13 UNIVERSAL GRAVITATION

Objectives

- Explain Newton's reasoning about the apple falling from the tree. (13.1)
- Explain why the moon doesn't hit Earth. (13.2)
- Explain how Newton's theory of gravity confirmed the Copernican theory of the solar system. (13.3)
- Describe what Newton discovered about gravity. (13.4)
- Describe how the force of gravity changes with distance. (13.5)
- Describe the gravitational field that surrounds Earth. (13.6)
- Describe the gravitational field at Earth's center. (13.7)
- Describe the sensation we interpret as weight. (13.8)
- Explain ocean tides. (13.9)
- Describe the gravitational field around a black hole. (13.10)
- Explain the importance of the formulation of the law of universal gravitation. (13.11)

discover!

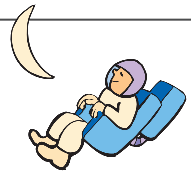
MATERIALS round balloon, marker

EXPECTED OUTCOME An area on the surface of the balloon will increase faster than the balloon's linear dimensions.

ANALYZE AND CONCLUDE

1. The area of the square increases faster than the diameter of the balloon.
2. 16
3. The area of the square increases as the diameter of the balloon squared.

13 UNIVERSAL GRAVITATION



THE BIG IDEA Everything pulls on everything else.

Objects such as leaves, rain, and satellites fall because of gravity. Gravity is what holds tea in a cup and what makes bubbles rise. It made Earth round, and it builds up the pressures that kindle every star that shines. These are things that gravity does. But what is gravity? Contrary to what some people think, gravity was not discovered by Isaac Newton. That discovery dates back to earlier times when Earth dwellers experienced the consequences of tripping and falling. What Newton discovered, prompted by a falling apple, was that gravity is a universal force—that it is not unique to Earth, as others of his time assumed.

discover!

How Does the Surface Area of a Balloon Vary With Diameter?

1. Inflate a round balloon to a diameter of 8 cm. Use a marker to draw a rectangle the size of a postage stamp on the balloon. Do not tie the end of the balloon.
2. Now inflate the balloon to a diameter of 16 cm. How many postage stamps will fit in the square you drew?
3. If possible, increase the diameter of the balloon to 24 cm and once again determine how many stamps will fit in the square.

Analyze and Conclude

1. **Observing** Describe how the area of the square grew as you increased the diameter of the balloon.
2. **Predicting** If you could increase the diameter of the balloon to 32 cm, how many postage stamps would fit in the expanded square?
3. **Making Generalizations** How does the area of the square drawn on the balloon's surface increase with increasing balloon diameter?

13.1 The Falling Apple

According to popular legend, the idea that gravity extends throughout the universe occurred to Newton while he was sitting underneath an apple tree on his mother's farm pondering the forces of nature. This scene is illustrated in Figure 13.1. Newton understood the concept of inertia developed earlier by Galileo; he knew that without an outside force, moving objects continue to move at constant speed in a straight line. He knew that if an object undergoes a change in speed or direction, then a force is responsible.

A falling apple triggered what was to become one of the most far-reaching generalizations of the human mind. Newton saw the apple fall, or maybe even felt it fall on his head—the story about this is not clear. Perhaps he looked up through the apple tree branches and noticed the moon. Newton was probably puzzled by the fact that the moon does not follow a straight-line path, but instead circles about Earth. He knew that circular motion is accelerated motion, which requires a force. But what was this force? Newton had the insight to see that the moon is falling toward Earth, just as the apple is. ✓ **Newton reasoned that the moon is falling toward Earth for the same reason an apple falls from a tree—they are both pulled by Earth's gravity.**

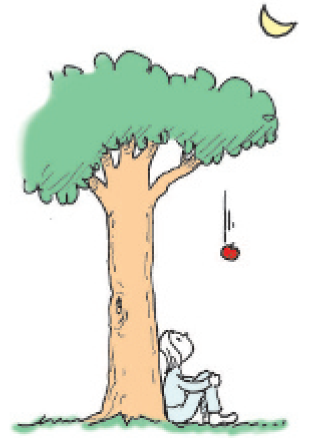


FIGURE 13.1 ▲ According to legend, Newton discovered that gravity extends to the moon (and beyond) while sitting under an apple tree.

CONCEPT CHECK What was Newton's reasoning about the apple falling from the tree?

13.2 The Falling Moon

Newton developed this idea further. He compared the falling apple with the falling moon. Newton realized that if the moon did not fall, it would move off in a straight line and leave its orbit, as suggested in Figure 13.2. His idea was that the moon must be falling *around* Earth. Thus the moon falls in the sense that it *falls beneath the straight line it would follow if no force acted on it.* He hypothesized that the moon was simply a projectile circling Earth under the attraction of gravity.

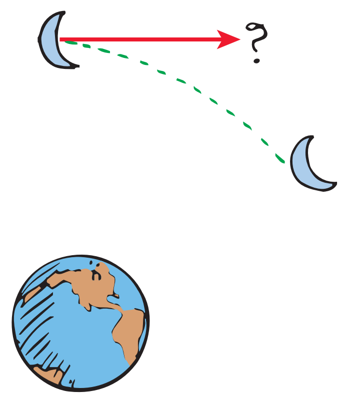


FIGURE 13.2 ▶ If the moon did not fall, it would follow a straight-line path.

13.1 The Falling Apple

Although the formula for Newton's law of universal gravitation is not shown until Section 13.4, I have found considerable success by beginning with the law right away. The formula focuses on what might be seen as diverse phenomena and all the examples relate to the formula.

PAUL

Common Misconceptions

Newton discovered gravity.

FACT Newton expanded Galileo's concept of inertia and discovered that gravity is universal.

Above Earth's atmosphere there is no Earth gravity.

FACT Every mass in the universe attracts every other one regardless of whether an atmosphere is present or not.

CONCEPT CHECK Newton reasoned that the moon is falling toward Earth for the same reason an apple falls from a tree—they are both pulled by Earth's gravity.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Conceptual Physics Alive! DVDs *Gravity I***

13.2 The Falling Moon

Common Misconception
The moon and planets are beyond the pull of Earth's gravity.

FACT All objects in the universe attract one another.

▶ **Teaching Tip** Review Newton's first law and relate it to this section: An object (the moon) will remain in motion in a straight line unless acted on by an outside unbalanced force (gravitational attraction).

▶ **Teaching Tip** Remind students that *tangential velocity* is the component of velocity that is parallel to Earth's surface. (The physics of the falling Earth is explained in more detail in Chapter 14. You may want to call attention to the comic strip "Satellite Physics," on page 264, if questions are raised about satellite motion.)

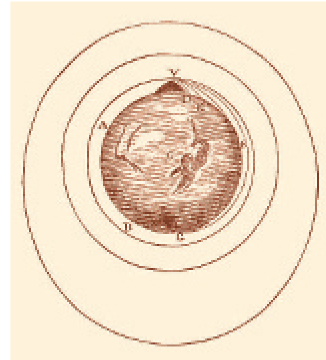


FIGURE 13.3 ▶
This original drawing by Isaac Newton shows how a projectile fired fast enough would fall around Earth and become an Earth satellite.

Newton's Hypothesis Newton compared the motion of the moon to a cannonball fired from the top of a high mountain. If the mountaintop was above Earth's atmosphere, air resistance would not impede the motion of the cannonball. If a cannonball were fired with a small horizontal speed, it would follow a parabolic path and soon hit Earth below. If it were fired faster, its path would be less curved and it would hit Earth farther away. If the cannonball were fired fast enough, its path would become a circle and the cannonball would circle indefinitely. Newton illustrated this in the drawing in Figure 13.3.

Both the orbiting cannonball and the moon have a component of velocity parallel to Earth's surface. This sideways or *tangential velocity*, as illustrated in Figure 13.4, is sufficient to ensure nearly circular motion *around* Earth rather than *into* it. **The moon is actually falling toward Earth but has great enough tangential velocity to avoid hitting Earth.** If there is no resistance to reduce its speed, the moon will continue "falling" around and around Earth indefinitely.

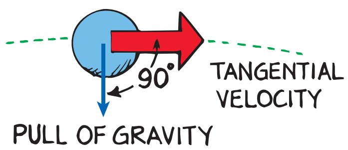


FIGURE 13.4 ▲
Tangential velocity is the "sideways" velocity—the component of velocity parallel to the surface of Earth and perpendicular to the pull of gravity.

Newton's Test For Newton's idea to advance from hypothesis to scientific theory, it would have to be tested. Newton's test was to see if the moon's "fall" beneath its otherwise straight-line path was in correct proportion to the fall of an apple or any object at Earth's surface. He reasoned that the mass of the moon should not affect how it falls, just as mass has no effect on the acceleration of freely falling objects on Earth. How far the moon falls, and how far an apple at Earth's surface falls, should relate only to their respective *distances* from Earth's center.

As illustrated in Figure 13.5, the moon was already known to be 60 times farther from the center of Earth than an apple at Earth's surface. The apple will fall 5 m in its first second of fall—or more precisely, 4.9 m. Newton reasoned that gravitational attraction to Earth must be "diluted" by distance. Does this mean the force of Earth's gravity would reduce to $\frac{1}{60}$ at the moon's distance? No, as we shall soon see, the influence of gravity should be diluted to $\frac{1}{60}$ of $\frac{1}{60}$, or to $\frac{1}{(60)^2}$. So in one second the moon should fall $\frac{1}{(60)^2}$ of 5 m, which is 1.4 millimeters.[13.2.1]

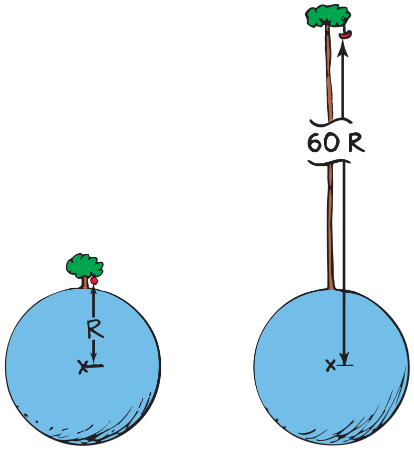


FIGURE 13.5
An apple falls 5 m during its first second of fall when it is near Earth's surface. Newton asked how far the moon would fall in the same time if it were 60 times farther from the center of Earth.

Newton's Calculation Using geometry, Newton calculated how far the circle of the moon's orbit lies below the straight-line distance the moon otherwise would travel in one second. His value turned out to be about the 1.4-mm distance accepted today, as shown in Figure 13.6. But he was unsure of the exact Earth–moon distance, and whether or not the correct distance to use was the distance between their centers. At this time he hadn't proved mathematically that the gravity of the spherical Earth (and moon) is the same as if all its mass were concentrated at its center.

Because of this uncertainty, and also because of criticisms he had experienced in publishing earlier findings in optics, he placed his papers in a drawer, where they remained for nearly 20 years. During this period he laid the foundation and developed the field of geometrical optics for which he first became famous.

Newton finally returned to the moon problem at the prodding of his astronomer friend Edmund Halley (of Halley's comet fame). It wasn't until after Newton invented a new branch of mathematics, calculus, to prove his center-of-gravity hypothesis, that he published what is one of the greatest achievements of the human mind—the law of universal gravitation.[13.2.2] Newton generalized his moon finding to all objects, and stated that all objects in the universe attract each other.

CONCEPT CHECK Why doesn't the moon hit Earth?

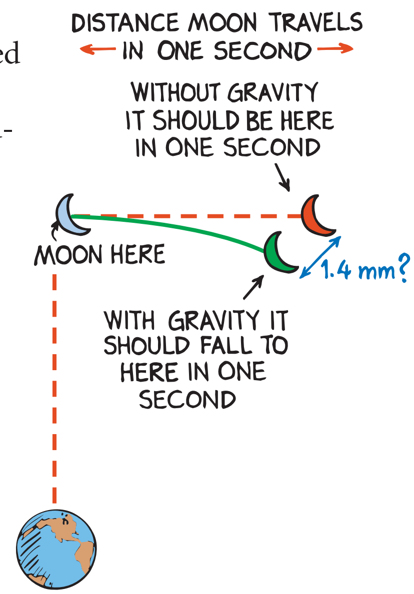


FIGURE 13.6
If the force that pulls apples off trees also pulls the moon into orbit, the circle of the moon's orbit should fall 1.4 mm below a point along the straight line where the moon would otherwise be one second later.

CONCEPT CHECK The moon is actually falling toward Earth but has great enough tangential velocity to avoid hitting Earth.

Teaching Resources
- Reading and Study Workbook
- Probeware Lab Manual *9*
- Transparency *19*
- Presentation*EXPRESS*
- Interactive Textbook

13.3 The Falling Earth

Common Misconception
Gravity gets stronger with altitude, as evidenced by objects carried up a flight of stairs feeling heavier at the top.

FACT Gravity actually decreases with increasing altitude because the distance from the center of Earth is increased.

▶ **Teaching Tip** Discuss how Newton developed the law of universal gravitation by applying what he knew about falling apples to the falling moon.

Demonstration

Whirl a ball on a string in a vertical circle. Relate the tension of the string to the gravitational force that holds the moon in orbit.

CONCEPT CHECK Newton's theory of gravity confirmed the Copernican theory of the solar system.

Teaching Resources

- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

Science, Technology, and Society

CRITICAL THINKING Answers will vary. Discuss all reasonable responses.

13.3 The Falling Earth

Newton's theory of gravity confirmed the Copernican theory of the solar system. No longer was Earth considered to be the center of the universe. Earth was not even the center of the solar system. The sun occupies the center, and it became clear that Earth and the planets orbit the sun in the same way that the moon orbits Earth. The planets continually "fall" around the sun in closed paths. Why don't the planets crash into the sun? They don't because the planets have tangential velocities, as illustrated in Figure 13.7.

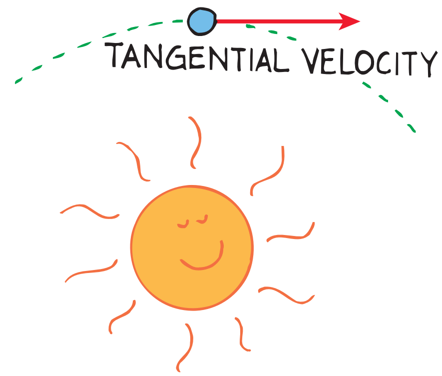


FIGURE 13.7 ▶ The tangential velocity of Earth about the sun allows it to fall around the sun rather than directly into it.

What would happen if the tangential velocities of the planets were reduced to zero? The answer is simple enough: Their motion would be straight toward the sun and they would indeed crash into it. Any objects in the solar system with insufficient tangential velocities have long ago crashed into the sun; what remains is the harmony we observe.

CONCEPT CHECK What theory of the solar system did Newton's theory of gravity confirm?

Science, Technology, and Society

Scientific Truth and Integrity

An advertiser who claims that 9 out of 10 doctors recommend the ingredient found in his or her advertised product may be telling the truth. But the implication being conveyed, that 9 out of 10 doctors recommend the product itself, may be quite false. An advertiser who claims that a certain brand of cooking oil will not soak through foods is telling the truth. What the advertiser doesn't say is that no other brands of cooking oil soak through foods either—at least not at ordinary temperatures and pressures. While the facts stated are true, the implications conveyed are not. There is a difference between truthfulness and integrity.

Critical Thinking Do you think advertisers have a responsibility to be completely truthful about their products? Explain why or why not.

236

13.4 Newton's Law of Universal Gravitation

Newton did not discover gravity. ✓ **Newton discovered that gravity is universal. Everything pulls on everything else in the universe in a way that involves only mass and distance.**

Newton's **law of universal gravitation** states that every object attracts every other object with a force. For any two objects, this force is directly proportional to the mass of each object. The greater the masses, the greater the force of attraction between them.[13.4.1] Newton also deduced that this force decreases as the square of the distance between the centers of the objects. The farther away the objects are from each other, the less the force of attraction between them.

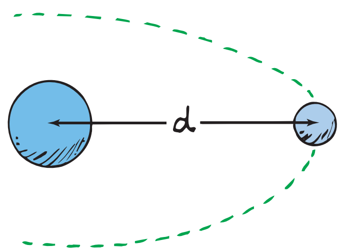
The law can be expressed as

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

or in symbol notation, as

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

where m_1 is the mass of one object, m_2 is the mass of the other, and d is the distance between their centers.



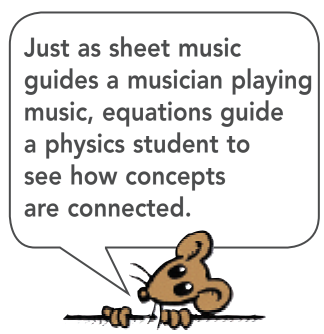
◀ **FIGURE 13.8**
The force of gravity between objects depends on the distance between their centers.

The Universal Gravitational Constant, *G* The law of universal gravitation can be expressed as an exact equation when a proportionality constant is introduced. In the equation for universal gravitation, the **universal gravitational constant,** G, describes the strength of gravity. Then the equation is

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

In words, the force of gravity between two objects is found by multiplying their masses, dividing by the square of the distance between their centers, and then multiplying this result by G. The magnitude of G is given by the magnitude of the force between two masses of 1 kilogram each, 1 meter apart: 0.0000000000667 newton. For these masses, this is an extremely weak force. The units of G are such as to make the force come out in newtons. In scientific notation,[13.4.2]

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



13.4 Newton's Law of Universal Gravitation

Key Terms
law of universal gravitation, universal gravitational constant

▶ **Teaching Tip** Acknowledge that many texts and references use the symbol *r* instead of *d* to represent distance. The *r* is used to indicate the radial distance from a body's CG and to emphasize the center-to-center rather than surface-to-surface nature of distance. It also prepares students to use *r* as a displacement vector. Here, simplify the concept and use *d* for distance.

▶ **Teaching Tip** Give examples of bodies pulling on each other to convey a clear idea of what the symbols in the equation mean and how they relate to one another.

Ask **How is the gravitational force between a pair of planets altered when the mass of one of the planets is doubled?** *The force is doubled.* **When both are doubled?** *The force is four times as great.* **When they are twice as far apart?** *The force is decreased to 1/4 as much.* **When they are three times as far apart?** *The force is decreased to 1/9 as much.* **Ten times as far apart?** *The force is decreased to 1/100 as much.*

▶ **Teaching Tip** Explain the gravitational constant *G* by comparing it to the constant π for circles. Begin by writing $C \sim D$. Draw several different-size circles on the board and show how the circumference and the diameter are proportional. State that if you divide the circumference *C* by the diameter *D* for any circle, you get the same result, $C/D = 22/7$. This constant is called π. When a constant of proportionality is introduced, a proportion can be written as an equation. In this case the equation is $C = \pi D$. Similarly, for the constant of proportionality *G* in Newton's gravitational force equation: When the force of gravity *F* between two bodies of mass m_1 and m_2 separated by a distance *d* is divided by m_1m_2/d^2, the number that results is the constant 6.67×10^{-11} N·m²/kg². The proportion $F \sim m_1m_2/d^2$ can be written as the exact equation $F = Gm_1m_2/d^2$.

▶ **Teaching Tip** Call attention to and discuss Philipp von Jolly's method of measuring the attraction between two masses (Figure 13.9).

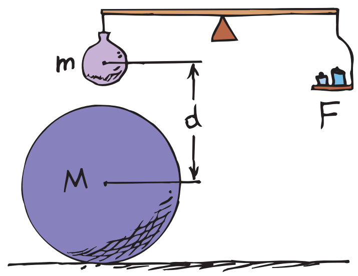
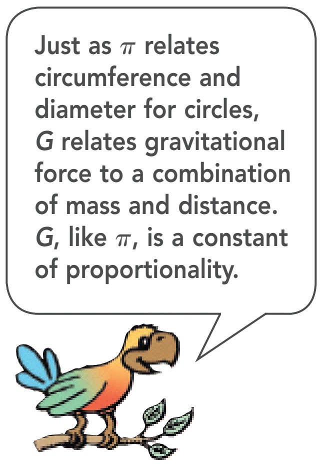


FIGURE 13.9 ▲
Philipp von Jolly developed a method of measuring the gravitational attraction between two masses.



Measuring *G* *G* was first measured 150 years after Newton's discovery of universal gravitation by an English physicist, Henry Cavendish. Cavendish accomplished this by measuring the tiny force between lead masses with an extremely sensitive torsion balance. A simpler method was later developed by Philipp von Jolly, who attached a spherical flask of mercury to one arm of a sensitive balance, as shown in Figure 13.9. After the balance was put in equilibrium, a 6-ton lead sphere was rolled beneath the mercury flask. The flask was pulled slightly downward. In effect, the gravitational force *F* between the lead mass and the mercury was equal to the weight that had to be placed on the opposite end of the balance to restore equilibrium. Since the quantities *F*, m_1, m_2, and *d* were all known, the value of *G* could be calculated:

$$G = \frac{F}{m_1m_2/d^2} = 6.67 \times 10^{-11} \frac{\text{N}}{\text{kg}^2/\text{m}^2} = 6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2$$

The value of *G* tells us that the force of gravity is a very weak force. It is the weakest of the presently known four fundamental forces. (The other three are the electromagnetic force and two kinds of nuclear forces.) We sense gravitation only when masses like that of Earth are involved. The force of attraction between you and a classmate is too weak to notice (but it's there!). The force of attraction between you and Earth, however, is easy to notice. It is your weight.

In addition to your mass, your weight also depends on your distance from the center of Earth. At the top of a mountain, like the one shown in Figure 13.10, your mass is the same as it is anywhere else, but your weight is slightly less than at ground level. Your weight is less because your distance from the center of Earth is greater.

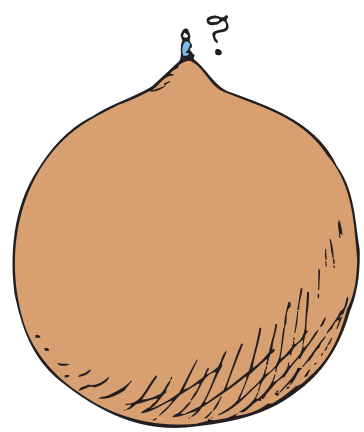


FIGURE 13.10 ▲
Your weight is less at the top of a mountain because you are farther from the center of Earth.

238

Interestingly, Cavendish's first measure of G was called the "Weighing the Earth" experiment, because once the value of G was known, the mass of Earth was easily calculated. The force that Earth exerts on a mass of 1 kilogram at its surface is 10 newtons. The distance between the 1-kilogram mass and the center of Earth is Earth's radius, 6.4×10^6 meters. Therefore, from $F = (Gm_1m_2/d^2)$, where m_1 is the mass of Earth,

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

Rearranging to solve for m_1 gives

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

from which the mass of Earth $m_1 = 6 \times 10^{24}$ kilograms.

CONCEPT CHECK **What did Newton discover about gravity?**

do the math!

How can you express very large and very small numbers in scientific notation?

Very large and very small numbers are conveniently expressed in a mathematical format called *scientific notation*. An example of a large number is the equatorial radius of Earth: 6,370,000 m. This number can be obtained by multiplying 6.37 by 10, and again by 10, and so on until 10 has been used as a multiplier six times. So 6,370,000 can be written as 6.37×10^6. That's 6.37 million meters. A thousand million is a billion, 10^9. To better comprehend the size of a billion:

- A billion meters is slightly more than the Earth–moon distance.
- A billion kilograms is the mass of about 120 Eiffel Towers.
- A billion Earths would equal the mass of about three suns.
- A billion seconds is 31.7 years.
- A billion minutes is 1903 years.
- A billion years ago there were no humans on Earth.
- A billion people live in China.
- A billion atoms make up the dot over this i.

Small numbers are expressed in scientific notation by dividing by 10 successive times. A millimeter (mm) is $\frac{1}{1000}$ m, or 1 m divided by 10 three times. In scientific notation, 1 mm = 10^{-3} m. The gravitational constant G is a very small number, 0.000000000066726 $\text{N}\cdot\text{m}^2/\text{kg}^2$. By dividing 6.6726 by 10 eleven times, and rounding off, it is $6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$.

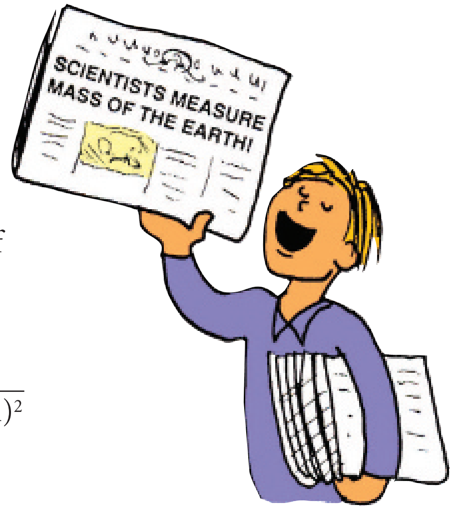


FIGURE 13.11 ▲
When G was first measured in the 1700s, newspapers everywhere announced the discovery as one that measured the mass of Planet Earth. This was particularly exciting at a time when a great portion of Earth's surface was still undiscovered.

▶ **Teaching Tip** Point out to students that weight is the force of attraction between an object and Earth.

▶ **Teaching Tip** Tell students that another reason there is less gravitation on the top of a mountain is the relatively low density of both the mountain and the extra thick crust beneath. Just as most of an iceberg extends beneath the water surface, the continental crust floats upon and extends deep into Earth's mantle. Like ice, the continental crust is less dense than the material it floats upon. Therefore, locally, a mountain top is farther from higher-density parts of Earth, as well as being farther from Earth's center.

▶ **Teaching Tip** Now would be a good time to have students brush up on their scientific notation and calculator skills in preparation for the Assess problems in this chapter.

CONCEPT CHECK Newton discovered that gravity is universal. Everything pulls on everything else in the universe in a way that involves only mass and distance.

Teaching Resources

- **Reading and Study Workbook**
- **Problem-Solving Exercises in Physics *8-1***
- **Presentation*EXPRESS***
- **Interactive Textbook**

13.5 Gravity and Distance: The Inverse-Square Law

Key Term
inverse-square law

▶ **Teaching Tip** Describe the inverse-square law in terms of the "butter gun" in Figure 13.12. The butter gun analogy shows how the strength of gravity varies inversely with distance.

▶ **Teaching Tip** Mention that the inverse-square law also applies to topics such as electrical forces between charges, spreading of light from a candle, and the weakening of radioactivity as distance from the source increases. (These topics will come later.) The inverse-square law applies whenever something dissipates equally in all directions from a small source.

Ask **Suppose a space probe is a certain distance, center to center, from a massive star. If it moves to four times as far from the star, how does its gravitational force toward the star compare?** *It is 1/16 as much.* **Suppose a sheet of photographic film is exposed to a point source of light that is a certain distance away. If the sheet is moved four times as far away and exposed to the same light, how does the intensity on the film compare?** *It is 1/16 as much.* **Suppose a radiation detector registers a certain amount of radioactivity when it is a certain distance away from a small piece of uranium. If the detector is moved four times farther away from the uranium, how does the radioactivity reading compare?** *It is 1/16 as much.*

13.5 Gravity and Distance: The Inverse-Square Law

We can understand how gravity is reduced with distance by considering an imaginary "butter gun" used in a busy restaurant for buttering toast. Imagine melted butter sprayed through a square opening in a screen. The opening is exactly the size of one piece of square toast. And imagine that a spurt from the gun deposits an even layer of butter 1 mm thick. Consider the consequences of holding the toast twice as far from the butter gun. You can see in Figure 13.12 that the butter would spread out for twice the distance and would cover twice as much toast vertically and twice as much toast horizontally. A little thought will show that the butter would now spread out to cover four pieces of toast. How thick will the butter be on each piece of toast? Since it has been diluted to cover four times as much area, its thickness will be one-quarter as much, or 0.25 mm.

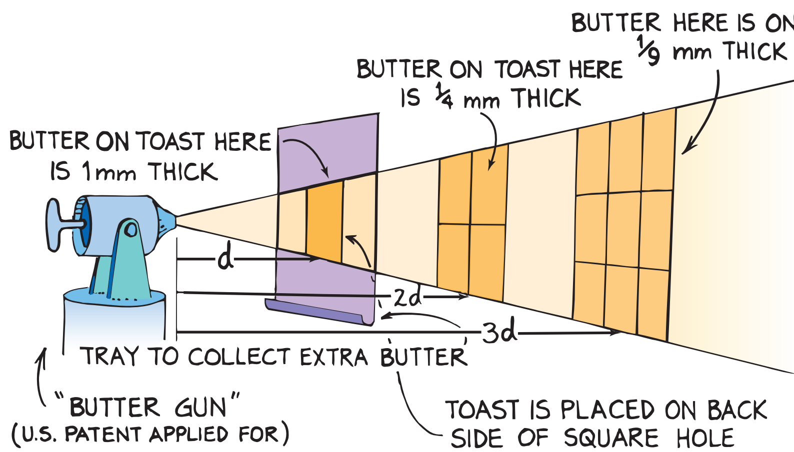
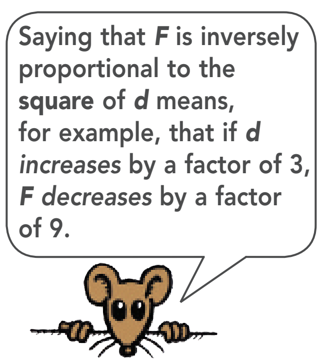


FIGURE 13.12 ▶
Butter spray travels outward from the nozzle of the butter gun in straight lines. Like gravity, the "strength" of the spray obeys an inverse-square law.

Note what has happened. When the butter gets twice as far from the gun, it is only $\frac{1}{4}$ as thick. More thought will show that if it gets 3 times as far, it will spread out to cover 3×3, or 9, pieces of toast. How thick will the butter be then? Can you see it will be $\frac{1}{9}$ as thick? And can you see that $\frac{1}{9}$ is the inverse *square* of 3? (The inverse of 3 is simply $\frac{1}{3}$; the inverse square of 3 is $(\frac{1}{3})^2$, or $\frac{1}{9}$.) When a quantity varies as the inverse square of its distance from its source, it follows an **inverse-square law.** **Gravity decreases according to the inverse-square law. The force of gravity weakens as the square of distance.** This law applies not only to the spreading of butter from a butter gun, and the weakening of gravity with distance, but to all cases where the effect from a localized source spreads evenly throughout the surrounding space. More examples are light, radiation, and sound.



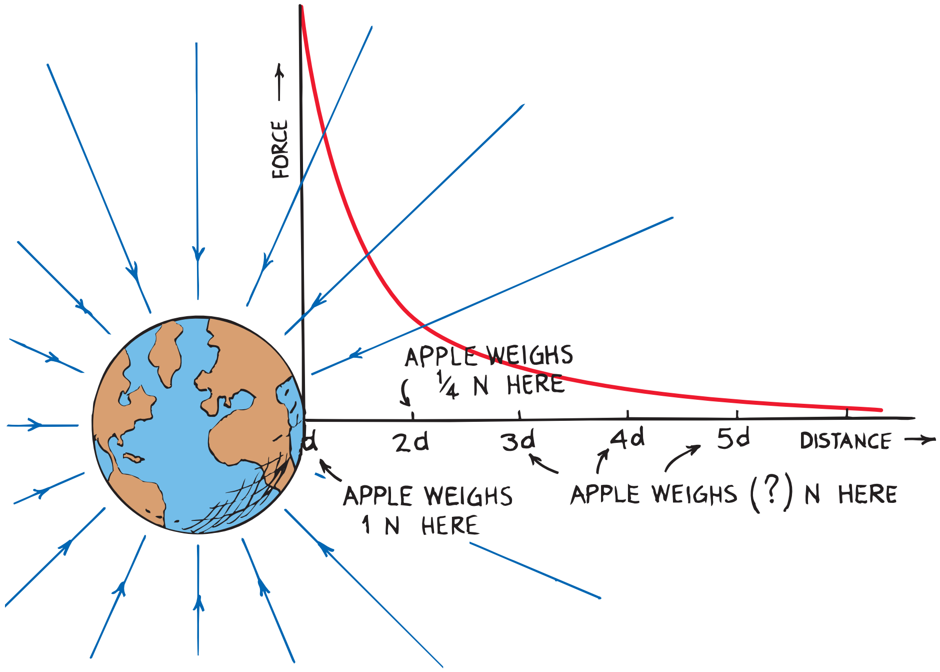


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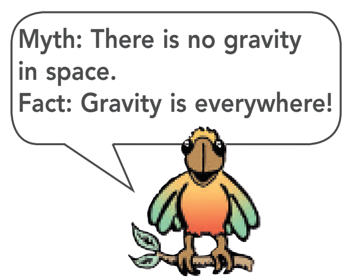
FIGURE 13.13
Gravitational force is plotted in red versus distance from Earth's center.

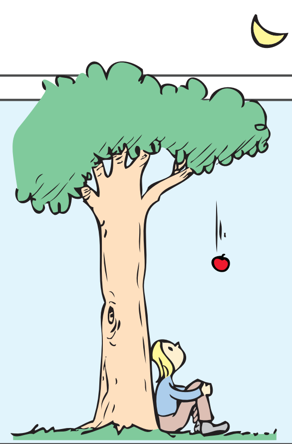
Figure 13.13 shows how the greater the distance from Earth's center, the less an object will weigh. An apple that weighs 1 N at Earth's surface weighs only 0.25 N when located twice as far from Earth's center because the pull of gravity is only $\frac{1}{4}$ as strong. When it is 3 times as far, it weighs only $\frac{1}{9}$ as much, or 0.11 N. If your little sister weighs 300 N at sea level, she will weigh only 299 N atop Mt. Everest. But no matter how great the distance, Earth's gravity does not drop to zero. Even if you were transported to the far reaches of the universe, the gravitational influence of Earth would be with you. It may be overwhelmed by the gravitational influences of nearer and more massive objects, but it is there. The gravitational influence of every object, however small or far away, is exerted through all space. That's impressive!



CONCEPT CHECK How does the force of gravity change with distance?

think!

Suppose that an apple at the top of a tree is pulled by Earth's gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity on the apple be only $\frac{1}{4}$ as strong? Explain your answer.
Answer: 13.5



▶ **Teaching Tip** Point out that the difference in the weight of a person at sea level and at the top of a tall mountain is rarely observed because it is only about one newton (one quarter of a pound).

Ask True or false? The force of Earth's gravity on the space shuttle in orbit is zero or nearly zero. *False! The force of Earth's gravity on the shuttle in orbit is nearly the same as the force of Earth's gravity on the shuttle at sea level. At an altitude of 200 km, well above Earth's atmosphere, the space shuttle is only 3% farther from Earth's center and experiences 94% of the gravitational pull at Earth's surface.* **True or false? At the far reaches of the universe, a body would experience zero Earth gravity.** *False! The equation guides thinking here: As distance d approaches infinity, force F approaches (but never reaches) zero. As a practical matter, at such a distance the force due to Earth's gravity may be negligible in comparison to the influences of closer and more massive bodies.*

CONCEPT CHECK Gravity decreases according to the inverse-square law. The force of gravity weakens as the square of distance.

Teaching Resources
- **Reading and Study Workbook**
- **Concept-Development Practice Book** *13-1*
- **Transparency** *20*
- **Presentation***EXPRESS*
- **Interactive Textbook**
- **Next-Time Questions** *13-1, 13-2*

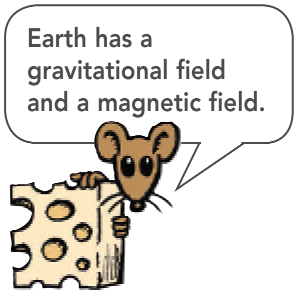
13.6 Gravitational Field

Key Term
gravitational field

The concept of force field introduced in this section is a good background for the concept of electric field discussed later in Chapter 33.
PAUL

Teaching Tip Describe the space around a magnet—a magnetic field. A magnetic field is a force field, because magnetic materials in it experience a force. The gravitational field around Earth (or any mass) is similar. A mass in the field region experiences a gravitational force. The field is strongest at the surface of Earth, and declines as the distance from Earth's center increases (declines as $1/r^2$).

Ask **Does the gravitational field about Earth decrease with increasing altitude? Does the force of gravity on an object decrease with increasing altitude? Does the acceleration *g* decrease with increasing altitude?** *Yes; yes; yes; at everyday altitudes, however, these decreases are small and can be neglected.*



13.6 Gravitational Field

We know Earth and the moon pull on each other. This is action at a distance, because both bodies interact with each other without being in contact. But we can look at this in a different way: we can regard the moon as in contact with the gravitational field of Earth. A **gravitational field** occupies the space surrounding a massive body. A gravitational field is an example of a *force field,* for any mass in the field space experiences a force.[13.6] **Earth can be thought of as being surrounded by a gravitational field that interacts with objects and causes them to experience gravitational forces.** It is common to think of rockets and distant space probes being influenced by the gravitational field at their locations in space rather than by Earth and other planets or stars acting from a distance. The force field concept plays an in-between role in our thinking about the forces between different masses.

A more familiar force field is the magnetic field of a magnet (look ahead to Figure 36.4). Iron filings sprinkled over a sheet of paper on top of a magnet reveal the shape of the magnet's magnetic field. The pattern of filings shows the strength and direction of the magnetic field at different locations around the magnet. Where the filings are close together, the field is strong. The direction of the filings shows the direction of the field at each point. Planet Earth is a giant magnet, and like all magnets, is surrounded in a magnetic field. Evidence of the field is easily seen by the orientation of a magnetic compass.

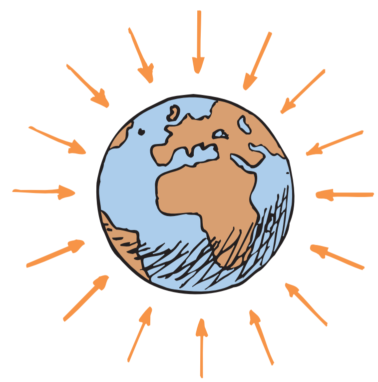
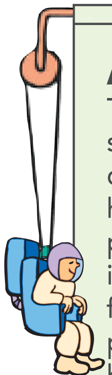


FIGURE 13.14 Field lines represent the gravitational field about Earth.

Field lines can also represent the pattern of Earth's gravitational field. Like the iron filings around a magnet, the field lines are closer together where the gravitational field is stronger. The arrows in Figure 13.14 show the field direction. A particle, astronaut, spaceship, or any mass in the vicinity of Earth will be accelerated in the direction of the field lines at that location. The strength of Earth's gravitational field, like the strength of its force on objects, follows the inverse-square law. Earth's gravitational field is strongest near Earth's surface and weaker at greater distances from Earth.

Another example of a force field is the one that surrounds electrical charges—the electric field, which we shall study in Chapter 33. In Chapter 36 we'll learn how magnets align with the magnetic fields of Earth to become compasses. In Chapter 11 we've already learned how the moon similarly aligns with Earth's gravitational field, resulting in the same side of the moon facing us. Force fields have far-reaching effects.

CONCEPT CHECK What kind of field surrounds Earth and causes objects to experience gravitational forces?



Physics on the Job

Astronaut

Three. Two. One. The Space Shuttle leaves Earth with its crew of seven astronauts. An astronaut pilots, or works on a spacecraft, or conducts experiments during spaceflights. Astronauts understand how the force of gravity will change throughout their trip. They apply physics to control the direction of a spacecraft, conduct experiments in space, and move outside the spacecraft. Astronauts usually have flight experience along with degrees in scientific disciplines such as physics or chemistry. The United States astronaut program is managed by the National Aeronautics and Space Administration (NASA).

Ask **What evidence would you look for to tell whether or not you were in a gravitational field?** *The presence of a gravitational force* **Compared to its strength at Earth's surface, what is the strength of the gravitational field at a distance of two Earth radii from the center of Earth?** *1/4 as much*

CONCEPT CHECK Earth can be thought of as being surrounded by a gravitational field that interacts with objects and causes them to experience gravitational forces.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *13-2, 13-3*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Conceptual Physics Alive! DVDs** *Gravity II*

13.7 Gravitational Field Inside a Planet

▶ **Teaching Tip** Consider a tunnel bored right through Earth. The gravitational force on a body located at the exact center of the tunnel is zero, so the gravitational field at Earth's center is zero. Now consider the magnitude of force a body would experience somewhere between the center and the surface. The gravitational field is between zero and the value at the surface. (The increase is not linear because the density is much greater at Earth's center.)

▶ **Teaching Tip** Discuss the motion of a body dropped in the same tunnel bored through Earth. Describe how it would keep rhythm with a circularly moving satellite of the same "amplitude." It takes nearly 90 minutes for a satellite to make a complete trip around Earth in close orbit, which is exactly the same time a body dropped from the same altitude into the tunnel would take to travel through Earth.

▶ **Teaching Tip** Explain that, strictly speaking, as a body falls through the tunnel, the part of Earth above doesn't pull "upward" on it. Gravitational forces from all parts of Earth above the body cancel, assuming uniform density. The acceleration of the body decreases because there is a smaller amount of mass in the core beneath the body. The radius of this core is the body's distance from the center and so it is zero at the center.

CONCEPT CHECK The gravitational field of Earth at its center is zero!

13.7 Gravitational Field Inside a Planet

think!

If you stepped into a hole bored completely through Earth and made no attempt to grab the edges at either end, what kind of motion would you experience?
Answer: 13.7

The gravitational field of Earth exists inside Earth as well as outside. To investigate the gravitational field beneath the surface, imagine a hole drilled completely through Earth, say from the North Pole to the South Pole, as shown in Figure 13.15. Forget about impracticalities such as lava and high temperatures, and consider the kind of motion you would undergo if you fell into such a hole.

If you started at the North Pole end, you'd fall and gain speed all the way down to the center, and then overshoot and lose speed all the way to the South Pole. You'd gain speed moving toward the center, and lose speed moving away from the center. Without air drag, the trip would take nearly 45 minutes. If you failed to grab the edge, you'd fall back toward the center, overshoot, and return to the North Pole in the same amount of time.

Suppose you had some way to measure your acceleration during this trip. At the beginning of the fall, your acceleration would be *g*, but you'd find acceleration progressively decreasing as you continue toward the center of Earth.[13.7] Why? Because as you are being pulled "downward" toward Earth's center, you are also being pulled "upward" by the part of Earth that is "above" you. In fact, as illustrated in Figure 13.16, when you get to the center of Earth, the pull "down" is balanced by the pull "up." You are pulled in every direction equally, so the net force on you is zero. There is no acceleration as you whiz with maximum speed past the center of Earth. ✓ **The gravitational field of Earth at its center is zero!**

CONCEPT CHECK **Describe the gravitational field of Earth at its center.**

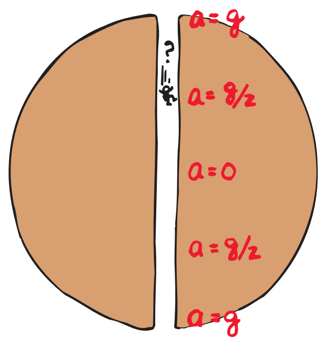


FIGURE 13.15 ▲
As you fall faster and faster into a hole bored through Earth, your acceleration diminishes because the pull of the mass above you partly cancels the pull below.

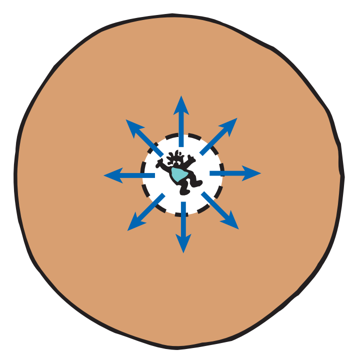


FIGURE 13.16 ▲
In a cavity at the center of Earth, your weight would be zero, because you would be pulled equally by gravity in all directions.

13.8 Weight and Weightlessness

The force of gravity, like any force, causes acceleration. Objects under the influence of gravity are pulled toward each other and accelerate (as long as nothing prevents the acceleration). We are almost always in contact with Earth. For this reason, we think of gravity primarily as something that presses us against Earth rather than as something that accelerates us. **Force against Earth is the sensation we interpret as weight.**

Stand on a bathroom scale that is supported on a stationary floor. The gravitational force between you and Earth pulls you against the supporting floor and scale. By Newton's third law, the floor and scale in turn push upward on you. Located between you and the supporting floor is a spring-like gauge inside the bathroom scale. This pair of forces compresses the gauge. The weight reading on the scale is linked to the amount of compression.

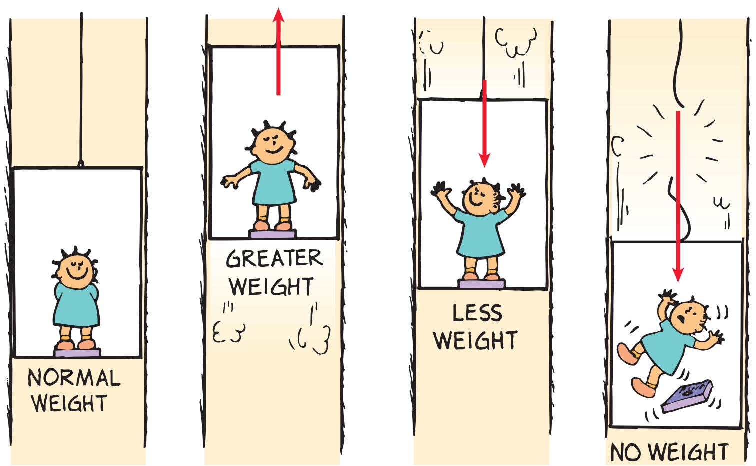


FIGURE 13.17
The sensation of weight is equal to the force that you exert against the supporting floor.

If you repeated this weighing procedure in a moving elevator, as shown in Figure 13.17, you would find your weight reading would vary—not during steady motion, but during accelerated motion. If the elevator accelerated upward, the bathroom scale and floor would push harder against your feet, and the gauge inside the scale would be compressed even more. The scale would show an increase in your weight.

If the elevator accelerated downward, the support force of the floor would be less and the scale would show a decrease in your weight. If the elevator cable broke and the elevator fell freely, the scale reading would register zero. According to the scale, you would be weightless. And you would feel weightless, for your insides would no longer be supported by your legs and pelvic region. Your organs would respond as though gravity were absent. But gravity is not absent, so would you really be weightless? The answer to this question depends on your definition of weight.

13.8 Weight and Weightlessness

Key Term
weightlessness

Teaching Tip Define weight in terms of support force. According to this definition, we are as heavy as we feel. Contrast this with apparent weightlessness and relate it to the queasy feeling your students may experience when in a car that speeds over the top of a hill. This feeling is what an astronaut is confronted with all the time in orbit! Ask how many of your students would still welcome the opportunity to take a ride aboard the space shuttle!

Ask Why would you feel weightless in an elevator with a broken cable? *There would be no support force—the floor would fall as fast as you.*

Teaching Tip Ask your students to imagine a video camera fixed to the inside of an elevator. Have them imagine themselves in the elevator, removing pens from their pockets and dropping them. The camera records the dropping of the pen. Ask what it would see if the pen-drop were repeated in an elevator that is in free fall. The camera would show the pen floating beside the student, as the student, pen, camera, and elevator all fall at *g*. Ask if there is a force of gravity in this case (as evidenced by the sudden stop!). Does the camera show the dropping motion? Compare this to what happens in orbit.

▶ **Teaching Tip** Describe the apparent weightlessness of astronauts orbiting in the space shuttle and how objects float around as if gravity wasn't present.

CONCEPT CHECK Force against Earth is the sensation we interpret as weight.

Teaching Resources

- Reading and Study Workbook
- Laboratory Manual *43*
- Presentation*EXPRESS*
- Interactive Textbook

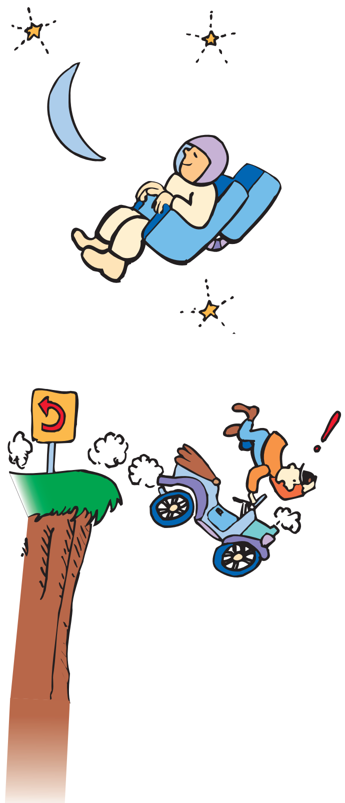
13.9 Ocean Tides

Key Terms
spring tide, neap tide

Common Misconception
The fact that the moon is the chief cause of ocean tides is evidence that the moon's pull on Earth is greater than the sun's pull.

FACT The moon "out-tides" the stronger-pulling sun because the *difference* in pulls on either side of Earth is greater for the closer moon.

FIGURE 13.18 ▼
Both people are without a support force and therefore experience weightlessness.



Rather than define your weight as the force of gravity that acts on you, it is more practical to define weight as the force you exert against a supporting floor (or weighing scales). According to this definition, you are as heavy as you feel. Thus, the condition of **weightlessness** is not the absence of gravity; rather, it is the absence of a support force. That queasy feeling you get when you are in a car that seems to leave the road momentarily when it goes over a hump, or worse, off a cliff, as shown in Figure 13.18, is not the absence of gravity. It is the absence of a support force.

Astronauts in orbit are without a support force and are in a sustained state of weightlessness. Astronauts sometimes experience "space sickness" until they get used to a state of sustained weightlessness. Future space travelers, however, need not be subjected to weightlessness. As mentioned in the previous chapter, lazily rotating giant wheels will likely supplant today's non-rotating space habitats. Rotation effectively supplies a support force and nicely provides weight.

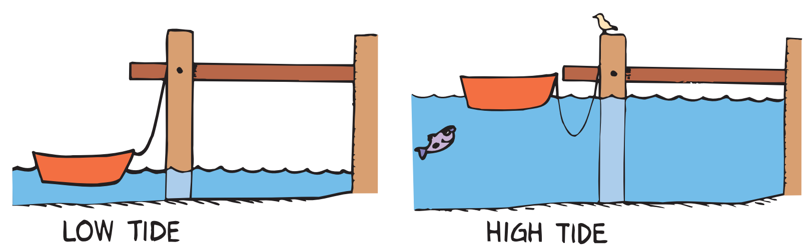
CONCEPT CHECK **What sensation do we interpret as weight?**

13.9 Ocean Tides

Seafaring people have always known there was a connection between the ocean tides and the moon, but no one could offer a satisfactory theory to explain why there are two high tides per day. You may have noticed this rise and fall of seawater, as shown in Figure 13.19, on visits to the ocean. ✓ **Newton showed that the ocean tides are caused by *differences* in the gravitational pull of the moon on opposite sides of Earth.** The moon's attraction is stronger on Earth's oceans closer to the moon, and weaker on the oceans farther from the moon because the gravitational force is weaker with increased distance.

This difference in pulls across Earth slightly elongates it. Through a similar effect of Earth on the moon, the moon is slightly elongated, too. Rather than being spherical, both Earth and moon are pulled into a shape that slightly resembles a football.

FIGURE 13.19 ▶
The ocean tides are caused by differences in the gravitational pull of the moon on opposite sides of Earth.



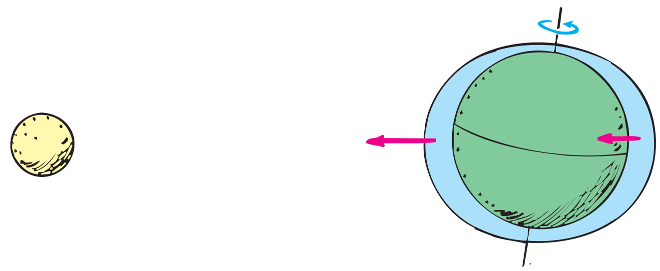


FIGURE 13.20
The two tidal bulges remain relatively fixed with respect to the moon while Earth spins daily beneath them.

For Earth, the elongation is mainly in the most pliable part—the oceans. The oceans bulge out about 1 meter on average, on opposite sides of Earth. Because Earth spins once per day, a fixed point on Earth passes beneath both of these bulges each day, as illustrated in Figure 13.20. This produces two sets of ocean tides per day—two high tides and two low tides.[13.9]

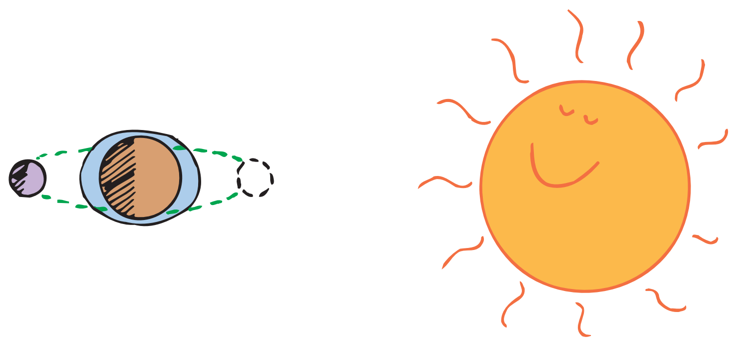


FIGURE 13.21
When the sun, the moon, and Earth are aligned, spring tides occur.

Factors Affecting Ocean Tides The sun also contributes to ocean tides, about half as much as the moon—even though its pull on Earth is 180 times greater than the moon's pull on Earth. Then why aren't tides due to the sun 180 times greater than lunar tides? Because the *difference* in gravitational pulls by the sun on opposite sides of Earth is very small (only about 0.017 percent, compared to 6.7 percent for the moon's gravitation).

Figure 13.21 illustrates the configuration of the sun, Earth, and moon that produces spring tides. A **spring tide** is a high or low tide that occurs when the sun, Earth, and moon are all lined up. The tides due to the sun and the moon coincide, making the high tides higher than average and the low tides lower than average. Spring tides occur at the times of a new or full moon (and have nothing to do with the spring season).

A **neap tide** occurs when the moon is halfway between a new moon and a full moon, in either direction. As illustrated in Figure 13.22, the pulls of the moon and sun are perpendicular to each other. As a result, the solar and lunar tides do not overlap, so the high tides are not as high and low tides are not as low.

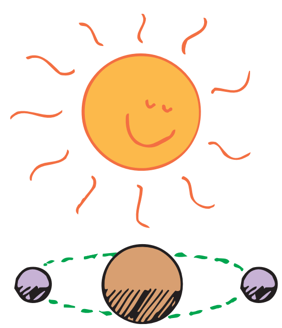


FIGURE 13.22
When the attractions of the sun and the moon are at right angles to each other (at the time of a half moon), neap tides occur.

Teaching Tip Ask your students to consider the consequences of someone pulling your coat. If some pulled only on the sleeve, for example, the coat would tear. But if every part of your coat were pulled equally, it and you would accelerate, but the coat wouldn't tear. It tears when one part is pulled harder than another because of a *difference* in forces acting on the coat. In a similar way, the spherical Earth is "torn" into an elliptical shape by differences in gravitational forces exerted by the moon—stronger between the moon and the near side of Earth, and weaker between the moon and the far side of Earth.

Teaching Tip Explain that tides are extra high when the moon and sun are lined up because the pulls add together and the two tides due to the moon and sun overlap. When the moon and sun are at right angles to each other, the high tide of the sun overlaps the low tide of the moon, and vice versa.

Ask Which pulls harder on the oceans of Earth, the sun or the moon? *The sun* **Which is most effective in raising tides?** *The moon*

Teaching Tip Explain why the highest high tides occur when Earth, the moon, and the sun are aligned—at the time of a new or a full moon.

Ask At the time of extra high tides, will extra low tides follow in the same day? *Yes, by the "conservation of water." There is only so much water on Earth—extra high tides in one part of the world means extra low tides in another.*

Teaching Tip Explain that for the same reason we have ocean tides, there are tides within Earth, which is mostly molten lava. Mount Everest rises and falls about 30 cm twice a day. There is a greater probability of earthquakes and volcanoes when there is an eclipse of the sun or the moon. This is when Earth experiences spring tides—greater stresses on Earth's crust.

Teaching Tidbit When you look at a globe you're seeing a snapshot of the continents as they have been for about one tenth of 1% of Earth's history.

CONCEPT CHECK Newton showed that the ocean tides are caused by *differences* in the gravitational pull of the moon on opposite sides of Earth.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *13-4*
- **Transparency** *21*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *13-3*

Science, Technology, and Society

CRITICAL THINKING Answers will vary but should include factors such as availability, cost, environmental concerns, etc.

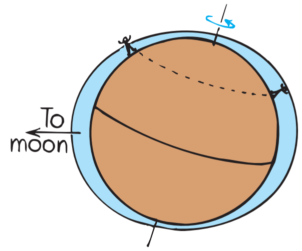


FIGURE 13.23 ▲
Earth's tilt causes the two daily high tides to be unequal.

Atmospheric tides influence the number of cosmic rays reaching Earth's surface. Like ocean tides, atmospheric tides are greatest when the moon, sun, and Earth are aligned.

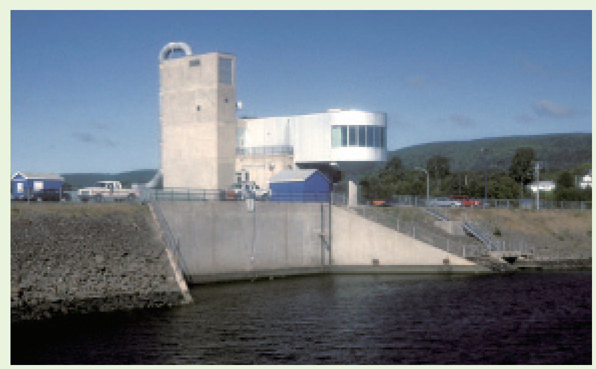
Other Types of Tides Because much of the Earth's interior is deformable, we have Earth tides, though they are less pronounced than ocean tides. Twice each day the solid surface of Earth rises and falls as much as one-quarter meter. There are also atmospheric tides, which affect the intensity of cosmic rays that reach Earth's surface. These rays, affected even more strongly by Earth's magnetic field, induce subtle changes in living things. Ocean tides, Earth tides, and atmospheric tides are greatest when the sun, Earth, and moon are aligned—at the time of a full or new moon. The tilt of Earth's axis, interfering landmasses, friction with the ocean bottom, and other factors complicate tidal motions. Figure 13.23 illustrates the effect of the tilt of Earth's axis on the tides.

Although the moon produces considerable tides in Earth's oceans, which are thousands of kilometers across, it produces scarcely any tides in a lake. That's because no part of the lake is significantly closer to the moon than any other part—this means there is no significant *difference* in the moon's pull on different parts of the lake. Similarly, any tides in the fluids of your body caused by the moon are negligible. You're not tall enough for tides. What micro-tides 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! Tides are fascinating.

CONCEPT CHECK What causes ocean tides?

Science, Technology, and Society

Power Production
Power plants that run on tidal power are numerous throughout the world. The first modern tidal power plant in North America has been operating since 1984 in Nova Scotia, Canada. A dam across an estuary gets its power from the rising and falling of the daily ocean tide. First the water is higher on one side of the dam, and is maintained at about 1.6 meters higher than the lower side. Water then flows through a series of gates to the lower side, turning a huge turbine in the process. When the tide changes, the flow of water is in the reverse direction, again turning the turbine. The dam produces more than 20 MW of power—enough to meet the electricity needs for 4500 homes. The largest tidal power plant produces 240 MW of electric power in Brittany, France. Watch for the growth of this green technology.



Critical Thinking What are the advantages of using ocean tides to produce electricity?

13.10 Black Holes

There are two main processes going on continously in stars like our sun. Figure 13.24 illustrates these two processes. One process is gravitation, which tends to crush all solar material toward the center. The other process is thermonuclear fusion consisting of reactions similar to those in a hydrogen bomb. These hydrogen bomb-like reactions tend to blow solar material outward. When the processes of gravitation and thermonuclear fusion balance each other, the result is the sun of a given size.

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Formation of Black Holes If the fusion rate increases, the sun will get hotter and bigger; if the fusion rate decreases, the sun will get cooler and smaller. What will happen when the sun runs out of fusion fuel (hydrogen)? The answer is, gravitation will dominate and the sun will start to collapse. For our sun, this collapse will ignite the nuclear ashes of fusion (helium) and fuse them into carbon. During this fusion process, the sun will expand to become the type of star known as a *red giant.* It will be so big that it will extend beyond Earth's orbit and swallow Earth. Fortunately, this won't take place until some 5 billion years from now. When the helium is all "burned," the red giant will collapse and die out. It will no longer give off heat and light. It will then be the type of star called a *black dwarf*—a cool cinder among billions of others.

The story is a bit different for stars more massive than the sun. For a heavy star, one that is at least two to three times more massive than our sun,[13.10] once the flame of thermonuclear fusion is extinguished, gravitational collapse takes over—and it doesn't stop! The star not only caves in on itself, but the atoms that compose the stellar material also cave in on themselves until there are no empty spaces. According to theory, the collapse never stops and the density becomes literally infinite. Gravitation near these shrunken configurations, which are called **black holes,** is so enormous that nothing can get back out. Even light cannot escape a black hole. They have crushed themselves out of visible existence.

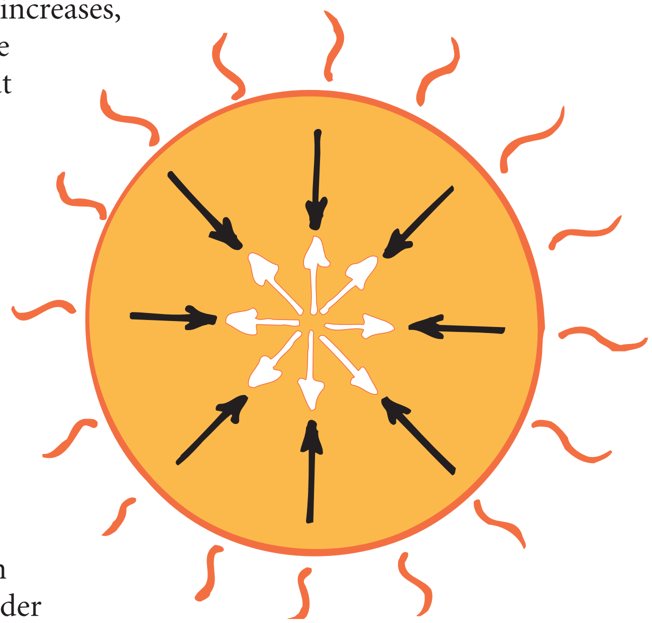


FIGURE 13.24 ▲ The size of the sun is the result of a "tug of war" between two opposing processes: nuclear fusion and gravitational contraction.

13.10 Black Holes

Key Term
black hole

▶ **Teaching Tip** To better understand a black hole, think of an indestructible you on the surface of a star that shrinks to half its size. The gravitational force on you increases by 4 (via the inverse-square law). If the star shrinks to one-tenth its size, gravity at the surface increases 100 times. So gravity at the surface increases with progressed shrinkage. Note that it's only near the black hole that the enormous increase in gravity occurs. Noting that no terms change the equation for gravity, we see that gravity in space above the star before shrinkage doesn't change at all. (The mass of the star is compressed, but not increased.)

▶ **Teaching Tip** Explain that a collapsed star represents condensed mass and therefore condensed gravity. The mass of a black hole is no more than the mass of the star that collapsed to form it. Hence, the gravitational field of the star and the black hole are the same at distances greater than the original radius of the star. It is only at closer distances that the enormous field occurs.

▶ **Teaching Tip** Discuss Figure 13.25. Show that as d approaches zero, the field Gm/d^2 approaches infinity.

Ask **Consider a satellite companion to a star that collapses to become a black hole. How will the orbit of the companion satellite be affected by the star's transformation to a black hole?** *Not at all; no terms in the gravitational equation change.*

Gravitational Field Near Black Holes Perhaps surprisingly, a black hole is no more massive than the star from which it collapsed. **When a massive star collapses into a black hole, there is no change in the gravitational field at any point beyond the original radius of the star.** The gravitational field near the black hole may be enormous, but, as shown in Figure 13.25, the field beyond the original radius of the star is no different after collapse than before. The amount of mass has not changed, so there is no change in the field at any point beyond this distance. Black holes will be formidable only to future astronauts who venture too close.

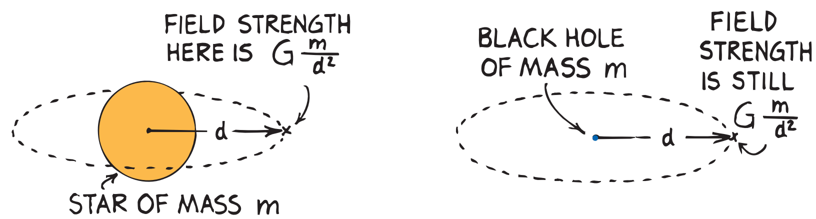
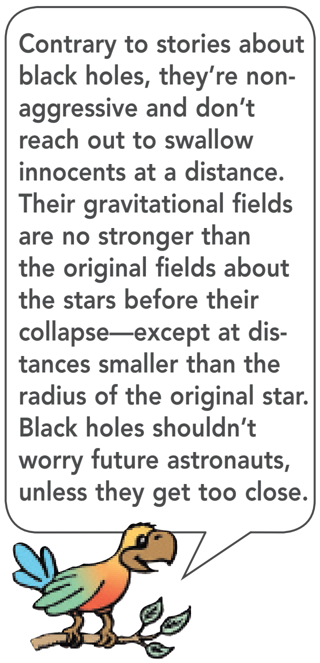


FIGURE 13.25 ▶
The gravitational field strength near a giant star that collapses to become a black hole is the same before collapse (left) and after collapse (right).



The configuration of the gravitational field about a black hole represents the collapse of space itself. The field is usually represented as a warped two-dimensional surface, as shown in Figure 13.26.

Astronauts could enter the fringes of this warp and, with a powerful spaceship, still escape. After a certain distance, however, they could not escape, and they would disappear from the observable universe. Don't go too close to a black hole!

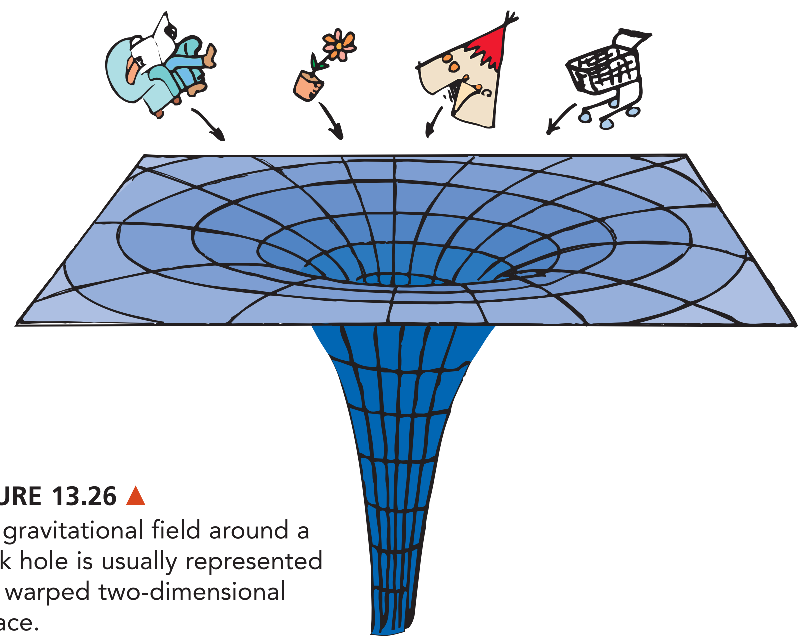


FIGURE 13.26 ▲
The gravitational field around a black hole is usually represented as a warped two-dimensional surface.

250

Effects of Black Holes Although black holes can't be seen, their effects can be. Many stars in the sky occur as binaries—pairs that orbit around each other. Sometimes only one star of a binary pair is seen. Matter streams from this visible star toward its invisible companion, emitting X-rays as it accelerates toward the "nothingness" that is probably a black hole. And near the centers of most galaxies are immensely massive yet very small centers of force that cause stars near them to speed around in tight orbits. These black holes, if that's what they are, are more massive than a million suns.

CONCEPT CHECK **What happens to the gravitational field of a star that has collapsed into a black hole?**

13.11 Universal Gravitation

We all know that Earth is round. But *why* is Earth round? It is round because of gravitation. Since everything attracts everything else, Earth had attracted itself together before it became solid. Any "corners" of Earth have been pulled in so that Earth is a giant sphere. The sun, the moon, and Earth are all fairly spherical because they have to be (rotational effects make them somewhat wider at their equators). Figure 13.27 shows how gravity played a role in the formation of the solar system. A slightly rotating ball of interstellar gas, which is illustrated in Figure 13.27a, contracted due to mutual gravitation, which is shown in Figure 13.27b. To conserve angular momentum, the rotational speed of the ball of gas increased. The increased momentum of the individual particles and clusters of particles caused them to sweep in wider paths about the rotational axis, producing an overall disk shape, as shown in Figure 13.27c. The greater surface area of the disk promoted cooling and clusters of swirling matter—the birthplace of the planets.

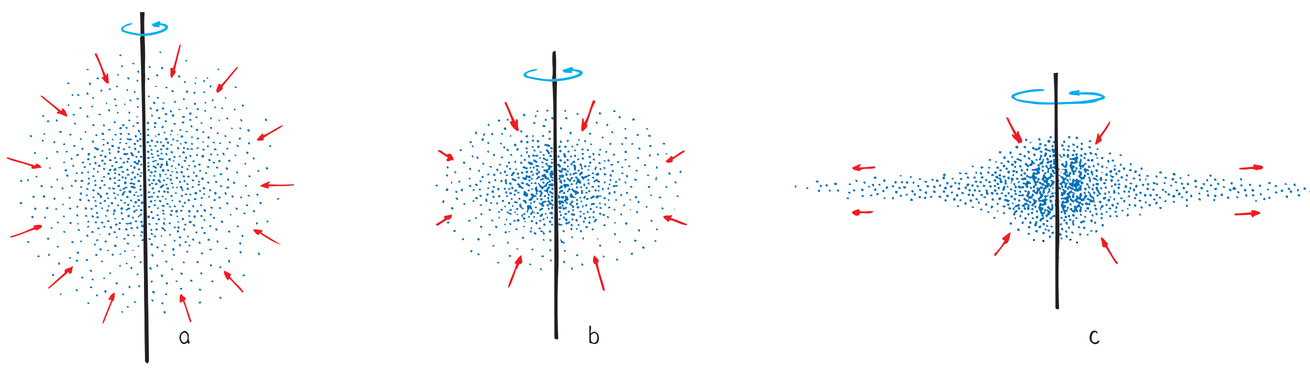


FIGURE 13.27 ▼
Gravity played an important role in the formation of the solar system.

CONCEPT CHECK When a massive star collapses into a black hole, there is no change in the gravitational field at any point beyond the original radius of the star.

Teaching Resources

- Reading and Study Workbook
- Transparency *22*
- PresentationEXPRESS
- Interactive Textbook
- Next-Time Question *13-4*

13.11 Universal Gravitation

Key Term
perturbation

▶ **Teaching Tip** Discuss the theory of the expanding universe and its possible oscillating mode. You can get class interest into high gear with speculations as to the possibility of past and future cycles.

▶ **Teaching Tip** Point out that Earth is not actually a perfect sphere but an oblate spheroid—a sphere flattened at the poles. Earth's spin helps produce an equatorial bulge.

Teaching Tip Tell your students that Newton showed that the same force that holds us to Earth is responsible for the motions of objects in space. Explain that Newton made physics a universal science. He showed that we had the potential to know not only the mechanics of things in our immediate surroundings, but our place in the universe itself.

Teaching Tidbit In pre-Copernican times the sun and moon were viewed as planets. Their planetary status was removed when Copernicus substituted the sun for Earth's central position. Only then was Earth regarded as a planet among others. More than 200 years later, in 1781, telescope observers added Uranus to the list of planets. Neptune was added in 1846. Pluto was added in 1930—and removed in 2006.

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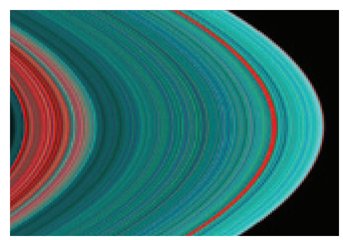
Perturbations in the Solar System If everything pulls on everything else, then the planets must pull on each other. The net force that controls Jupiter, for example, is not just from the sun, but from the planets also. Their effect is small compared with the pull of the more massive sun, but it still shows. When the planet Saturn is near Jupiter, for example, its pull disturbs the otherwise smooth path of Jupiter. Both planets deviate from their normal orbits. The deviation of an orbiting object from its path around a center of force caused by the action of an additional center of force is called a **perturbation.**

Until the middle of the last century astronomers were puzzled by unexplained perturbations of the planet Uranus. Even when the influences of the other planets were taken into account, Uranus was behaving strangely. Either the law of gravitation was failing at this great distance from the sun, or some unknown influence such as another planet was perturbing Uranus.

The source of Uranus's perturbation was uncovered in 1845 and 1846 by two astronomers, John Adams in England and Urbain Leverrier in France. With only pencil and paper and the application of Newton's law of gravitation, both astronomers independently arrived at the same conclusion: A disturbing body beyond the orbit of Uranus was the culprit. They sent letters to their local observatories with instructions to search a certain part of the sky. The request by Adams was delayed by misunderstandings at Greenwich, England, but Leverrier's request to the director of the Berlin Observatory was heeded right away. The planet Neptune was discovered within a half hour.

Link to ASTRONOMY

Planetary Rings Four planets in the solar system have a system of planetary rings. The rings of Saturn were brought vividly to life in 2004 by the Cassini-Huygens space probe. Tidal forces may have caused the formation of these rings. A satellite experiences competing forces—the tidal forces that tend to tear it apart, and the self-gravitation that holds it together. Early in the life of the solar system, Saturn (and other outer planets) may have had one or more moons orbiting too close to the planet's surface. Powerful tidal forces could have stretched them and torn them apart. During billions of years fragments could have separated into billions of still smaller pieces spreading out to form the beautiful rings we see today. Our moon is sufficiently far away to resist this tidal disintegration. But if it were to come too close, within a few hundred kilometers of Earth, the increased tidal forces would tear the moon apart. Then Earth, like Saturn, Jupiter, Uranus, and Neptune, would have a system of planetary rings!

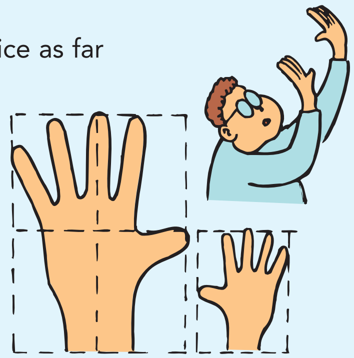


252

discover!

Which Hand Is Bigger?

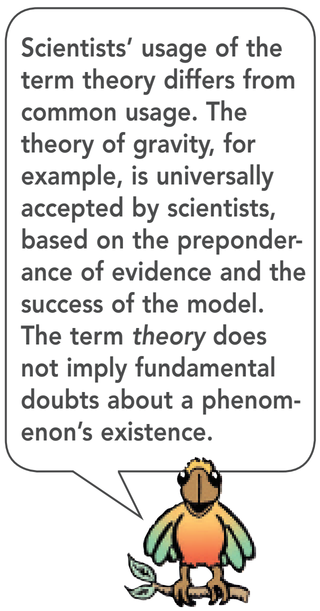
1. Hold your hands outstretched, one twice as far from your eyes as the other.
2. Make a casual judgment about which hand looks bigger.
3. Now, overlap your hands slightly and carefully view them with one eye closed.
4. **Think** Why does one hand appear bigger than the other?



Subsequent tracking of the orbits of both Uranus and Neptune led to the prediction of another massive body beyond Neptune. In 1930, at the Lowell Observatory in Arizona, Pluto was discovered. Whatever you may have learned in your early schooling, astronomers now regard Pluto as a dwarf planet and not a full-fledged planet. Pluto takes 248 years to make a single revolution about the sun, so no one will see it in its discovered position again until the year 2178.

The Expanding Universe The shapes of distant galaxies provide further evidence that the law of gravity applies to larger distances. According to current scientific understanding, the universe originated and grew from the explosion of a primordial fireball some 13.7 billion years ago. This is the "Big Bang" theory of the origin of the universe. All the matter of the universe was hurled outward from this event and continues in an outward expansion. Evidence for this includes precise measurements of the earliest remnant of the Big Bang: its cosmic microwave background.

More recent evidence suggests the universe is not only expanding, but *accelerating* outward. It is pushed by an anti-gravity *dark energy* that makes up an estimated 73 percent of the universe. Twenty-three percent of the universe is composed of the yet-to-be discovered particles of exotic *dark matter*. Ordinary matter—the stuff of stars, cabbages, and kings—makes up only 4 percent. The concepts of dark matter and dark energy will continue to inspire exciting research throughout this century. They may hold clues to how the cosmos began and where it is headed, and may be the key to understanding the fate of the universe. Our present view of the universe has progressed appreciably beyond the universe as Newton perceived it.



discover!

MATERIALS no special materials required

EXPECTED OUTCOME With their hands outstretched, most students will see their hands to be about the same size, while a few see the nearer hand as slightly bigger. Almost nobody upon casual inspection sees the nearer hand as four times as big. When they overlap their hands and view them with one eye closed, students will see the nearer hand as clearly bigger.

THINK By the inverse-square law, the nearer hand should appear twice as tall and twice as wide and therefore occupy four times as much of your visual field as the farther hand. However, your belief that your hands are the same size is so strong that you likely overrule this information.

▶ **Teaching Tidbit** When you're looking at stars, do you ever wonder if you're looking at other people's suns?

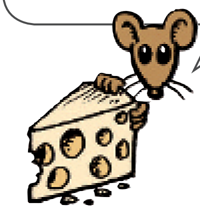
▶ **Teaching Tip** The first great discovery of this 21st century was confirming that other stars have planets—lots of them. In 2007 European astronomers discovered a planet in the habitable zone of Gliese 581, a red dwarf in the constellation Libra. Science types all over the world are thrilled. More and more we come to feel we are not alone in the universe. Ask your class if they think humans will visit another star system someday. Most will likely say yes. But further investigation damps this initial yes. How near is the closest star? How long would humans be prepared to travel? How big will the spaceship have to be? How much energy would be involved? How will time aboard be passed? There's got to be at least a table tennis table! And then some! Whatever happens should be fascinating to those who follow in time.

CONCEPT CHECK The formulation of the law of universal gravitation provided hope that other phenomena of the world might also be described by equally simple and universal laws.

Teaching Resources

- Reading and Study Workbook
- Problem-Solving Exercises in Physics *8-2*
- Presentation*EXPRESS*
- Interactive Textbook

Your author wonders about readers of this book who will continue in their study of physics and help to decipher the nature of dark matter, dark energy, and other wonders of the universe yet to be discovered.



Newton's Impact on Science Few theories have affected science and civilization as much as Newton's theory of gravity. The successes of Newton's ideas ushered in the Age of Reason, or Century of Enlightenment. Newton demonstrated that by observation and reason, people could uncover the workings of the physical universe. How profound it is that all the moons and planets and stars and galaxies have such a beautifully simple rule to govern them, namely,

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

✓ **The formulation of the law of universal gravitation is one of the major reasons for the success in science that followed, for it provided hope that other phenomena of the world might also be described by equally simple and universal laws.**

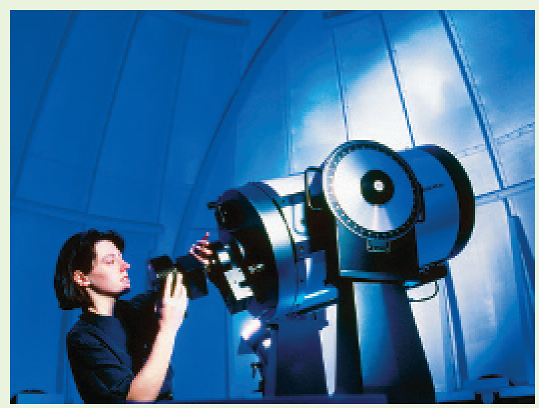
This hope nurtured the thinking of many scientists, artists, writers, and philosophers of the 1700s. One of these was the English philosopher John Locke, who argued that observation and reason, as demonstrated by Newton, should be our best judge and guide in all things. Locke urged that all of nature and even society should be searched to discover any "natural laws" that might exist. Using Newtonian physics as a model of reason, Locke and his followers modeled a system of government that found adherents in the 13 British colonies across the Atlantic. These ideas culminated in the Declaration of Independence and the Constitution of the United States of America.

CONCEPT CHECK How did the formulation of the law of universal gravitation affect science?

Physics on the Job

Astronomer

Astronomers study the physics of nature's extremes—from the coldness of empty space to the fiery hotness of exploding stars, and from tiny elementary particles of matter to the vastness of the universe itself. Astronomers work mainly for university and government observatories. Whereas most of the efforts of early astronomers were in cataloging objects in the sky, astronomers today employ much physics as they study the history of the universe from the Big Bang to the present and seek to understand black holes, "dark matter" and "dark energy." It can truly be said that astronomers are far-out people.



13 REVIEW

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Concept Summary

- Newton reasoned that the moon is falling toward Earth for the same reason an apple falls from a tree—they are both pulled by Earth's gravity.
- The moon is actually falling toward Earth but has great enough tangential velocity to avoid hitting Earth.
- Newton's theory of gravity confirmed the Copernican theory of the solar system.
- Newton discovered that gravity is universal.
- Gravity decreases according to the inverse-square law.
- Earth can be thought of as being surrounded by a gravitational field that causes objects to experience gravitational forces.
- The gravitational field of Earth at its center is zero.
- Force against Earth is the sensation we interpret as weight.
- The ocean tides are caused by *differences* in the gravitational pull of the moon on opposite sides of Earth.
- When a massive star collapses into a black hole, there is no change in the gravitational field at any point beyond the original radius of the star.
- The formulation of the law of universal gravitation provided hope that other phenomena of the world might also be described by equally simple and universal laws.

Key Terms

law of universal gravitation *(p. 237)*
universal gravitational constant *(p. 237)*
inverse-square law *(p. 240)*
gravitational field *(p. 242)*
weightlessness *(p. 246)*
spring tide *(p. 247)*
neap tide *(p. 247)*
black hole *(p. 249)*
perturbation *(p. 252)*

think! Answers

13.5 No, because the twice-as-tall apple tree is not twice as far from Earth's center. The taller tree would have to have a height equal to the radius of Earth (6370 km) before the weight of the apple would reduce to $\frac{1}{4}$N. Before its weight decreases by 1%, an apple or any object must be raised 32 km—nearly four times the height of Mt. Everest, the tallest mountain in the world. So as a practical matter we disregard the effects of everyday changes in elevation.

13.7 You would oscillate back and forth, approximating *simple harmonic motion.* A round trip would take nearly 90 minutes. Interestingly enough, we will see in the next chapter that an Earth satellite in close orbit about Earth also takes the same 90 minutes to make a complete round trip. This is not a coincidence, but a feature of simple harmonic motion (Chapter 25).

13 REVIEW

Teaching Resources

- Teacher*EXPRESS*
- Virtual Physics Labs *15, 16*
- Conceptual Physics Alive! DVDs *Gravity I, II*

13 ASSESS

Check Concepts

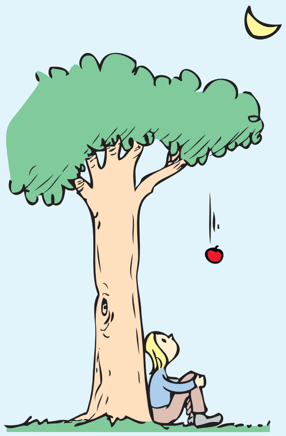
1. Both are falling toward Earth.
2. The moon falls beneath the straight line it would follow if there were no forces acting on it.
3. Tangential velocity must be great enough so that the planet falls around, rather than into, the sun.
4. 6.67×10^{-11} N
5. As the first measure of Earth's mass; once *G* was known, Earth's mass could be determined by a simple calculation.
6. The force of gravity is directly proportional to the product of the masses.
7. Inversely as the square of the distance between their centers
8. The force is 1/4 as much, in accord with the inverse-square law.
9. The intensity is 1/4 as much, in accord with the inverse-square law.
10. No; in the gravitation equation, *d* would have to approach infinity for *F* to approach zero.
11. At no distance from Earth; gravitational force approaches zero with great distances, but never actually reaches zero. (At Earth's center, however, gravitation *cancels* to zero!)
12. True
13. Zero
14. A one-way trip takes ~45 minutes so a round trip takes ~90 minutes.

13 ASSESS

Check Concepts

Section 13.1

1. In Newton's insight, what did a falling apple have in common with the moon?



Section 13.2

2. In what sense does the moon "fall"?

Section 13.3

3. How does the tangential velocity of a planet relate to it orbiting around the sun?

Section 13.4

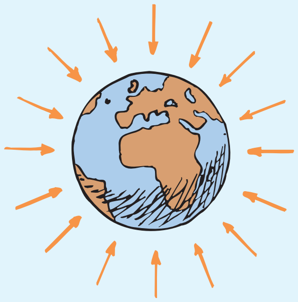
4. What is the gravitational force between two 1-kilogram bodies that are 1 meter apart?
5. When *G* was first measured in the 1700s, how did newspapers report the experiment?
6. In what way does the force of gravity between two objects depend on their masses?

Section 13.5

7. How does the force of gravity depend on the distance between two objects?
8. How does the force of gravity between two bodies change when the distance between them is doubled?
9. How does the intensity of light, radiation, and sound change when a point source is twice as far away?
10. Do you escape from Earth's gravity if you're above the atmosphere? By being on the moon? Defend your answers.
11. At what distance away from Earth is Earth's gravitational force on an object zero?

Section 13.6

12. True or false: The strength of a gravitational field equals the gravitational force per mass on a particle in the field.



Section 13.7

13. What is the value of Earth's gravitational field at the center of Earth?
14. If you stepped into a hole that passed completely through Earth, you'd oscillate down and up. How long would a one-way trip take? How long would a round trip take?

Section 13.8

15. Would the gauge inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that accelerated upward? Downward?

Section 13.9

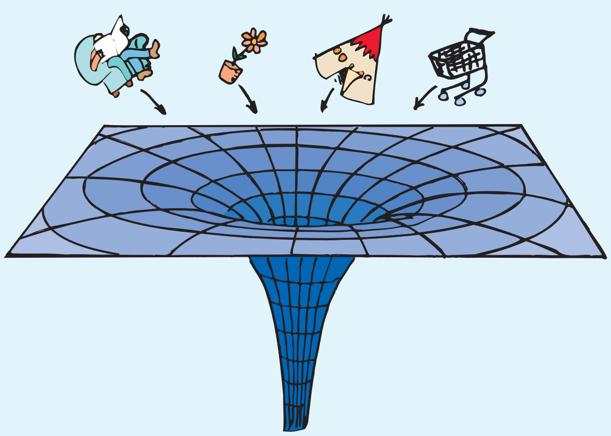
16. Do tides depend more on the strength of gravitational pull or on the *difference* in strengths? Explain.

17. Why are ocean tides higher at the time of a full moon?

Section 13.10

18. What two competing effects determine the size of a star?

19. Why are black holes black?



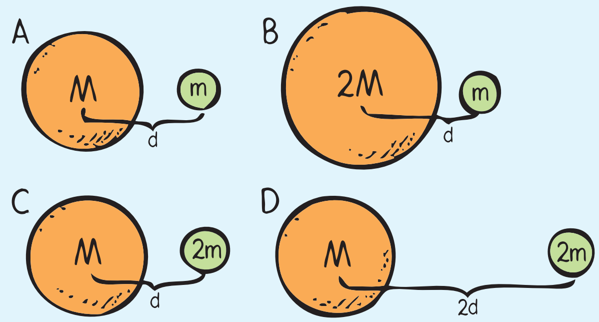
Section 13.11

20. What was the cause of perturbations discovered in the orbit of Planet Uranus?

Think and Rank

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

21. The planet and its moon gravitationally attract each other. Rank gravitational attractions between them from greatest to least.



Plug and Chug

The equation for gravitational force between two bodies separated by a distance is shown below.

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

22. Calculate the force of gravity on a 1-kg mass at Earth's surface. The mass of Earth is 6×10^{24} kg, and its radius is 6.4×10^6 m.

23. Calculate the force of gravity on the same 1-kg mass if it were 6.4×10^6 m above Earth's surface (that is, if it were 2 Earth radii from Earth's center).

15. More compressed; less compressed

16. Tides depend on differences in the strength of gravitational pull. Tides are caused by elongation in the oceans.

17. The sun, the moon, and Earth are aligned at that time, all pulling together.

18. High pressure from the hot interior pushes outward and gravitation pulls inward. When both are in balance, the size of the star is established.

19. They are black because they absorb light without emitting or reflecting it. Hence they are completely dark.

20. Gravity from Neptune

Think and Rank

21. B = C, A, D

Plug and Chug

22. $F = Gm_1m_2/d^2 = (6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2)(1\ \text{kg}) \times (6 \times 10^{24}\ \text{kg})/(6.4 \times 10^6\ \text{m})^2 = 9.77$ N (or rounded, 9.8 N)

23. $F = Gm_1m_2/(2d)^2 = 9.8\ \text{N}/4 = 2.44$ N (or 2.45 N)

24. $F = Gm_1m_2/d^2 =$ $(6.67 \times 10^{-11} \text{N·m}^2/\text{kg}^2) \times$ $(6.0 \times 10^{24} \text{ kg})(7.4 \times 10^{22} \text{ kg})$ $\div (3.8 \times 10^8 \text{ m})^2 =$ 2.1×10^{20} N

25. $F = Gm_1m_2/d^2 =$ $(6.67 \times 10^{-11} \text{N·m}^2/\text{kg}^2) \times$ $(6.0 \times 10^{24} \text{ kg})(2.0 \times 10^{30} \text{ kg})$ $\div (1.5 \times 10^{11} \text{ m})^2 =$ 3.6×10^{22} N

26. $F = Gm_1m_2/d^2 = 2.7 \times 10^{-8}$ N

27. 2.2×10^{-7} N; obstetrician; 8.1 times more

Think and Explain

28. No cause for concern, simply the law of gravity

29. Acceleration of fall = force *per* mass, which is the same for all objects (as learned in Chapter 6).

30. Disagree; the law of gravitation states that the gravitational force on objects of equal masses at the same location is the same.

31. No; the gravitational force is the same on two pieces of paper of equal mass. The crumpled piece falls faster due to reduced air resistance, not an increased gravitational force.

32. Same

33. 500 N toward Earth's center

34. Tangentially in straight-line paths

35. Earth curves proportionally; the 1.4-mm "fall" would bring it closer to Earth; yes, it would move in an ellipse.

13 ASSESS *(continued)*

24. Calculate the force of gravity between Earth (mass = 6.0×10^{24} kg) and the moon (mass = 7.4×10^{22} kg). The average Earth–moon distance is 3.8×10^8 m.

25. Calculate the force of gravity between Earth and the sun (sun's mass = 2.0×10^{30} kg; average Earth–sun distance = 1.5×10^{11} m).

26. Calculate the force of gravity between a newborn baby (mass = 4 kg) and the planet Mars (mass = 6.4×10^{23} kg), when Mars is at its position closest to Earth (distance = 8×10^{10} m).

27. Calculate the force of gravity between a newborn baby of mass 4 kg and the obstetrician of mass 75 kg, who is 0.3 m from the baby. Which exerts more gravitational force on the baby, Mars or the obstetrician? By how much?

Think and Explain

28. Comment on whether or not this label on a consumer product should be cause for concern. *CAUTION: The mass of this product affects every other mass in the universe, with an attractive force that is proportional to the product of the masses and inversely proportional to the square of the distance between them.*

29. Gravitational force acts on all objects in proportion to their masses. Why, then, doesn't a heavy object fall faster than a lighter one? (Is the answer something you learned much earlier?)

30. Irene says that Earth's force of gravity is stronger on a piece of iron than on a piece of wood of the same mass. Do you agree? Defend your answer.

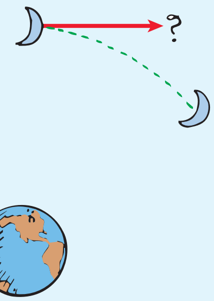
31. Stephan says that the force of gravity is stronger on a piece of paper after it's crumpled. His classmates disagree, so Stephan "proves" his point by dropping two pieces of paper, one crumpled and the other not. Sure enough, the crumpled piece falls faster. Has Stephan proven his point? Explain.

32. Earth and the moon are gravitationally attracted to each other. Does the more massive Earth attract the moon with a greater force, the same force, or less force than the moon attracts Earth?

33. What is the magnitude and direction of the gravitational force that acts on a woman who weighs 500 N at the surface of Earth?

34. If the gravitational forces of the sun on the planets suddenly disappeared, in what kind of paths would the planets move?

35. The moon "falls" 1.4 mm each second. Does this mean that it gets 1.4 mm closer to Earth each second? Would it get closer if its tangential velocity were reduced? Explain.

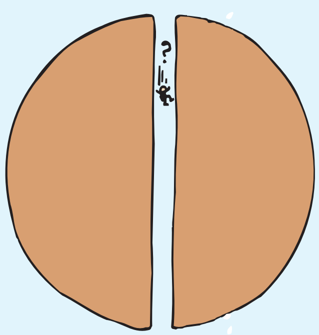


258

36. If the moon were twice as massive, would the attractive force of Earth on the moon be twice as large? Of the moon on Earth?

37. The weight of an apple near the surface of Earth is 1 N. What is the weight of Earth in the gravitational field of the apple?

38. A friend proposes an idea for launching space probes that consists of boring a hole completely through Earth. Your friend reasons that a probe dropped into such a hole would accelerate all the way through and shoot like a projectile out the other side. Defend or oppose the reasoning of your friend.



39. If you stand on a shrinking planet, so that in effect you get closer to its center, your weight will increase. But if you instead burrow into the planet and get closer to its center, your weight will decrease. Explain.

40. If you were unfortunate enough to be in a freely falling elevator, you might notice the bag of groceries you were carrying hovering in front of you, apparently weightless. Cite the frames of reference in which the groceries would be falling, and those in which they would not be falling.

41. What two forces act on you in a moving elevator? When are these forces equal in magnitude, and when are they not?

42. A friend says that astronauts in orbit are weightless because they're beyond the pull of Earth's gravity. Correct your friend's ignorance.

43. The sun exerts almost 200 times more force on the oceans of Earth than the moon does. Why then, is the moon more effective in raising tides?

44. From a point of view at the sun, does the moon circle Earth, or does Earth circle the moon?

45. What would be the effect on Earth's tides if the diameter of Earth were larger than it is? If Earth were as it presently is, but the moon were larger—with the same mass?

46. Whenever the ocean tide is unusually high, will the following low tide be unusually low? Defend your answer in terms of "conservation of water." (If you slosh water in a tub so that it is extra deep at one end, will water at the other end be extra shallow?)

36. Yes; yes; same interaction

37. 1 N

38. The probe will accelerate only toward the center, and then decelerate until it reaches the far end. It will simply oscillate back and forth.

39. At the surface, all the concentrating mass pulls you toward the CG. But if you instead burrow into a planet, the shell "above you" effectively cancels, and doesn't contribute to your downward pull.

40. Falling relative to Earth; not falling relative to the falling elevator

41. Normal and gravitational forces; they are equal in the absence of acceleration but unequal when there is an acceleration.

42. Astronauts are still in the grip of gravity. Weightlessness is due to the absence of a support force.

43. The moon pulls with proportionally more force on the near side of Earth than on the far side. Δg is greater for the moon.

44. Neither; both Earth and the moon circle the center of mass of the Earth–moon system.

45. Greater difference in pulls on the near and far sides, so tides would be greater; no effect

46. Yes; deep water in one area means shallow water in another.

47. No; the effects are too tiny to noticeably affect the body, due to negligible difference in gravity across the body.

48. Gravitation is the same at the same distance from a star before and after it collapses to become a black hole—unless that distance is within the initial radius of the star. After collapse, only those regions within the initial radius have an increase in gravitational field strength because all the mass is now inside those radii that used to have some mass below and some above.

49. From Earth to the moon; more work must be done to move against Earth's gravity.

50. Inconsistent; a recently discovered "dark energy" counters the force of gravity and pushes the universe further outward; explanation is not yet at hand.

51. The radius of Jupiter is greater so there's a greater distance between the object's and Jupiter's CGs.

52. No, because the law of universal gravitation has been demonstrated by experiment

Think and Solve

53. $mg = GmM/R^2$; cancel m to get $g = GM/R^2$.

54. Note that the mass m of a falling object doesn't appear in $g = GM/R^2$. Any mass, m or $2m$, accelerates at g. (The M in the equation is the mass of Earth, not the mass of the falling object.)

55. 1 Newton = 1 kg·m/s^2; so N/kg = kg·m/s^2/kg = m/s^2. (Note that kg cancels.)

56. $m_1(2m_2)/(2d)^2$ = 1/2 as much

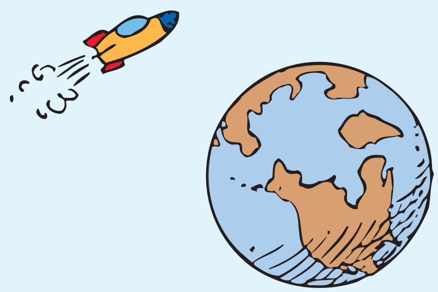
57. From $F = Gm_1m_2/d^2$, $F_{new} = G(2m_1)(2m_2)/(2d)^2 = 4Gm_1m_2/4d^2 = Gm_1m_2/d^2$, which means the force of gravitation is unchanged.

13 ASSESS *(continued)*

47. The human body is more than 50% water. Is it likely that the moon's gravitational pull causes any significant biological tides—cyclic changes in water flow among the body's fluid compartments? (*Hint:* Is any part of your body appreciably closer to the moon than any other part? Is there a *difference* in lunar pulls?)

48. A black hole is no more massive than the star from which it collapsed. Why then, is gravitation so intense near a black hole?

49. Which requires more fuel—a rocket going from Earth to the moon, or a rocket coming from the moon to Earth? Why?



50. Recent evidence indicates that the present expansion of the universe is accelerating. Is this consistent with, or contrary to, the law of gravity? Explain.

51. The planet Jupiter is about 300 times as massive as Earth, but an object on its surface would weigh only 2.5 times as much as it would on Earth. Can you come up with an explanation? (*Hint:* Let the terms in the equation for gravitational force guide your thinking.)

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

Think and Solve

53. Equate your weight mg to Newton's equation for gravitational force,

$$G\frac{mM}{R^2}$$

where M is the mass of Earth and R is Earth's radius. Show that acceleration of free fall is

$$g = \frac{GM}{R^2}$$

54. Isabella drops a chunk of iron of mass m from the roof of her high school and it accelerates at g. Then she ties two chunks of iron together, of mass $2m$. Show that when she drops the double chunk, the acceleration of fall is also g.

55. The symbol g can mean acceleration due to gravity or gravitational field strength. Show that the units of g can be expressed as either m/s^2 or N/kg.

56. By what factor would your weight change if the Earth's diameter were doubled and its mass were also doubled?

57. Find the change in the force of gravity between two objects when both masses are doubled and the distance between them is also doubled.

260

58. If you stood atop a ladder that was so tall that you doubled your distance from Earth's center, how would your weight compare with its present value?

59. Suppose you stood atop a ladder that was so tall that you were three Earth radii from Earth's center. Show that your weight would be one ninth its present value.

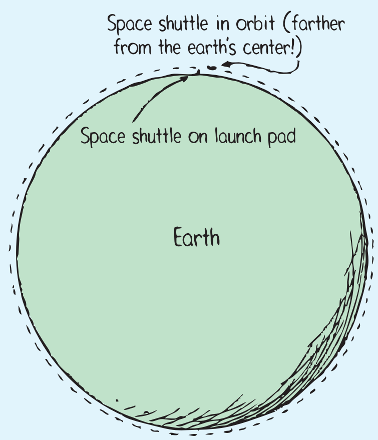
60. Consider a pair of planets that both somehow double in mass while keeping their same distance apart. By what factor does the force of gravity change between them?

61. By what factor does the force of gravity between two planets change when masses remain the same but the distance between them is increased by four?

62. By what factor does the force of gravity between two planets change when the masses remain the same, but the distance between them is *decreased* by four?

63. By what factor does the force of gravity between two planets change when the masses of the planets remain unchanged, but the distance between them is *decreased* by five?

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



More Problem-Solving Practice
Appendix F

58. $W = m_1m_2/(2d)^2 = 1/4$ as much

59. In $F = GmM/d^2$, $(3d)^2$ is $9d^2$, so the new force is one-ninth your surface weight. [$F_{new} = (GmM)/(9d^2) = 1/9(GmM/d^2) = 1/9F_{old}$]

60. In $F = GmM/d^2$, replace m with $2m$ and M with $2M$ to get $4mM$, instead of mM, which means the gravitational force between the two planets is 4 times greater.

61. In $F = GmM/d^2$, replace d by $4d$ to get $16d^2$ in the denominator. Thus the force is reduced to 1/16 of the original force.

62. In $F = GmM/d^2$, $(1/4d)^2$ is $1/16d^2$, so force is 16 times the initial force.

63. In $F = GmM/d^2$, replace d with $1/5d$ to get $1/25d^2$ in the denominator. The force is then 25 times greater than before.

64. Force in orbit ÷ Force on ground = $[GmM/(d + 200\text{ km})^2] \div (GmM/d^2) = d^2/(d + 200\text{ km})^2$ $= (6380\text{ km})^2/(6580\text{ km})^2$ $= 0.94 = 94\%$

Teaching Resources

- Computer Test Bank
- Chapter and Unit Tests