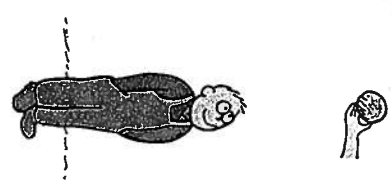


FIGURE 9.16 The tidal force difference due to a 1 kg body 1 m over the head of an average height person is about 60 trillionths (6×10^{-11}) N/kg. For an overhead Moon, it is about 0.3 trillionth (3×10^{-13}) N/kg. So holding a melon over your head produces about 200 times as much tidal effect in your body as the Moon does.

Conceptual Physics
Paul G Hewitt

Ocean Tides

Seafaring people have always known that there is a connection between the ocean tides and the Moon, but no one could offer a satisfactory theory to explain the two high tides per day. Newton showed that the ocean tides are caused by *differences* in the gravitational pull between the Moon and the Earth on opposite sides of the Earth. Gravitational force between the Moon and the Earth is stronger on the side of the Earth nearer to the Moon, and it is weaker on the side of the Earth that is farther from the Moon. This is simply because the gravitational force is weaker with increased distance.

To understand why the difference in gravitational pulls by the Moon on opposite sides of the Earth produces tides, pretend you have a big spherical ball of Jell-O. If you were to exert the same force on every part of the ball, it would remain spherical as it accelerated. But, if you were to pull harder on one side than the other, there would be a difference in accelerations and the ball would become elongated (Figure 9.13). That is what happens to this big ball we're living on. The side closer to the Moon is pulled with a greater force and has a greater acceleration toward the Moon than the far side—thus, the Earth is somewhat football shaped. But does the Earth accelerate toward the Moon? Yes, it must, because a force acts on it, and, where there is a net force, there is acceleration. It is a *centripetal* acceleration, for Earth circles the center of mass of the Earth–Moon system (a point within the Earth about three-quarters of the way from the center to the surface). Both the Earth and the Moon undergo centripetal acceleration as they circle each other about the Earth–Moon center of mass. This makes both the Earth and the Moon slightly elongated. The elongation of the Earth is mainly in its oceans, which bulge equally on opposite sides.

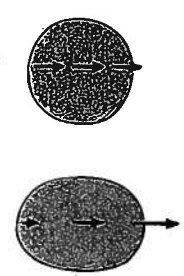
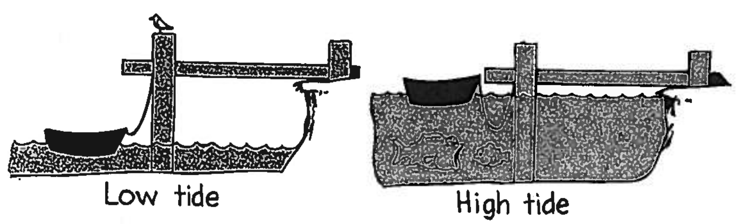


FIGURE 9.13 A ball of Jell-O remains spherical when all parts of it are pulled equally in the same direction. When one side is pulled more than the other, however, its shape is elongated.



CHECK YOUR ANSWER

In both cases, you'd experience weightlessness. Drifting in deep space, you would remain weightless because no discernable force acts on you. Stepping from a stepladder, you would be only momentarily weightless because of a momentary lapse of support force.

On a world average, the ocean bulges are nearly 1 meter above the average surface level of the ocean. Earth spins once per day, so a fixed point on Earth passes beneath both of these bulges each day. This produces two sets of ocean tides per day. Any part of the Earth that passes beneath one of the bulges has a high tide. When Earth has made a quarter turn 6 hours later, the water level at the same part of the ocean is nearly 1 meter below the average sea level. This is low tide. The water that "isn't there" is under the bulges that make up the high tides. A second high tidal bulge is experienced when Earth makes another quarter turn. So we have two high tides and two low tides daily. It turns out that, while the Earth spins, the Moon moves in its orbit and appears at the same position in our sky every 24 hours and 50 minutes, so the two-high-tide cycle is actually at 24-hour-and-50-minute intervals. That is why tides do not occur at the same time every day.

FIGURE 9.14 Two tidal bulges remain relatively fixed with respect to the Moon while the Earth spins daily beneath them.

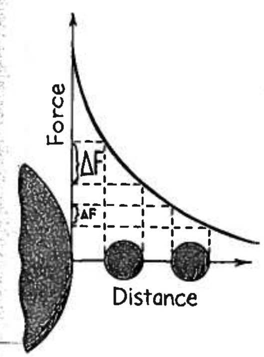


FIGURE 9.15 A plot of gravity versus distance (not to scale). The greater the distance from the Sun, the smaller the force F, which varies as $1/d^2$, and the smaller the difference in gravitational pulls on opposite sides of a planet, ΔF, which varies as $1/d^3$, and, hence, the smaller the tides.

The Sun also contributes to ocean tides, although it is less than half as effective as the Moon in raising tides—even though its pull on the Earth is 180 times greater than the pull of the Moon. Why doesn't the Sun cause tides 180 times greater than lunar tides? The answer has to do with a key word: *difference*. Because of the great distance of the Sun, the difference in its gravitational pull on opposite sides of the Earth is very small (Figure 9.15). The percentage difference in the Sun's pulls across the Earth is only about 0.017%, compared with 6.7% across the Earth by the Moon. It is only because the pull of the Sun is 180 times stronger than the Moon's that the Sun tides are almost half as high (180×0.017 percent = 3%, nearly half of 6.7%).

Newton deduced that the difference in pulls decreases as the *cube* of the distance between the centers of the bodies—twice as far away produces 1/8 the tide; three times as far, only 1/27 the tide, and so on. Only relatively close distances result in appreciable tides, and so the nearby Moon produces larger tides than the enormously more massive but more distant Sun. The amount of tide also depends on the size of the body experiencing tides. Although the Moon produces a considerable tide in the Earth's oceans, which are thousands of kilometers apart, it produces scarcely any tide in a lake. That's because no part of the lake is significantly closer to the Moon than any other part, so there is no significant *difference* in Moon pulls on the lake. Similarly for the fluids in your body. Any tides in the fluids of your body caused by the Moon are negligible. You're not tall enough for tides. What microtides the Moon may produce in your body are only about one two-hundredth the tides produced by a one-kilogram melon held one meter above your head (Figure 9.16).

CHECK YOURSELF

We know that both the Moon and the Sun produce our ocean tides. And we know the Moon plays the greater role because it is closer. Does its closeness mean that it pulls on the Earth's oceans with more gravitational force than the Sun?

When the Sun, Earth, and Moon are aligned, the tides due to the Sun and the Moon coincide. Then we have higher-than-average high tides and lower-than-average low tides. These are called spring tides (Figure 9.17). (Spring tides have nothing to do with the spring season.) You can tell when the Sun, Earth, and Moon are aligned by the full Moon or by the new Moon. When the Moon is full, the Earth is between the Sun and Moon. (If all three are *exactly* in line, then we have a lunar eclipse, for the full Moon passes into Earth's shadow.) A new Moon occurs when the Moon is between the Sun and the Earth, when the nonilluminated hemisphere of the Moon faces the Earth. (When this alignment is perfect, the Moon blocks the Sun and we have a solar eclipse.) Spring tides occur at the times of a new or full Moon.

FIGURE 9.17
When the attractions of the Sun and the Moon are lined up with each other, spring tides occur.

All spring tides are not equally high because Earth–Moon and Earth–Sun distances vary; the orbital paths of the Earth and the Moon are elliptical rather

CHECK YOUR ANSWER

No, the Sun's pull is much stronger. Gravitational pull weakens as the distance squared. But the *difference* in pulls across the Earth's oceans weakens as the distance cubed. When the distance to the Sun is squared, gravitation from the Sun is still stronger than gravitation from the closer Moon because of the Sun's enormous mass. But, when the distance to the Sun is cubed, as is the case for tidal forces, the Sun's influence is less than the Moon's. Differences in distance are the key to tidal forces. If the Moon were closer to Earth, the tides on both the Earth and the Moon would increase as the cube of the closer distance. Being too close could catastrophically tear the Moon into pieces—the likely cause of the planetary rings of Saturn and other planets.

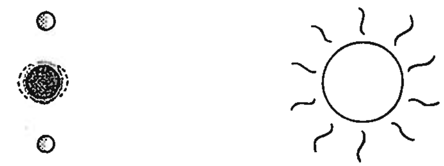


FIGURE 9.18
When the attractions of the Sun and the Moon are about 90° apart (at the time of a half Moon), neap tides occur.

than circular. The Moon's distance from Earth varies by about 10% and its effect in raising tides varies by about 30%. Highest spring tides occur when the Moon and Sun are closest to Earth.

When the Moon is halfway between a new Moon and a full Moon, in either direction (Figure 9.18), the tides due to the Sun and the Moon partly cancel each other. Then, the high tides are lower than average and the low tides are not as low as average low tides. These are called neap tides.

Another factor that affects the tides is the tilt of the Earth's axis (Figure 9.19). Even though the opposite tidal bulges are equal, Earth's tilt causes the two daily high tides experienced in most parts of the ocean to be unequal most of the time.

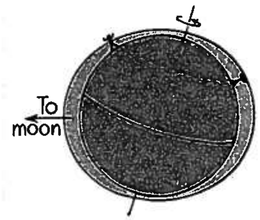
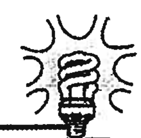


FIGURE 9.19
The inequality of the two high tides per day. Because of the Earth's tilt, a person may find the tide nearest the Moon much lower (or higher) than the tide half a day later. Inequalities of tides vary with the positions of the Moon and the Sun.

Our treatment of tides is quite simplified here, for tides are actually more complicated. Interfering land masses and friction with the ocean floor, for example, complicate tidal motions. In many places, the tides break up into smaller "basins of circulation," where a tidal bulge travels like a circulating wave that moves around in a small basin of water that is tilted. For this reason, the high tide may be hours away from an overhead Moon. In midocean, the variation in water level—the range of the tide—is usually about a meter. This range varies in different parts of the world; it is greatest in some Alaskan fjords and is most notable in the basin of the Bay of Fundy, between New Brunswick and Nova Scotia in eastern Canada, where tidal differences sometimes exceed 15 meters. This is largely due to the ocean floor, which funnels shoreward in a V-shape. The tide often comes in faster than a person can run. Don't dig clams near the water's edge at low tide in the Bay of Fundy!



In addition to ocean tides, the Moon and Sun make atmospheric tides—highest then lowest during a full Moon. Does this explain why some of your friends are weird when the Moon is full?

Insights

Tides in the Earth and Atmosphere

Earth is not a rigid solid but, for the most part, is molten liquid covered by a thin, solid, and pliable crust. As a result, the Moon–Sun tidal forces produce Earth tides as well as ocean tides. Twice each day, the solid surface of Earth rises and falls as much as one-quarter meter! As a result, earthquakes and volcanic eruptions have a slightly higher probability of occurring when Earth is experiencing an Earth spring tide—that is, near a full or new Moon.

We live at the bottom of an ocean of air that also experiences tides. Being at the bottom of the atmosphere, we don't notice these tides (just as a fish in deep water doesn't notice the ocean tides). In the upper part of the atmosphere is the ionosphere, so named because it contains many ions—electrically charged atoms that are the result of ultraviolet light and intense cosmic ray bombardment. Tidal effects in the ionosphere produce electric currents that alter the magnetic field that surrounds the Earth. These are magnetic tides. They, in turn, regulate the degree to which cosmic rays penetrate into the lower atmosphere. The cosmic-ray penetration is evident in subtle changes in the behaviors of living things. The highs and lows of magnetic tides are greatest when the atmosphere