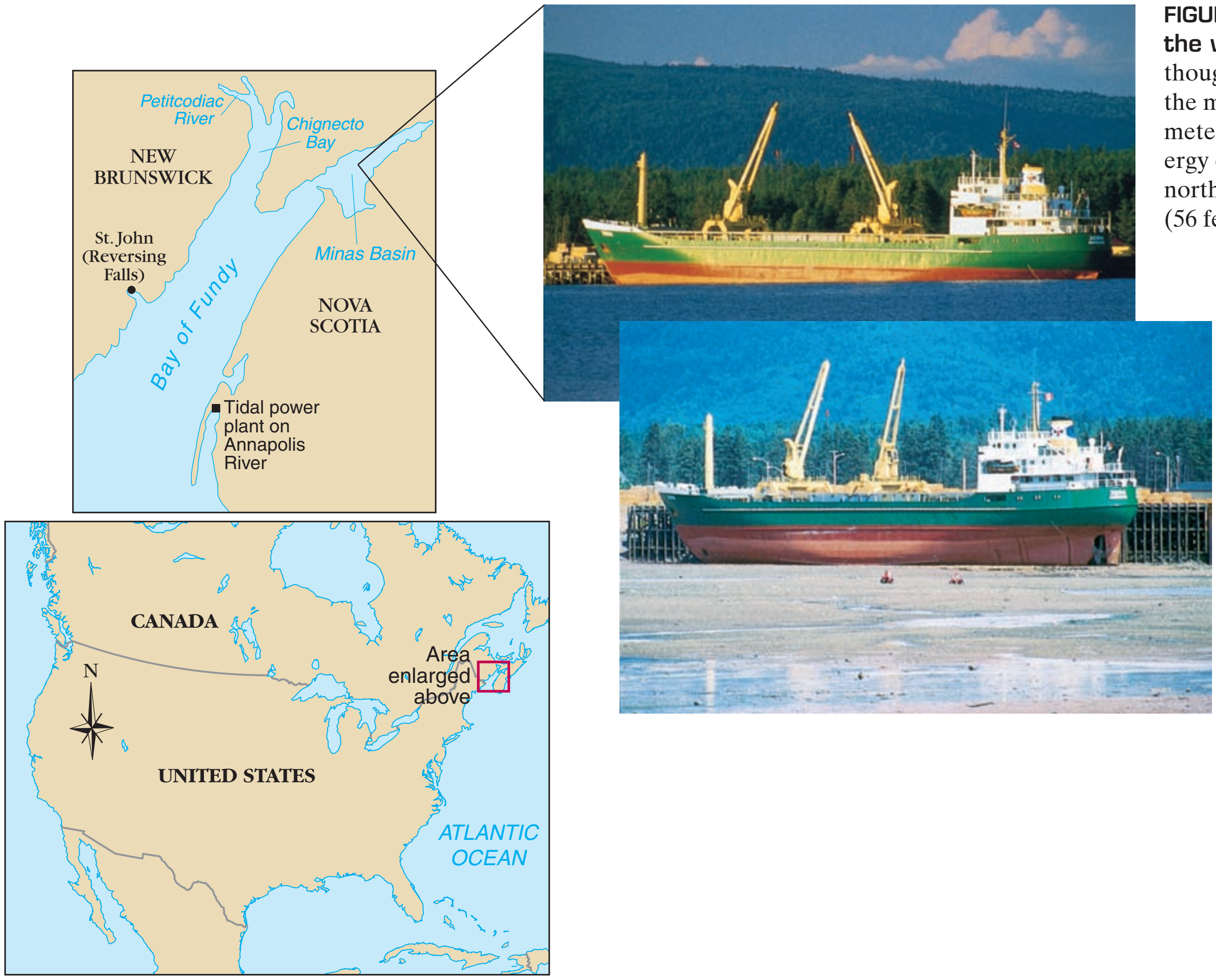

FIGURE 9.18 The Bay of Fundy, site of the world's largest tidal range. Even though the maximum spring tidal range at the mouth of the Bay of Fundy is only 2 meters (6.6 feet), amplification of tidal energy causes a maximum tidal range at the northern end of Minas Basin of 17 meters (56 feet), often stranding ships (*insets*).

During maximum spring tide conditions, the tidal range at the mouth of the bay (where it opens to the ocean) is only about 2 meters (6.6 feet). However, the tidal range increases progressively from the mouth of the bay northward. In the northern end of Minas Basin, the maximum spring tidal range is 17 meters (56 feet), which leaves boats high and dry during low tide (Figure 9.18, *insets*).

WEB VIDEO
Tidal Bore and Tidal Bore Surfing

WEB VIDEO
Grunion Run

Coastal Tidal Currents

The current that accompanies the slowly turning tide crest in a Northern Hemisphere basin rotates counterclockwise, producing a **rotary current** in the open portion of the basin. Friction increases in nearshore shoaling waters, so the rotary current changes to an alternating or **reversing current** that moves into and out of restricted passages along a coast.

The velocity of rotary currents in the open ocean is usually well below 1 kilometer (0.6 mile) per hour. Reversing currents, however, can reach velocities up to 44 kilometers (28 miles) per hour in restricted channels such as between islands of coastal waters.

Reversing currents also exist in the mouths of bays (and some rivers) due to the daily flow of tides. Figure 9.19 shows that a **flood current** is produced when water rushes into a bay (or river) with an incoming high tide. Conversely, an **ebb current** is produced when water drains out of a bay (or river) because a low tide is approaching. No currents occur for several minutes during either **high slack water** (which occurs at the peak of each high tide) or **low slack water** (at the peak of each low tide).

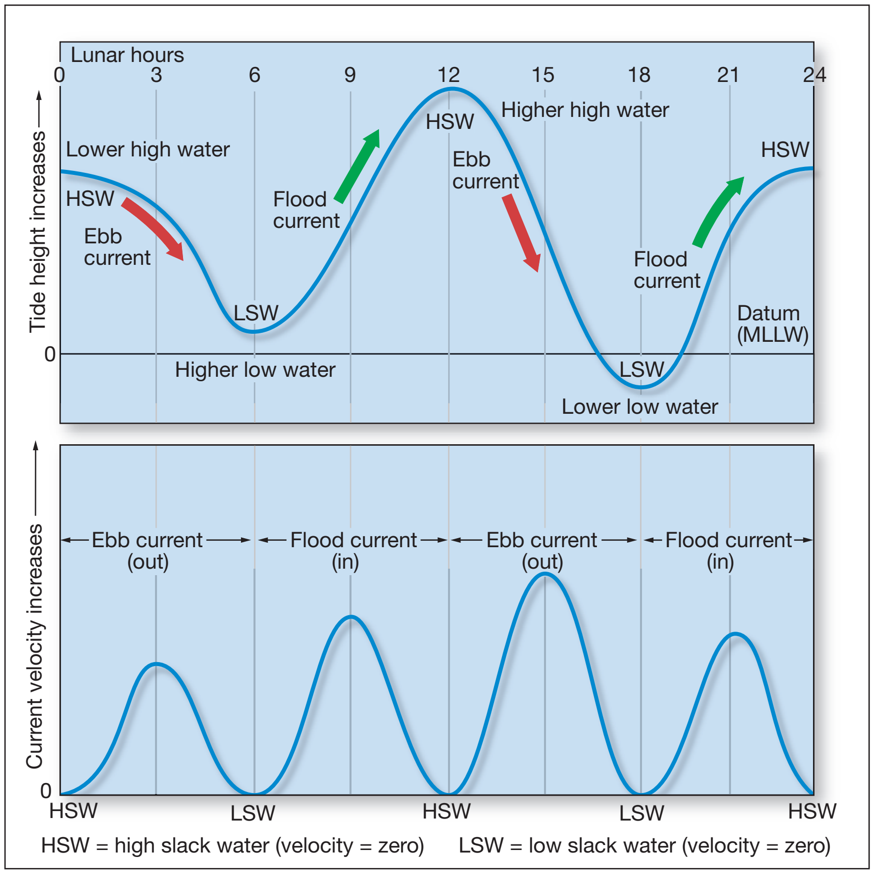

FIGURE 9.19 Reversing tidal currents in a bay. *Top*: Tidal curve for a bay, showing ebb currents are created by an outgoing low tide and flood currents are created by an incoming high tide. No currents occur during either high slack water (*HSW*) or low slack water (*LSW*). The datum MLLW stands for *mean lower low water,* which is the average of the lower of the two low tides that occur daily in a mixed tidal pattern. *Bottom*: Corresponding chart showing velocity of ebb and flood currents.

KEY CONCEPT

Coastal tidal phenomena include large tidal ranges (the largest of which occurs in the Bay of Fundy, where reflection and amplification produce a maximum spring tide range of 17 meters 56 feet), tidal currents, and rapidly spinning vortices called whirlpools.

Reversing currents in bays can sometimes reach speeds of 40 kilometers (25 miles) per hour, creating a navigation hazard for ships. On the other hand, the daily flow of these currents often keeps sediment from closing off the bay and replenishes the bay with seawater and ocean nutrients.

Tidal currents can be significant even in deep ocean waters. For example, tidal currents were encountered shortly after the discovery of the remains of the *Titanic* at a depth of 3795 meters (12,448 feet) on the continental slope south of Newfoundland's Grand Banks in 1985. These tidal currents were so strong that they forced researchers to abandon the use of the camera-equipped, tethered, remotely-operated vehicle *Jason Jr.*

Whirlpools: Fact or Fiction?

A **whirlpool**—a rapidly spinning body of water, which is also termed a *vortex* (*vertere* = to turn)—can be created in some restricted coastal passages due to reversing tidal currents. Whirlpools most commonly occur in shallow passages connecting two large bodies of water that have different tidal cycles. The different tidal heights of the two bodies cause water to move vigorously through the passage. As water rushes through the passage, it is affected by the shape of the shallow sea floor, causing turbulence, which, along with spin due to opposing tidal currents, creates whirlpools. The larger the tidal difference between the two bodies of water and the smaller the passage, the greater the vortex caused by the tidal currents. Because whirlpools can have high flow rates of up to 16 kilometers (10 miles) per hour, they can cause ships to spin out of control for a short time.

One of the world's most famous whirlpools is the *Maelstrom* (*malen* = to grind in a circle, *strom* = stream), which occurs in a passage off the west coast of Arctic Norway (Figure 9.20). This and another famous whirlpool in the Strait of Messina, which separates mainland Italy from Sicily, are probably the source of ancient legends of huge churning funnels of water that destroy ships and carry mariners to their deaths, although they are not nearly as deadly as legends suggest. Other notable whirlpools occur off the west coast of Scotland, in the Bay of Fundy at the border between Maine and the Canadian province of New Brunswick, and off Japan's Shikoku Island.

9.6 Can Tidal Power Be Harnessed as a Source of Energy?

Throughout history, ocean tides have been used as a source of power. During high tide, water can be trapped in a basin and then harnessed to do work as it flows back to the sea. In the 12th century, for example, water wheels driven by the tides were used to power gristmills and sawmills. During the 17th and 18th centuries, much of Boston's flour was produced at a tidal mill.

Today, tidal power is considered a clean, renewable resource with vast potential. The initial cost of building a tidal power-generating plant may be higher than a conventional thermal power plant, but the operating costs would be less because it does not use fossil fuels or radioactive substances to generate electricity.

One disadvantage of tidal power, however, is the periodicity of the tides, allowing power to be generated only during a portion of a 24-hour day. People

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FIGURE 9.20 The Maelstrom. The Maelstrom, located off the west coast of Norway, is one of the strongest whirlpools in the world and can cause ships to spin out of control. It is created by tidal currents that pass through a narrow, shallow passage between Vest Fjord and the Norwegian Sea.

operate on a solar period, but tides operate on a lunar period, so the energy available from the tides would coincide with need only part of the time. Power would have to be distributed to the point of need at the moment it was generated, which could be a great distance away, resulting in an expensive transmission problem. The power could be stored, but even this alternative presents a large and expensive technical problem.

To generate electricity effectively, electrical turbines (generators) need to run at a constant speed, which is difficult to maintain when generated by the variable flow of tidal currents in two directions (flood tide and ebb tide). Specially designed turbines that allow both advancing and receding water to spin their blades are necessary to solve the problem of generating electricity from the tides.

Another disadvantage of tidal power is harm to wildlife and other unwanted environmental effects resulting from the modification of tidal current flow. In addition, a tidal power plant would likely interfere with many traditional uses of coastal waters, such as transportation and fishing.

Tidal Power Plants

Tidal power can be harnessed in one of two ways: (1) Tidal water trapped behind coastal barriers in bays and estuaries can be used to turn turbines and generate electrical energy, and (2) tidal currents that pass through narrow channels can be used to turn underwater pivoting turbines, which produce energy (see Chapter 7). Although the first type is much more commonly employed, Norway, the United Kingdom, and the United States have recently installed offshore turbines that harness swift coastal tidal currents and plan to expand these devices into tidal energy farms.

Worldwide, there are only a few small tidal power plants that use water trapped behind coastal barriers. One successful tidal power plant has been operating in the

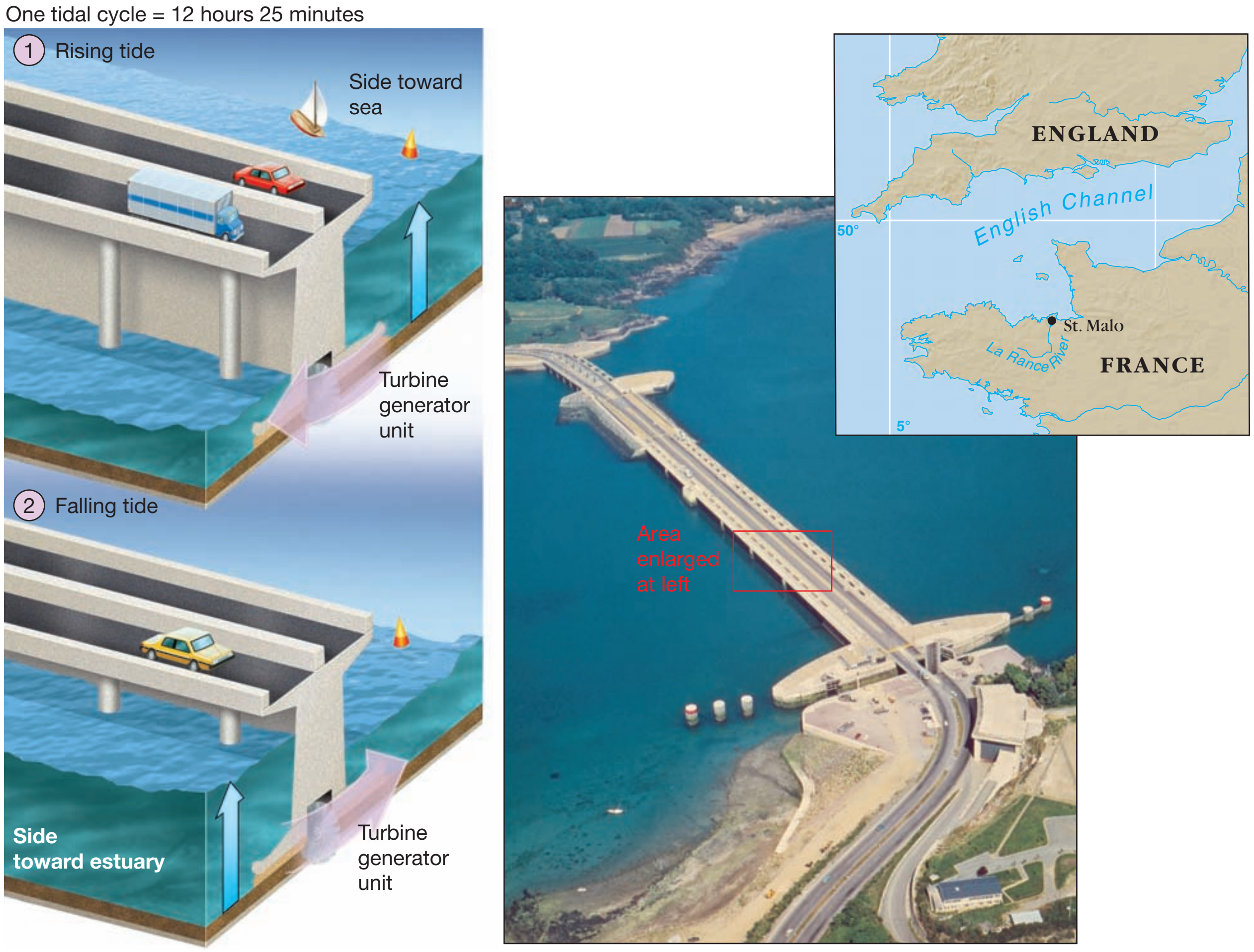

FIGURE 9.21 La Rance tidal power plant at St. Malo, France. Electricity is generated at the La Rance tidal power plant at St. Malo, France, when water from a rising tide (*1*) flows into the estuary and turns turbines; electricity is also generated when water from a falling tide (*2*) exits the estuary and turns turbines in the other direction.

estuary of La Rance River in northern France (Figure 9.21) since 1967. The estuary has a surface area of approximately 23 square kilometers (9 square miles), and the tidal range is 13.4 meters (44 feet). Usable tidal energy increases as the area of the basin increases and as the tidal range increases.

The power-generating barrier was built across the estuary a little over 3 kilometers (2 miles) upstream to protect it from storm waves. The barrier is 760 meters (2500 feet) wide and supports a two-lane road (Figure 9.21). Water passing through the barrier powers 24 electricity-generating units that operate beneath the power plant. At peak operating capacity, each unit can generate 10 megawatts of electricity for a total of 240 megawatts.[13]

To generate electricity, the La Rance plant needs a sufficient water height between the estuary and the ocean—which only occurs about half of the time. Annual power production of about 540 million kilowatt-hours can be increased to 670 million kilowatt-hours by using the turbine generators as pumps to move water into the estuary at proper times.

Within the Bay of Fundy, which has the largest tidal range in the world, the Canadian province of Nova Scotia constructed a small tidal power plant in 1984 that can generate 20 megawatts of electricity. The plant is built on the Annapolis River estuary, an arm of the Bay of Fundy (see Figure 9.18), where maximum tidal range is 8.7 meters (26 feet).

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[13] Each megawatt of electricity is enough to serve the energy needs of about 800 average U.S. homes.

In 2006, the first Asian tidal power plant came online in Daishan County of eastern China's Zhejiang province. This small power station has the capability to produce 40 kilowatts of electricity, and China has proposed building another larger plant.

Larger power plants that avoid some of the shortcomings of smaller plants have often been considered. For example, a tidal power plant could be made to generate electricity continually if it were located on the Passamaquoddy Bay near the U.S.–Canadian border near the entrance to the Bay of Fundy. Although a tidal power plant across the Bay of Fundy has often been proposed, it has never been built. Potentially, the usable tidal energy seems large compared to the La Rance plant, because the flow volume is over 100 times greater.

Recognizing the benefits of tidal power, the United Kingdom has proposed building a tidal power barrage across the Severn Estuary that separates England and Wales. The Severn River has the second-largest tidal range in the world and is a prime target for producing tidal power. If completed, it would be the world's largest tidal power plant with a 12-kilometer- (7.5-mile-) long dam that could produce 8.6 gigawatts of energy, or about 5% of the electricity currently used in the United Kingdom.

KEY CONCEPT

The daily change in water level as a result of ocean tides can be harnessed as a source of energy. In spite of significant drawbacks, several tidal power plants in coastal estuaries successfully extract tidal energy today.

Chapter in Review

- *Gravitational attraction of the Moon and Sun create Earth's tides*, which are fundamentally long wavelength waves. According to a *simplified model of tides*, which assumes an ocean of uniform depth and ignores the effects of friction, small horizontal forces (the tide-generating forces) tend to push water into *two bulges on opposite sides of Earth*. One bulge is directly facing the tide-generating body (the Moon and the Sun), and the other is directly opposite.

- Despite its vastly smaller size, *the Moon has about twice the tide-generating effect of the Sun* because the Moon is so much closer to Earth. The tidal bulges due to the Moon's gravity (the lunar bulges) dominate, so lunar motions dominate the periods of Earth's tides. However, the changing position of the solar bulges relative to the lunar bulges modifies tides. According to the simplified idealized tide theory, *Earth's rotation carries locations on Earth into and out of the various tidal bulges*.

- Tides would be easy to predict if Earth were a uniform sphere covered with an ocean of uniform depth. For most places on Earth, *the time between successive high tides would be 12 hours 25 minutes (half a lunar day). The 29½ monthly tidal cycle* would consist of tides with maximum tidal range (spring tides) and minimum tidal range (neap tides). *Spring tides would occur each new moon and full moon, and neap tides would occur each first- and third-quarter phases of the Moon*.

- The *declination of the Moon* varies between 28.5 degrees north or south of the equator during the lunar month, and the *declination of the Sun* varies between 23.5 degrees north or south of the equator during the year, so *the location of tidal bulges usually creates two high tides and two low tides of unequal height per lunar day*. Tidal ranges are greatest when Earth is nearest the Sun and Moon.

- *When friction and the true shape of ocean basins are considered, the dynamics of tides becomes more complicated*. Moreover, the two bulges on opposite sides of Earth cannot exist because they cannot keep up with the rotational speed of Earth. Instead, the bulges are broken up into *several tidal cells that rotate around an amphidromic point*—a point of zero tidal range. Rotation is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. *Many other factors influence tides on Earth*, too, such as the positions of the continents, the varying depth of the ocean, and coastline shape.

- The *three types of tidal patterns* observed on Earth are *diurnal* (a single high and low tide each lunar day), *semidiurnal* (two high and two low tides each lunar day), and *mixed* (characteristics of both). Mixed tidal patterns usually consist of semidiurnal periods with significant diurnal inequality. Mixed tidal patterns are the most common type in the world.

- There are many types of *observable tidal phenomena in coastal areas. Tidal bores are true tidal waves* (a wave produced by the tides) that occur in certain rivers and bays due to an incoming high tide. The effects of constructive interference together with the shoaling and narrowing of coastal bays creates the *largest tidal range in the world—17 meters (56 feet)—at the northern end of Nova Scotia's Bay of Fundy. Tidal currents follow a rotary pattern* in open-ocean basins but are converted to *reversing currents* along continental margins. The maximum velocity of reversing currents occurs during flood and ebb currents when the water is halfway between high and low slack waters. *Whirlpools* can be created in some restricted coastal passages due to reversing tidal currents. *The tides are also important to many marine organisms*. For instance, *grunion*—small silvery fish that inhabit waters along the West Coast of North America—time their spawning cycle to match the pattern of the tides.

- *Tides can be used to generate power* without need for fossil or nuclear fuel. There are some *significant drawbacks*, however, to creating successful tidal power plants. Still, many sites worldwide have the *potential for tidal power generation*.

Key Terms

Amphidromic point (p. 271)
Aphelion (p. 269)
Apogee (p. 269)
Barycenter (p. 261)
Bay of Fundy (p. 274)
Centripetal force (p. 263)
Cotidal line (p. 271)
Declination (p. 268)
Diurnal tidal pattern (p. 273)
Ebb current (p. 277)
Ebb tide (p. 266)
Ecliptic (p. 268)
Flood current (p. 277)
Flood tide (p. 266)
Full moon (p. 266)
Gravitational force (p. 262)
Grunion (*Leuresthes tenuis*) (p. 276)
High slack water (p. 277)
Low slack water (p. 277)
Lunar bulge (p. 264)
Lunar day (p. 265)
Mixed tidal pattern (p. 274)
Nadir (p. 263)
Neap tide (p. 267)
New moon (p. 266)
Newton, Isaac (p. 261)
Newton's law of universal gravitation (p. 262)
Perigee (p. 269)
Perihelion (p. 269)
Proxigean (p. 269)
Quadrature (p. 267)
Quarter moon (p. 266)
Resultant force (p. 264)
Reversing current (p. 277)
Rotary current (p. 277)
Semidiurnal tidal pattern (p. 274)
Solar bulge (p. 265)
Solar day (p. 265)
Spring tide (p. 267)
Syzygy (p. 267)
Tidal bore (p. 275)
Tidal period (p. 265)
Tidal range (p. 266)
Tide (p. 261)
Tide-generating force (p. 264)
Waning crescent (p. 268)
Waning gibbous (p. 268)
Waxing crescent (p. 268)
Waxing gibbous (p. 268)
Whirlpool (p. 278)
Zenith (p. 263)

Review Questions

1. Explain why the Sun's influence on Earth's tides is only 46% that of the Moon, even though the Sun is so much more massive than the Moon.

2. Why is a lunar day 24 hours 50 minutes long, while a solar day is 24 hours long?

3. Which is more technically correct: The tide comes in and goes out; or Earth rotates into and out of the tidal bulges? Why?

4. Explain why the maximum tidal range (spring tide) occurs during new and full moon phases and the minimum tidal range (neap tide) at first-quarter and third-quarter moons.

5. If Earth did not have the Moon orbiting it, would there still be tides? Why or why not?

6. What is declination? Discuss the degree of declination of the Moon and Sun relative to Earth's equator. What are the effects of declination of the Moon and Sun on the tides?

7. Are tides considered deep-water waves anywhere in the ocean? Why or why not?

8. Describe the number of high and low tides in a lunar day, the period, and any inequality of the following tidal patterns: diurnal, semidiurnal, and mixed.

9. Discuss factors that help produce the world's largest tidal range in the Bay of Fundy.

10. Discuss the difference between rotary and reversing tidal currents.

11. Of flood current, ebb current, high slack water, and low slack water, when is the best time to enter a bay by boat? When is the best time to navigate in a shallow, rocky harbor? Explain.

12. Describe the spawning cycle of grunion, indicating the relationship among tidal phenomena, where grunion lay their eggs, and the movement of sand on the beach.

13. Discuss at least two positive and two negative factors related to tidal power generation.

14. Explain how a tidal power plant works, using as an example an estuary that has a mixed tidal pattern. Why does potential for usable tidal energy increase with an increase in the tidal range?

Critical Thinking Exercises

1. From memory, draw the positions of the Earth–Moon–Sun system during a complete monthly tidal cycle. Indicate the tide conditions experienced on Earth, the phases of the Moon, the time between those phases, and syzygy and quadrature.

2. Assume that there are two moons in orbit around Earth that are on the same orbital plane but always on opposite sides of Earth and that each moon is the same size and mass of our Moon. How would this affect the tidal range during spring and neap tide conditions?

3. Diagram the Earth–Moon system's orbit about the Sun. Label the positions on the orbit at which the Moon and Sun are closest to and farthest from Earth, stating the terms used to identify them. Discuss the effects of the Moon's and Earth's positions on Earth's tides.

4. Observe the Moon from a reference location every night at about the same time for two weeks. Keep track of your observations about the shape (phase) of the Moon and its position in the sky. Then compare these to the reported tides in your area and report your findings.

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