**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)

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**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.

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**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.

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**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.

**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.

**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.

**Common Misconceptions**

- **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.
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.

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 \( \frac{1}{60^2} \) at the moon’s distance? No, as we shall soon see, the influence of gravity should be diluted to \( \frac{1}{60} \) of \( \frac{1}{60^2} \), 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.
CHAPTER 13
UNIVERSAL GRAVITATION

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. 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
- PresentationEXPRESS
- Interactive Textbook
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?
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. 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.

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,\(^{13,4.2}\)

\[ G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2 \]

\( \square \) FIGURE 13.8 The force of gravity between objects depends on the distance between their centers.
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:

$$G = \frac{F}{m_1 m_2 / d^2} = 6.67 \times 10^{-11} \frac{N}{kg^2/m^2} = 6.67 \times 10^{-11} N \cdot m^2/kg^2$$

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.
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, \( 6.4 \times 10^6 \) meters. Therefore, from \( F = (Gm_1m_2d^2) \), 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 \( 6.37 \times 10^6 \). 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 \( \frac{1}{1000} \text{ m} \), or 1 m divided by 10 three times. In scientific notation, 1 mm = \( 10^{-3} \text{ m} \). The gravitational constant \( G \) is a very small number, \( 0.0000000000066726 \text{ N} \cdot \text{m}^2/\text{kg}^2 \). 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.

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**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.

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**Teaching Resources**

- **Reading and Study Workbook**
- **Problem-Solving Exercises in Physics 8-1**
- **PresentationEXPRESS**
- **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.

**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 \( 3 \times 3 \), 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 \( \frac{1}{3} \) 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.
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*
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. 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?

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**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).

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**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
- PresentationEXPRESS
- 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.

**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. 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.

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**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.

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.

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.
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.

**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.
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.

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.
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 continuously 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.

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, 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.
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.
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
- Presentation EXPRESS
- 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.
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.

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!
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.

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**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?

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**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?
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,

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

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?
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 1/4N. 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).
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 \times 10^{-11} \text{ 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.

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?

Section 13.6

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 13.7

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

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 \(6 \times 10^{24}\) kg, and its radius is \(6.4 \times 10^6\) m.

23. Calculate the force of gravity on the same 1-kg mass if it were \(6.4 \times 10^6\) m above Earth’s surface (that is, if it were 2 Earth radii from Earth’s center).
24. Calculate the force of gravity between Earth (mass = 6.0 × 10^{24} \text{ kg}) and the moon (mass = 7.4 × 10^{22} \text{ kg}). The average Earth–moon distance is 3.8 × 10^{8} \text{ m}.

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

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

28. Comment on whether or not this label on a consumer product should be cause for concern. CAUTION: \text{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.
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. 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. 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?)
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/R²; cancel m to get g = GM/R².

54. Note that the mass m of a falling object doesn’t appear in g = GM/R². 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/s²; so N/kg = kg·m/s²/kg = m/s². (Note that kg cancels.)

56. m₁(2m₂)/(2d)² = 1/2 as much

57. From F = Gm₁m₂/d², F₁new = G(2m₁)(2m₂)/(2d)² = 4Gm₁m₂/4d² = Gm₁m₂/d², which means the force of gravitation is unchanged.

58. 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/s² 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.
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 \( \frac{6}{110^2} \times 10^{24} \) kg, and its radius is \( 6.38 \times 10^6 \) 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.