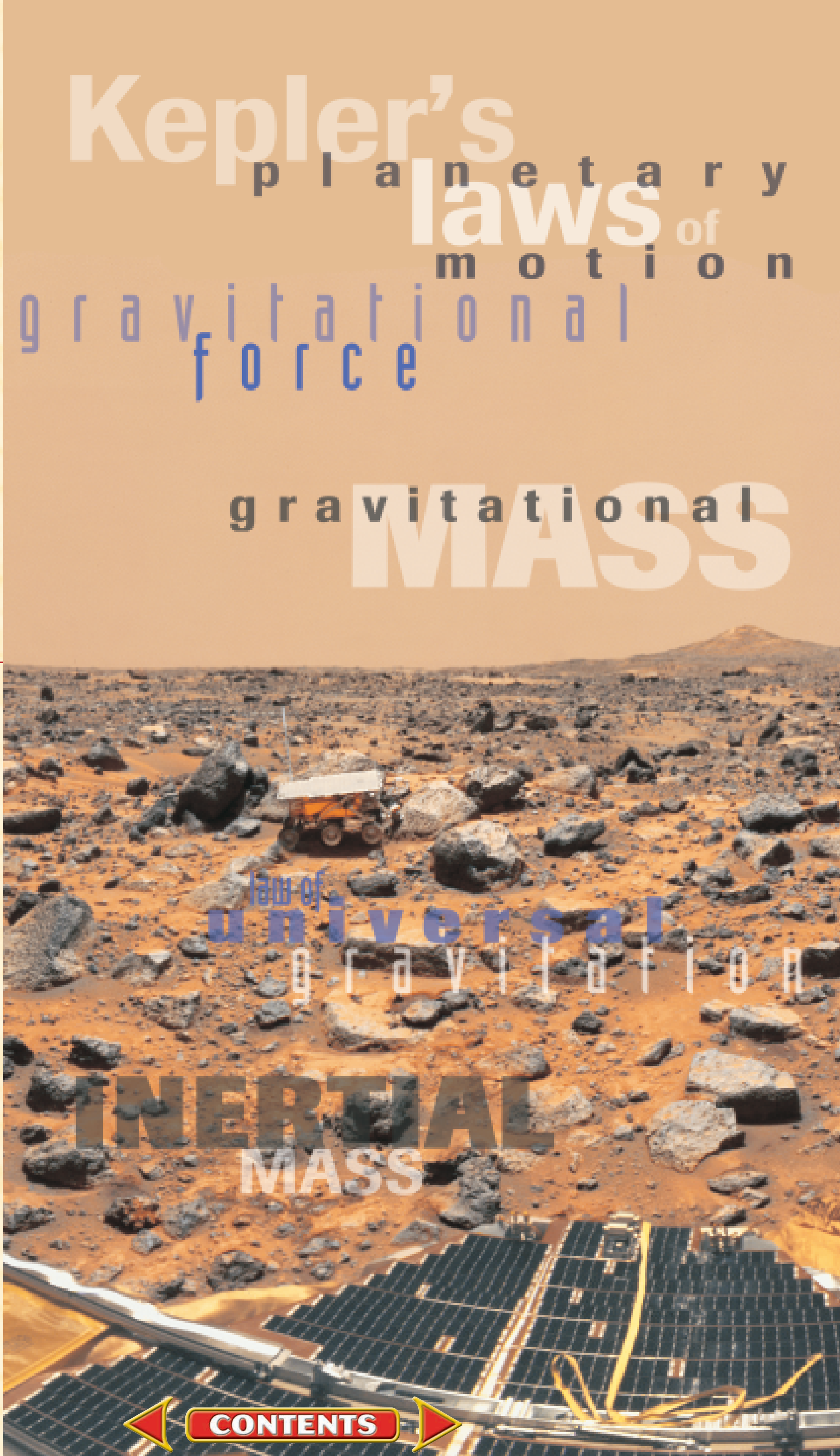


What Goes Up, Must Come Down

***Pathfinder* ferried its rover, *Sojourner,* across millions of kilometers of space to land on Mars. Why were NASA scientists certain that the law of gravitation that's valid on Earth works everywhere in the solar system?**

Look at the text on page 182 for the answer.

CHAPTER

8 Universal Gravitation

Throw anything up in the air—a basketball, a book, a marble, or some popcorn—and you can predict what will happen. You know that each object will fall back to Earth. But why do objects fall toward Earth?

Ancient Greek scientists believed that objects simply either rose or fell according to their nature; such things as hot air and smoke rose, while other things fell, such as rocks and shoes. The Greeks gave the names *levity*, meaning lightweight, and *gravity*, meaning heavy, to these properties. If you were asked "Why do objects fall toward Earth?," you probably would say "because of gravity." But how does the name *gravity* explain why objects fall to Earth?

About 400 years ago, Galileo wrote in response to a statement that "gravity" is why stones fall downward,

> *What I am asking you for is not the name of the thing, but its essence, of which essence you know not a bit more than you know about the essence of whatever moves the stars around . . . we do not really understand what principle or what force it is that moves stones downward.*

During the twentieth century, Albert Einstein gave a more in-depth, and very different, description of gravitational attraction. Nevertheless, today we still know only how things fall, not why. As you study this chapter, you will learn how to describe the motion of objects under gravitational attraction.

WHAT YOU'LL LEARN

- You will learn the nature of the gravitational force.
- You will relate Kepler's laws of planetary motion to Newton's laws of motion.
- You will describe the orbits of planets and satellites using the law of universal gravitation.

WHY IT'S IMPORTANT

- Without a knowledge of universal gravitation, space travel and an understanding of planetary motion would be impossible.

PHYSICS Online

To find out more about universal gravitation, visit the Glencoe Science Web site at **science.glencoe.com**

CLICK HERE

8.1 Motion in the Heavens and on Earth

OBJECTIVES

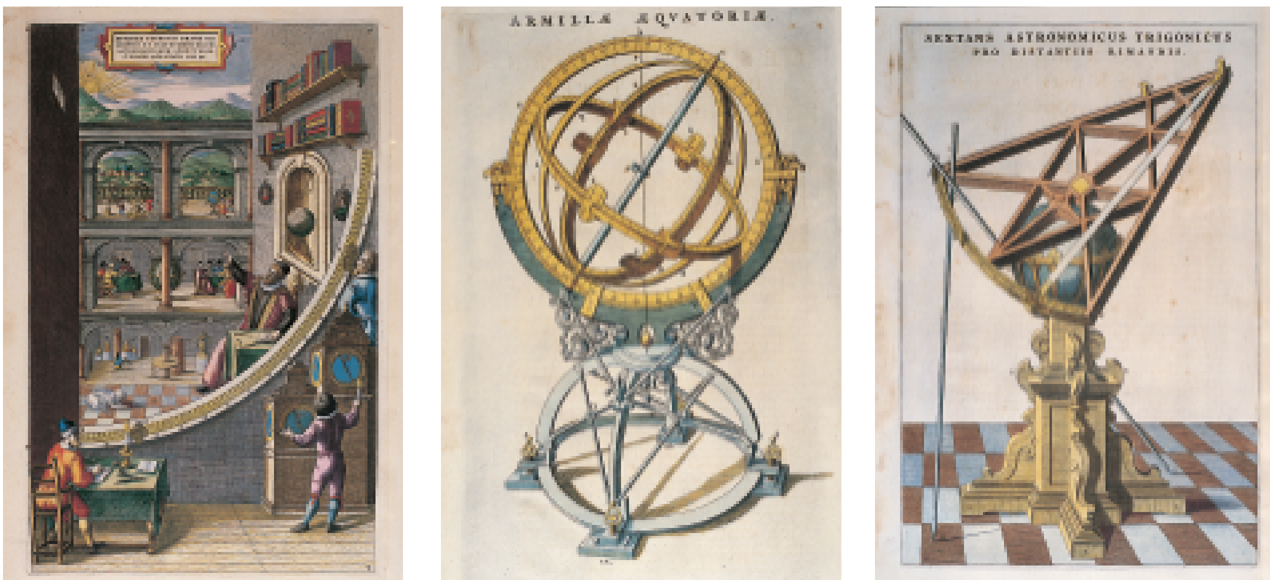
- **Relate** Kepler's laws of planetary motion to Newton's law of universal gravitation.
- **Calculate** the periods and speeds of orbiting objects.
- **Describe** the method Cavendish used to measure *G* and the results of knowing *G*.

We know how objects move on Earth. We can describe and even calculate projectile motion. Early humans could not do that, but they did notice that the motions of stars and other bodies in the heavens were quite different. Stars moved in regular paths. Planets—or wanderers, as they were called—moved through the sky in much more complicated paths. Comets were even more erratic. These mysterious bodies spouting bright tails appeared without warning. Because of the work of Galileo, Kepler, Newton, and others, we now know that all of these objects follow the same laws that govern the motion of golf balls and other objects here on Earth.

Observed Motion

As a boy of 14 in Denmark, Tycho Brahe (1546–1601) observed an eclipse of the sun on August 21, 1560, and vowed to become an astronomer. In 1563, he observed two planets in conjunction, that is, located at the same point in the sky. The date of that event as predicted by all the books of that period was off by two days, so Brahe decided to dedicate his life to making accurate predictions of astronomical events.

Brahe studied astronomy as he traveled throughout Europe for five years. In 1576, he persuaded King Frederick II of Denmark to give him the island of Hven as the site for the finest observatory of its time. Using huge instruments like those shown in **Figure 8–1,** Brahe spent the next 20 years carefully recording the exact positions of the planets and stars.



a　　b　　c

FIGURE 8–1 Among the huge astronomical instruments that Tycho Brahe had constructed to use at Hven **(a)** were an astrolabe **(b)** and a sextant **(c).**

Kepler's laws In 1597, after falling out of favor with the new Danish king, Brahe moved to Prague. There, he became the astronomer to the court of Emperor Rudolph of Bohemia where, in 1600, a 29-year-old German named Johannes Kepler (1571–1630) became one of his assistants. Although Brahe still believed strongly that Earth was the center of the universe, Kepler wanted to use a sun-centered system to explain Brahe's precise data. He was convinced that geometry and mathematics could be used to explain the number, distance, and motion of the planets. By doing a careful mathematical analysis of Brahe's data, Kepler discovered three mathematical laws that describe the behavior of every planet and satellite. **Kepler's laws of planetary motion** can be stated as follows.

1. The paths of the planets are ellipses, with the sun at one focus.

2. An imaginary line from the sun to a planet sweeps out equal areas in equal time intervals. Thus, planets move faster when they are closer to the sun and slower when they are farther away from the sun, as illustrated in **Figure 8–2.**

3. The square of the ratio of the periods of any two planets revolving about the sun is equal to the cube of the ratio of their average distances from the sun. Thus, if T_A and T_B are the planets' periods, and r_A and r_B are their average distances from the sun, the following is true.

Kepler's Third Law $$\left(\frac{T_A}{T_B}\right)^2 = \left(\frac{r_A}{r_B}\right)^3$$

Note that the first two laws apply to each planet, moon, or satellite individually. The third law, however, relates the motion of several satellites about a single body. For example, it can be used to compare the distances and periods of the planets about the sun. It also can be used to compare distances and periods of the moon and artificial satellites orbiting around Earth. **Table 8–1** on the next page shows some of these data.

Pocket Lab

Strange Orbit

Does the moon affect the motion of Earth in its orbit around the sun? Make your prediction. Then, build the following model planet and moon system. Push a small ball of clay onto the end of a drinking straw to represent the moon. Push a larger ball of clay, representing the planet, onto the opposite end. Tape a piece of string to the balance point on the straw so that the straw will stay parallel to the table when it is lifted. Give the moon a gentle push so that it moves in a slow circle.

Analyze and Conclude Does the planet move in response to the motion of the moon? What effect would a more massive moon have on the planet? What might you conclude about Earth's motion?

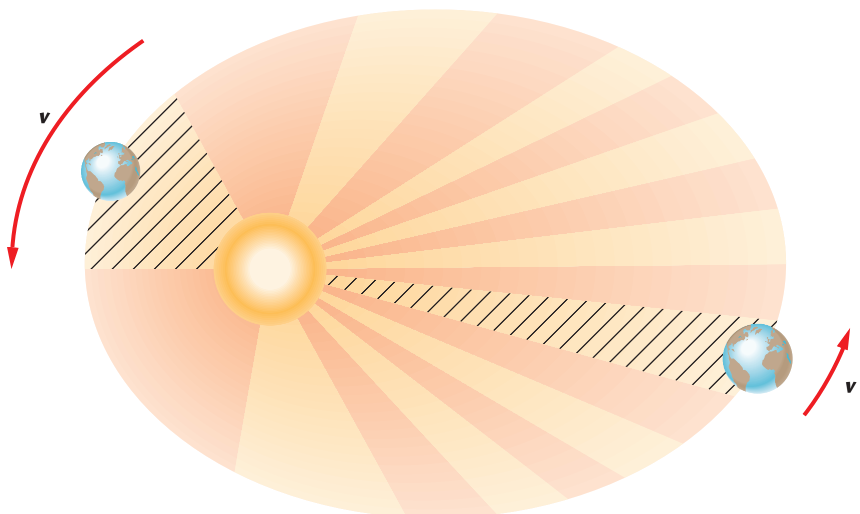


FIGURE 8–2 An imaginary line from Earth to the sun sweeps out equal areas each second, whether Earth is close to or far from the sun.

TABLE 8–1

Planetary Data

Name	Average Radius (m)	Mass (kg)	Mean Distance from Sun (m)
Sun	696×10^6	1.99×10^{30}	–
Mercury	2.44×10^6	3.30×10^{23}	5.79×10^{10}
Venus	6.05×10^6	4.87×10^{24}	1.08×10^{11}
Earth	6.38×10^6	5.97×10^{24}	1.50×10^{11}
Mars	3.40×10^6	6.42×10^{23}	2.28×10^{11}
Jupiter	71.5×10^6	1.90×10^{27}	7.78×10^{11}
Saturn	60.3×10^6	5.69×10^{26}	1.43×10^{12}
Uranus	25.6×10^6	8.66×10^{25}	2.87×10^{12}
Neptune	24.8×10^6	1.03×10^{26}	4.50×10^{12}
Pluto	1.15×10^6	1.5×10^{22}	5.91×10^{12}

Physics & Technology

Global Positioning Systems

Do you find it difficult to navigate around town? If so, then a global positioning system, or GPS, might be just what you need. A GPS consists of two parts: a system of transmitters and a receiver. Transmitters aboard two dozen Earth-orbiting satellites send out radio signals that give the exact time and the location of the satellites when the signals are sent. A handheld GPS receiver, which is about the size of a pocket calculator, determines the time it takes the signals to arrive from the satellites. The receiver then calculates the distance to each satellite. When the distances to at least four different satellites are known, the exact location of the person or object using the receiver can be calculated by triangulation. Then, the latitude, longitude, and altitude—all within about 16 m—of the person or object are displayed on the receiver. And because each satellite carries one or more clocks, which are set to agree with the atomic clocks on Earth, the user of a GPS can tell the time to within a few billionths of a second!

Initially, global positioning systems were used primarily by the U.S. Department of Defense. Today, however, for a few hundred dollars, a person can purchase a GPS receiver that will allow him or her to hike the Rockies or sail the Pacific without getting lost. Geologists who use a GPS are able to measure the rates at which Earth's landmasses are moving. Biologists are trying to use a GPS to track grizzly bears in Yellowstone National Park.

Probably one of the best-known uses of a GPS by a search-and-rescue team occurred in 1995, when the plane piloted by Captain Scott O'Grady was shot down over Bosnia-Herzegovina. After O'Grady had spent four days in enemy territory, rescuers were able to locate him using a GPS.

Thinking Critically In addition to determining an object's location, a GPS can determine its velocity to within 0.03 m/s. Propose a possible method by which a GPS can determine an object's velocity. How would research to improve GPS technology impact and benefit society?

Physics Lab

The Orbit

Problem

How does the gravitational force vary at different points of an elliptical orbit?

Materials

2 pushpins
21-cm × 28-cm piece of cardboard or corkboard
sheet of paper
30-cm piece of string or thread
pencil
metric ruler

Procedure

1. Place the paper on top of the cardboard. Push the pushpins into the paper and cardboard so that they are between 7 and 10 cm apart.
2. Make a loop with the string. Place the loop over the two pushpins. Keep the loop tight as you draw the ellipse, as shown.
3. Remove the pins and string. Draw a small star centered at one of the pinholes.
4. Draw the position of a planet in the orbit where it is farthest from the star. Measure and record the distance from this position to the center of the star.
5. Draw a 1-cm-long force vector from this planet directly toward the star. Label this vector 1.0 ***F***.
6. Draw the position of a planet when it is nearest the star. Measure and record the distance from this position to the star's center.

Data and Observations	
Farthest Distance	
Nearest Distance	

Analyze and Conclude

1. **Calculating Results** Calculate the amount of force on the planet at the closest distance. Gravity is an inverse square force. If the planet is 0.45 times as far as the closest distance, the force is $1/(0.45)^2$ as much, or 4.9 ***F***. Hint: The force will be more than 1.0 ***F***.
2. **Diagramming Results** Draw the force vector, using the correct length and direction, for this position and at two other positions in the orbit. Use the scale 1.0 ***F***: 1.0 cm.

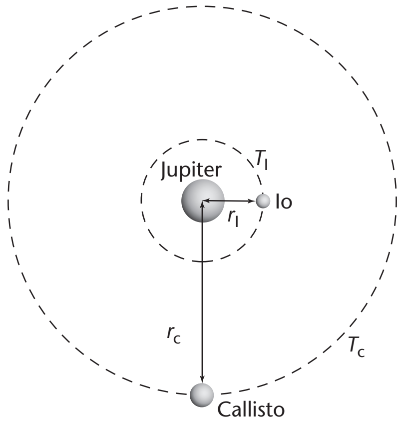
Apply

1. Draw a velocity vector at each planet position to show the direction of motion. Assume that the planet moves in a clockwise pattern on the ellipse. Predict where the planet moves fastest. Use an orbital motion simulation program for a computer to verify your prediction.
2. Look at the direction of the velocity vectors and the direction of the force vectors at each position of the planet. Infer where the planet gains and loses speed. Explain your reasoning.

Example Problem

Kepler's Third Law of Planetary Motion

Galileo discovered the moons of Jupiter. He could measure their orbital sizes only by using the diameter of Jupiter as a unit of measure. He found that Io, which had a period of 1.8 days, was 4.2 units from the center of Jupiter. Callisto, Jupiter's fourth moon, had a period of 16.7 days. Using the same units that Galileo used, predict Callisto's distance from Jupiter.



Sketch the Problem

- Sketch the orbits of Io and Callisto, noting that a longer period implies a larger orbit.
- Label radii and periods.

Calculate Your Answer

Known:

$T_C = 16.7$ days

$T_I = 1.8$ days

$r_I = 4.2$ units

Unknown:

$r_C = ?$

Strategy:

Start with Kepler's third law.

Rearrange to isolate the unknown r_C.

Calculations:

$$\left(\frac{T_C}{T_I}\right)^2 = \left(\frac{r_C}{r_I}\right)^3 \text{ or } r_C{}^3 = r_I{}^3\left(\frac{T_C}{T_I}\right)^2$$

$$r_C{}^3 = (4.2 \text{ units})^3\left(\frac{16.7 \text{ days}}{1.8 \text{ days}}\right)^2$$

$$= 6.4 \times 10^3 \text{ units}^3$$

$$r_C = (6.4 \times 10^3 \text{ units}^3)^{1/3} = 19 \text{ units}$$

Check Your Answer

- Are the units correct? Work algebra on the units to ensure that your answer is in Galileo's units.
- Do the signs make sense? All quantities are positive. Radius and period are never negative.
- Is the magnitude realistic? Expect a larger radius because the period is larger.

Math Handbook

To review **properties of exponents,** see the Math Handbook, Appendix A, page 741.

Practice Problems

1. An asteroid revolves around the sun with a mean (average) orbital radius twice that of Earth's. Predict the period of the asteroid in Earth years.

2. From **Table 8–1,** you can calculate that, on the average, Mars is 1.52 times as far from the sun as Earth is. Predict the time required for Mars to circle the sun in Earth days.
3. The moon has a period of 27.3 days and has a mean distance of 3.90×10^5 km from the center of Earth. Find the period of a satellite that is in orbit 6.70×10^3 km from the center of Earth.
4. Using the data on the period and radius of revolution of the moon in problem 3, predict what the mean distance from Earth's center would be for an artificial satellite that has a period of 1.00 day.

Universal Gravitation

In 1666, some 45 years after Kepler did his work, 24-year-old Isaac Newton was living at home in rural England because an epidemic of the black plague had closed all the schools. Newton had used mathematical arguments to show that if the path of a planet were an ellipse, which was in agreement with Kepler's first law of planetary motion, then the magnitude of the force, F, on the planet resulting from the sun must vary inversely with the square of the distance between the center of the planet and the center of the sun.

$$F \propto \frac{1}{d^2}$$

The symbol $\propto$ means *is proportional to,* and d is the distance between the centers of the two bodies. Newton also showed that the force acted in the direction of the line connecting the centers of the two bodies. But was the force that acted between the planet and the sun the same force that caused objects to fall to Earth?

Newton later wrote that the sight of a falling apple made him think about the problem of the motion of the planets. He recognized that the apple fell straight down because Earth attracted it. He wondered whether this force might extend beyond the trees to the clouds, to the moon, and even beyond. Could gravity be the force that also attracts the planets to the sun? Newton hypothesized that the force on the apple must be proportional to its mass. In addition, according to his own third law of motion, the apple also would attract Earth. Thus, the force of attraction also must be proportional to the mass of Earth. This attractive force that exists between all objects is known as **gravitational force.**

Newton was so confident that the laws governing motion on Earth would work anywhere in the universe that he assumed that the same force of attraction would act between any two masses, m_A and m_B. He proposed his **law of universal gravitation,** which is represented by the following equation.

Law of Universal Gravitation $F = G\frac{m_A m_B}{d^2}$

USING A CALCULATOR

Cube Root

When you use Kepler's third law of motion to find the radius of the orbit of a planet or satellite, first solve for the cube of the radius, then take the cube root. This is easier to do if your calculator has a cube-root key, $\sqrt[3]{x}$. If your calculator has the key y^x or x^y , you also can find the cube root using this key. Check the instructions of your calculator, but you usually enter the cube of the radius, press the y^x key, then enter 0.3333333 and press = .

What Goes Up, Must Come Down

Answers question from page 174.

In the equation, d is the distance between the centers of the masses, and G is a universal constant—one that is the same everywhere. According to Newton's equation, if the mass of a planet near the sun were doubled, the force of attraction would be doubled. Similarly, if the planet were near a star having twice the mass of the sun, the force between the two bodies would be twice as great. In addition, if the planet were twice the distance from the sun, the gravitational force would be only one quarter as strong. **Figure 8–3** illustrates these relationships pictorially, and **Figure 8–4** illustrates them graphically. Because the force depends on $1/d^2$, it is called an inverse square law.

Using Newton's Law of Universal Gravitation

Newton was able to state his law of universal gravitation in terms that applied to the motion of the planets about the sun. This agreed with Kepler's third law of planetary motion and provided confirmation that Newton's law fit the best observations of the day.

You can use the symbol m_p for the mass of a planet, m_s for the mass of the sun, and r for the radius of the planet's orbit. Then, Newton's second law of motion, $F = ma$, can be stated as $F = m_p a_c$, where F is the gravitational force, m_p is the mass, and a_c is the centripetal acceleration of the planet. For the sake of simplicity, assume circular orbits. Recall from your study of uniform circular motion in Chapter 7 that, for a circular orbit, $a_c = 4\pi^2 r/T^2$. This means that $F = m_p a_c$ may now be written as

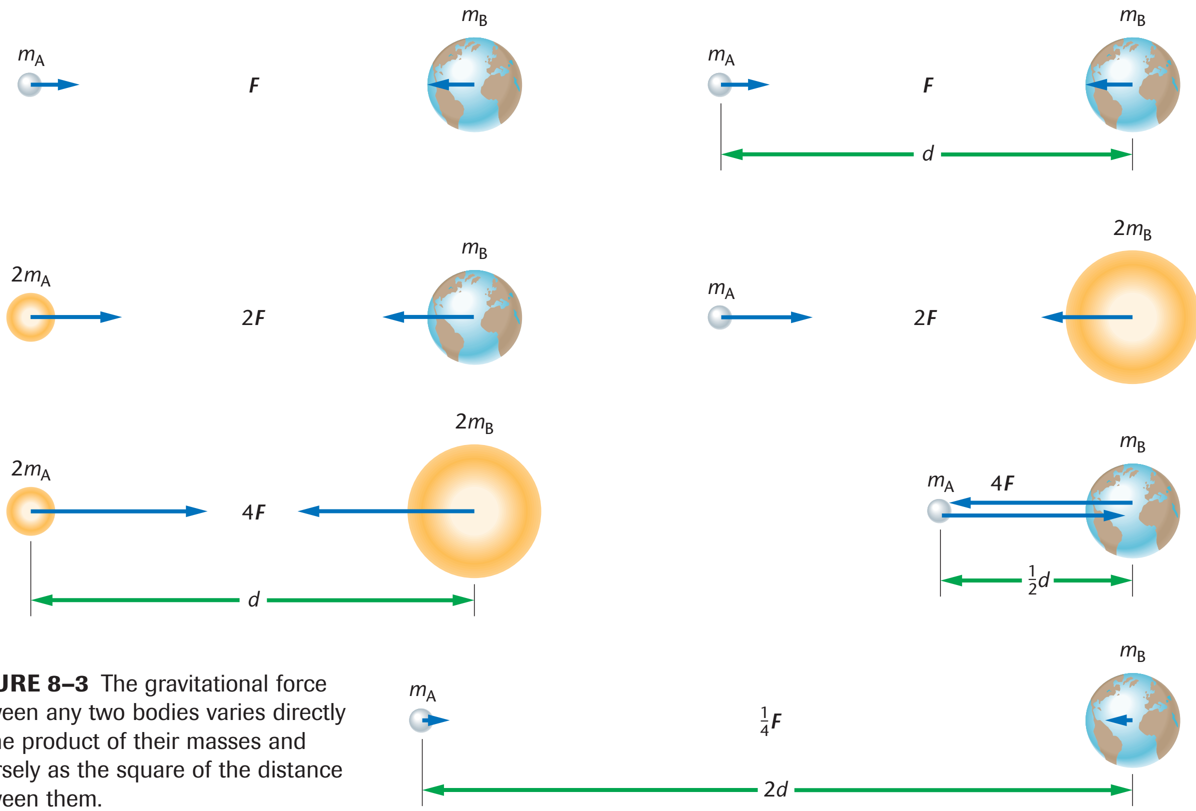


FIGURE 8–3 The gravitational force between any two bodies varies directly as the product of their masses and inversely as the square of the distance between them.

$F = m_p 4\pi^2 r/T^2$. If you set the right side of this equation equal to the right side of Newton's law of universal gravitation, you arrive at the following result.

$$G\frac{m_s m_p}{r^2} = \frac{m_p 4\pi^2 r}{T^2}$$

In this equation, T is the time required for the planet to make one complete revolution about the sun. The equation can be rearranged into the following form.

Period of Planetary Motion $T^2 = \left(\frac{4\pi^2}{Gm_s}\right)r^3$

This equation is Kepler's third law of planetary motion—the square of the period is proportional to the cube of the distance that separates the masses. The proportionality constant, $4\pi^2/Gm_s$, depends only on the mass of the sun and Newton's universal gravitational constant, G. It does not depend on any property of the planet. Thus, Newton's law of universal gravitation leads to Kepler's third law. In the derivation of this equation, it is assumed that the orbits of the planets are circles. Newton found the same result for elliptical orbits.

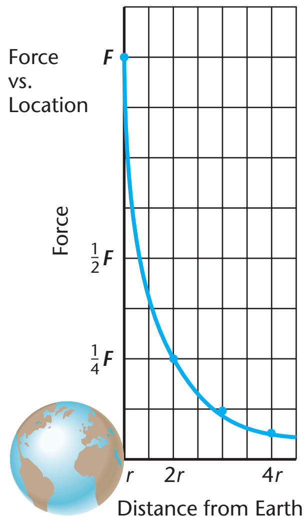


FIGURE 8–4 The change in gravitational force with distance follows the inverse square law.

Weighing Earth

How large is the constant G? As you know, the force of gravitational attraction between two objects on Earth is relatively small. You can't feel the slightest attraction even between two massive bowling balls. In fact, it took 100 years from the time of Newton's work before an apparatus that was sensitive enough to measure the force was developed. In 1798, Englishman Henry Cavendish (1731–1810) used equipment similar to the apparatus sketched in **Figure 8–5** to measure the gravitational force between two objects. Rod A, about 20 cm long, had a small lead ball, B, attached to each end. The rod was suspended by a thin wire, C, so that it could rotate. Cavendish measured the force on the balls that was needed to rotate the rod through given angles by the twisting of the wire. Then he placed a large lead ball, D, close to each of the two small balls. The position of the large balls was fixed. The force of attraction between the large and the small balls caused the rod to rotate. It stopped rotating only when the force required to twist the wire equaled the gravitational forces between the balls. By measuring the angle through which the rod turned, Cavendish was able to calculate the attractive force between the masses. He measured the masses of the balls and the distance between their centers. Substituting these values for force, mass, and distance into Newton's law, he found an experimental value for G. Newton's law of universal gravitation is stated as follows.

$$F = G\frac{m_A m_B}{d^2}$$

When m_A and m_B are measured in kilograms, d in meters, and F in newtons, then $G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$.

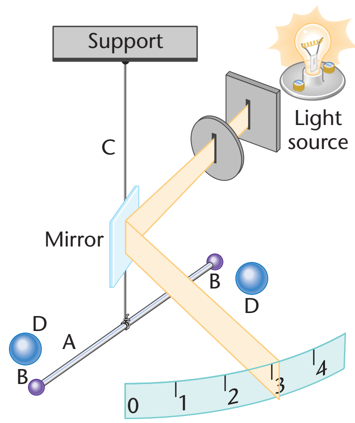


FIGURE 8–5 Cavendish verified the existence of gravitational forces between masses by measuring, with the help of a mirror and light source, the amount of twist in the suspending wire.

Now that you know the value of G, you can use Newton's law to find the gravitational force between two objects. For example, the attractive gravitational force between two bowling balls, each of mass 7.26 kg, with their centers separated by 0.30 m, is represented as follows.

$$F_g = \frac{(6.67 \times 10^{-11} \mathrm{N \cdot m^2/kg^2})(7.26\ \mathrm{kg})(7.26\ \mathrm{kg})}{(0.30\ \mathrm{m})^2} = 3.9 \times 10^{-8}\ \mathrm{N}$$

Cavendish's experiment is often called "weighing the earth." You know that on Earth's surface, the weight of an object of mass m is a measure of Earth's gravitational attraction: $F_g = mg$. According to Newton, however, the following is true.

$$F_g = \frac{Gm_E m}{r^2}, \text{ so } g = \frac{Gm_E}{r^2}$$

Because Cavendish measured the constant G, this equation can be rearranged.

$$m_E = \frac{gr^2}{G}$$

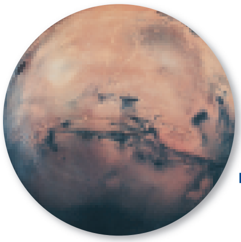
Using 6.38×10^6 m as the radius of Earth, 9.80 m/s^2 as gravitational acceleration, and $G = 6.67 \times 10^{-11}$ N·m^2/kg^2, the following result is obtained.

$$m_E = \frac{(9.80\ \mathrm{m/s^2})(6.38 \times 10^6\ \mathrm{m})^2}{6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}} = 5.98 \times 10^{24}\ \mathrm{kg}$$

When you compare the mass of Earth to that of a bowling ball, you can see why the gravitational attraction between everyday objects is not easily observed.

8.1 Section Review

1. Earth is attracted to the sun by the force of gravity. Why doesn't Earth fall into the sun? Explain.
2. If Earth began to shrink but its mass remained the same, what would happen to the value of g on Earth's surface?
3. Cavendish did his experiment using lead balls. Suppose he had used equal masses of copper instead. Would his value of G be the same or different? Explain.
4. Evaluate the impact of Kepler's research with Brahe's data on scientific thought.
5. **Critical Thinking** Picking up a rock requires less effort on the moon than on Earth.
   - **a.** How will the weaker gravitational force on the moon's surface affect the path of the rock if it is thrown horizontally?
   - **b.** If the rock drops on the thrower's toe, will it hurt more or less than it would on Earth? Explain.



Using the Law of Universal Gravitation

8.2

The planet Uranus was discovered in 1741. By 1830, it was clear that Newton's law of gravitation didn't correctly predict its orbit. This fact puzzled astronomers. Then, two astronomers proposed that Uranus was being attracted not only by the sun but also by an unknown planet, not yet discovered. They calculated the orbit of such a planet in 1845 and, one year later, astronomers at the Berlin Observatory began to search for it. During the first evening of their search, they found the giant planet now called Neptune.

OBJECTIVES

- **Solve** problems involving orbital speed and period.
- **Relate** weightlessness to objects in free fall.
- **Describe** gravitational fields.
- **Distinguish** between inertial mass and gravitational mass.
- **Contrast** Newton's and Einstein's views about gravitation.

Motion of Planets and Satellites

Newton used a drawing similar to the one shown in **Figure 8–6** to illustrate a thought experiment on the motion of satellites. Imagine a cannon, perched high atop a mountain, firing a cannonball horizontally with a given horizontal speed. The cannonball is a projectile, and its motion has both vertical and horizontal components. Like all projectiles on Earth, it follows a parabolic trajectory. During its first second of flight, the ball falls 4.9 m. If its horizontal speed were increased, it would travel farther across the surface of Earth, but it would still fall 4.9 m in the first second of flight. Because the surface of Earth is curved, it is possible for a cannonball with just the right horizontal speed to fall 4.9 m at a point where Earth's surface has curved 4.9 m away from the horizontal. This means that, after one second, the cannonball is at the same height above Earth as it was initially. The curvature of the projectile will continue to just match the curvature of Earth, so that the cannonball never gets any closer or farther away from Earth's curved surface. When this happens, the ball is said to be in orbit.

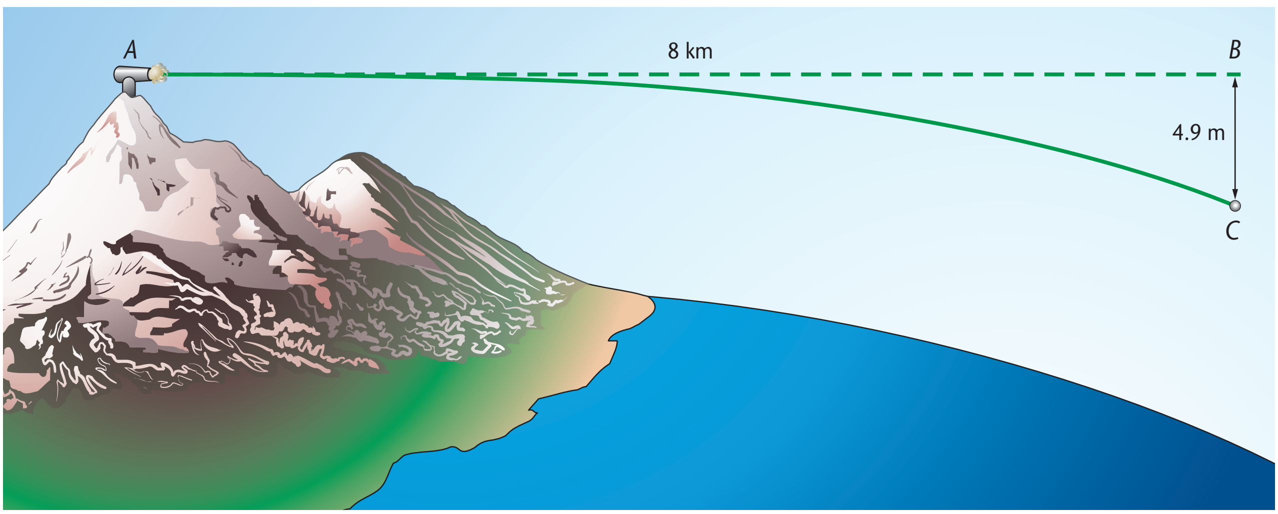


FIGURE 8–6 If the cannonball travels 8 km horizontally in 1 s, it will fall the same distance toward Earth as Earth curves away from the cannonball.

HELP WANTED

PILOT

We need "safety-first" people who can make quick but correct decisions, even under occasionally adverse conditions.

A current FAA commercial license with instrument rating and the ability to continue to pass strict physical, vision, hearing, flying, and rules exams are a must. Graduates of accredited flying schools or colleges or those with military flying experience will be considered equally. For information contact:

Air Line Pilots Association
1625 Massachusetts Ave. NW
Washington, DC 20036

Newton's drawing shows that Earth curves away from a line tangent to its surface at a rate of 4.9 m for every 8 km. That is, the altitude of the line tangent to Earth at A will be 4.9 m above Earth at B. If the cannonball were given just enough horizontal speed to travel from A to B in one second, it would also fall 4.9 m and arrive at C. The altitude of the ball in relation to Earth's surface would not have changed. The cannonball would fall toward Earth at the same rate that Earth's surface curves away. An object at Earth's surface with a horizontal speed of 8 km/s will keep the same altitude and circle Earth as an artificial satellite.

Newton's thought experiment ignored air resistance. The mountain would have had to be more than 150 km above Earth's surface to be above most of the atmosphere. A satellite at or above this altitude encounters little air resistance and can orbit Earth for a long time.

A satellite in an orbit that is always the same height above Earth moves with uniform circular motion. Recall from Chapter 7 that its centripetal acceleration is given by $a_c = v^2/r$. Newton's second law, $F = ma$, can be rewritten as $F = mv^2/r$. Combining this with Newton's inverse square law produces the following equation.

$$\frac{Gm_Em}{r^2} = \frac{mv^2}{r}$$

Solving this for the speed of an object in circular orbit, v, yields the following.

Speed of an Object in Circular Orbit $v = \sqrt{\dfrac{Gm_E}{r}}$

By using Newton's law of universal gravitation, you saw that the time, T, for a satellite to circle Earth is given by the following.

Period for Satellite Circling Earth $T = 2\pi\sqrt{\dfrac{r^3}{Gm_E}}$

Note that both the orbital speed, v, and period, T, are independent of the mass of the satellite.

Satellites are accelerated to the speeds they need to achieve orbit by large rockets, such as the shuttle booster rocket. Because the acceleration of any mass must follow Newton's second law of motion, $F = ma$, more force is required to put a more massive satellite into orbit. Thus, the mass of a satellite is limited by the capability of the rocket used to launch it.

These equations for the speed and period of a satellite can be used for any body in orbit about another. The mass of the central body would replace m_E in the equations, and r would be the distance between the centers of the sun and the orbiting body. If the mass of the central body is much greater than the mass of the orbiting body, then r is equal to the distance between the central body and the orbiting body.

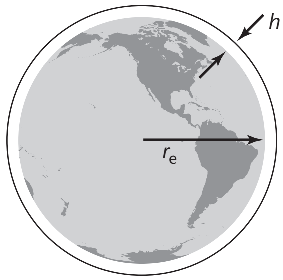
Example Problem

Finding the Speed of a Satellite

A satellite orbits Earth 225 km above its surface. What is its speed in orbit and its period?

Sketch the Problem

- Draw Earth, showing the height of the satellite's orbit.



Calculate Your Answer

Known:	**Unknown:**
$h = 2.25 \times 10^5$ m	$v = ?$
$r_E = 6.38 \times 10^6$ m	$T = ?$
$m_E = 5.97 \times 10^{24}$ kg	
$G = 6.67 \times 10^{-11}$ N·m²/kg²	

Strategy:

Determine the radius of the satellite's orbit by adding the height to Earth's radius.

Calculations:

$$r = h + r_E$$

$$r = 2.25 \times 10^5 \text{ m} + 6.38 \times 10^6 \text{ m} = 6.61 \times 10^6 \text{ m}$$

Use the velocity equation.

$$v = \sqrt{\frac{Gm_E}{r}}$$

$$v = \sqrt{\frac{(6.67 \times 10^{-11} \text{ N·m}^2/\text{kg}^2)(5.97 \times 10^{24} \text{ kg})}{6.61 \times 10^6 \text{ m}}}$$

$$= 7.76 \times 10^3 \text{ m/s}$$

Use the definition of velocity to find the orbital period.

$$v = \frac{d}{t} = \frac{2\pi r}{T}$$

Rearrange and solve for T.

$$T = \frac{2\pi r}{v}$$

$$T = \frac{2(3.14)(6.61 \times 10^6 \text{ m})}{7.76 \times 10^3 \text{ m/s}} = 5350 \text{ s} = 89.2 \text{ min} \approx 1.5 \text{ h}$$

Check Your Answer

- Are the units correct? Be sure that v is in m/s and T is in s.
- Do the signs make sense? Orbital speed and period are always positive.
- Is the magnitude realistic? The speed is close to the 8 km/s obtained in Newton's thought experiment. The period, about 1 1/2 hours, is typical of low Earth orbits.

Pocket Lab

Weight in a Free Fall

Tie a string to the top of a spring scale. Hang a 1.0-kg mass on the spring scale. Hold the scale in your hand.

Analyze and Conclude
Observe the weight of the mass. What will the reading be when the string is released (as the mass and scale are falling)? Why?

Practice Problems

Assume a circular orbit for all calculations.

5. Use Newton's thought experiment on the motion of satellites to solve the following.
  a. Calculate the speed that a satellite shot from the cannon must have in order to orbit Earth 150 km above its surface.
  b. How long, in seconds and minutes, would it take for the satellite to complete one orbit and return to the cannon?

6. Use the data for Mercury in **Table 8–1** to find
  a. the speed of a satellite in orbit 265 km above Mercury's surface.
  b. the period of the satellite.

7. Find the speeds with which Mercury and Saturn move around the sun. Does it make sense that Mercury is named after a speedy messenger of the gods, whereas Saturn is named after the father of Jupiter?

8. The sun is considered to be a satellite of our galaxy, the Milky Way. The sun revolves around the center of the galaxy with a radius of 2.2×10^{20} m. The period of one revolution is 2.5×10^{8} years.
  a. Find the mass of the galaxy.
  b. Assuming that the average star in the galaxy has the same mass as the sun, find the number of stars.
  c. Find the speed with which the sun moves around the center of the galaxy.

Weight and Weightlessness

The acceleration of objects due to Earth's gravitation can be found by using Newton's law of universal gravitation and second law of motion. For a free-falling object,

$$F = \frac{Gm_Em}{d^2} = ma, \text{ so } a = \frac{Gm_E}{d^2}.$$

On Earth's surface, $d = r_E$, and the following equation can be written.

$$g = \frac{Gm_E}{{r_E}^2}$$

Thus,

$$a = g\left(\frac{r_E}{d}\right)^2.$$

As you move farther from Earth's center, that is, as d becomes larger, the acceleration due to gravity is reduced according to this inverse square relationship.

You have probably seen photos similar to the one in **Figure 8–7,** in which astronauts are training for the environment on the space shuttle, often called "zero-g" or "weightlessness." The shuttle orbits Earth about 400 km above its surface. At that distance, $g = 8.7\ m/s^2$, only slightly less than on Earth's surface. Thus, Earth's gravitational force is certainly not zero in the shuttle. In fact, gravity causes the shuttle to circle Earth. Why, then, do the astronauts appear to have no weight? Just as with Newton's cannonball, the shuttle and everything in it are falling freely toward Earth as they orbit around it.

Astronauts have weight because the gravitational force is exerted on them, but do they have any apparent weight? Remember that you sense weight when something such as the floor or your chair exerts a force on you. But if you, your chair, and the floor are all accelerating toward Earth together, then no contact forces are exerted on you. Your apparent weight is zero. You are experiencing weightlessness.

The Gravitational Field

You may recall from Chapter 6 that many common forces are contact forces. Friction is exerted where two objects touch; the floor and your chair or desk push on you. Gravity is different. It acts on an apple falling from a tree and on the moon in orbit; it even acts on you in midair. In other words, gravity acts over a distance. It acts between bodies that are not touching or even close to one another. Newton himself was uneasy with this idea. He wondered how the sun could exert a force on planet Earth, which was hundreds of millions of kilometers away.

The answer to the puzzle arose from a study of magnetism. In the nineteenth century, Michael Faraday developed the concept of the field to explain how a magnet attracts objects. Later, the field concept was applied to gravity. It was proposed that anything with a mass is surrounded by a gravitational field. It is this gravitational field that interacts with objects, resulting in a force of attraction. The field acts on a body at the location of that body.

Pocket Lab

Water, Water, Everywhere

This activity is best done outdoors. Use a pencil to poke a hole in the bottom and side of a cup. Hold your fingers over the two holes as you pour colored water into the cup until it is 2/3 full. Predict what will happen as the cup is allowed to fall. Drop the cup and watch closely.

Analyze and Conclude What happened? Why?

FIGURE 8–7 Astronauts train on Earth in a diving aircraft to practice procedures they will perform in space. They experience about 20 seconds of weightlessness during each dive. In space, however, they would experience weightlessness as long as they were in orbit. A portion of the 1995 class of astronaut candidates poses here for their class picture.

To find the strength of a gravitational field, you can place a small body of mass m in the field and measure the force on the body. The gravitational field, $\boldsymbol{g}$, is defined as the force divided by the mass.

Gravitational Field Strength $\boldsymbol{g} = \dfrac{\boldsymbol{F}}{m}$

Gravitational fields are often measured in newtons per kilogram. The direction of $\boldsymbol{g}$ is in the direction of the force. Recall that $\boldsymbol{g}$ is also called acceleration due to gravity.

On Earth's surface, the strength of the gravitational field is 9.80 N/kg, and its direction is toward Earth's center. From Newton's law of universal gravitation, you know that the gravitational field is independent of the size of an object's mass. The field can be represented by a vector of length g pointing toward the center of the object producing the field being measured. You can picture the gravitational field of Earth as a collection of vectors surrounding Earth and pointing toward it, as shown in **Figure 8–8.** The strength of the field varies inversely with the square of the distance from the center of Earth.

Two Kinds of Mass

When the concept of mass was first introduced in Chapter 6, it was defined as the slope of a graph of force versus acceleration; that is, the ratio of the net force exerted on an object and its acceleration. This kind of mass is related to the inertia of an object and is called the **inertial mass.** The inertial mass of an object is measured by applying a force to the object and measuring its acceleration.

$$m_{\text{inertial}} = \frac{F_{\text{net}}}{a}$$

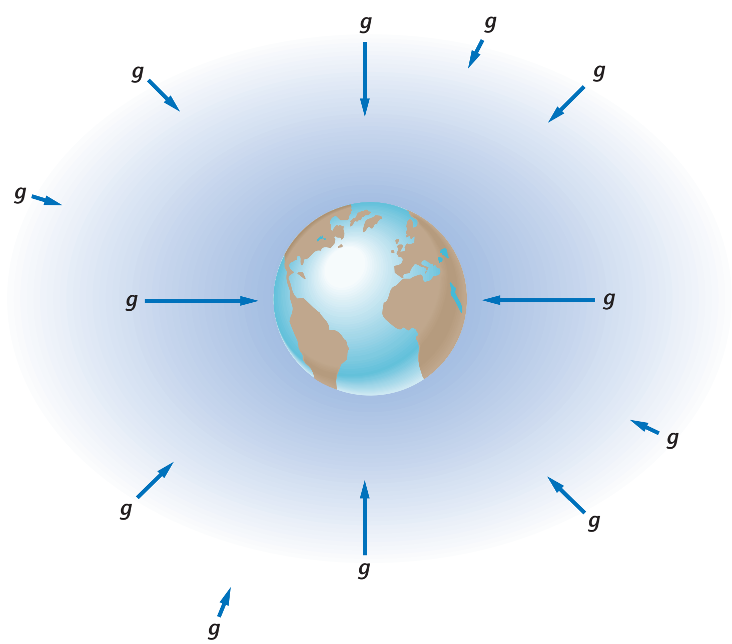


FIGURE 8–8 Vectors can be used to show Earth's gravitational field.

Newton's law of universal gravitation, $F = Gm_Am_B/d^2$, also involves mass, but it is a different kind of mass. Mass as used in the law of gravitation determines the size of the gravitational attraction between two objects. This kind of mass is called **gravitational mass.** It can be measured using a simple balance, such as the one shown in **Figure 8–9.** If you measure the attractive force exerted on an object by another object of mass *m,* at a distance *r,* then you can define the gravitational mass in the following way.

$$m_{\text{gravitational}} = \frac{r^2F_{\text{grav}}}{Gm}$$

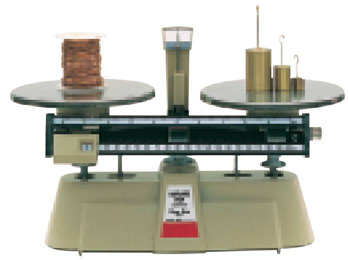


FIGURE 8–9 The platform balance shown here allows you to compare an unknown mass to a known mass. Using an inertial balance, you can calculate the mass from the back-and-forth motion of the mass.

How different are these two kinds of masses? Suppose you have a block of ice in the back of a pickup truck. If you accelerate the truck forward, the ice will slide backwards relative to the bed of the truck. This is a result of its inertial mass—its resistance to acceleration. Now suppose the truck climbs a steep hill at a constant speed. The ice will again slide backwards. But this time, it moves as a result of its gravitational mass. The ice is being attracted downward toward Earth. Newton made the claim that these two masses are identical. This hypothesis is called the principle of equivalence. It has been tested very carefully in many experiments. If any difference exists between the two kinds of mass, it is less than one part in 100 billion. But why should the two masses be equivalent? Albert Einstein (1879–1955) was intrigued by this equivalence and made it a central point in the treatment of gravity in his general theory of relativity.

Einstein's Theory of Gravity

Newton's law of universal gravitation allows us to calculate the force that exists between two bodies because of their masses. The concept of a gravitational field allows us to picture the way gravity acts on bodies far away. However, neither explains the origin of gravity.

F.Y.I.

Little Miss Muffet
Sits on her tuffet
in a nonchalant sort of a way.
With her force field around her
The spider, the bounder,
is not in the picture today.
—Frederick Winsor
The Space Child's Mother Goose

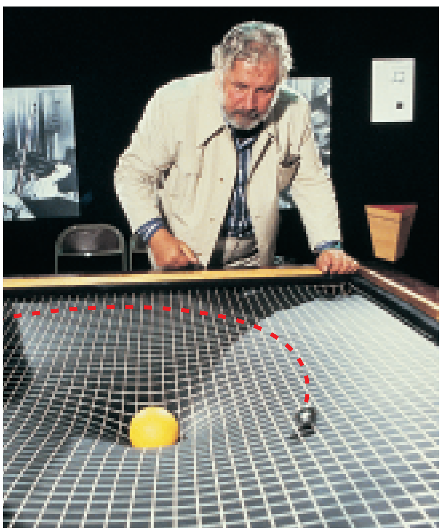


FIGURE 8–10 Matter causes space to curve just as a mass on a rubber sheet curves the sheet around it. Moving bodies near the mass follow the curvature of space, as indicated by the dotted line.

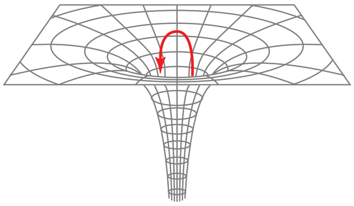


FIGURE 8–11 A black hole is so massive and of such unimaginable density that light leaving it will be bent back to it.

To do this, Einstein proposed that gravity is not a force, but an effect of space itself. According to Einstein, a mass changes the space around it. Mass causes space to be curved, and other bodies are accelerated because of the way they follow this curved space.

One way to picture how space is affected by mass is to compare space to a large, two-dimensional rubber sheet, as shown in **Figure 8–10** on the previous page. The yellow ball on the sheet represents a massive object. It forms an indentation. A marble rolling across the sheet simulates the motion of an object in space. If the marble moves near the sagging region of the sheet, it will be accelerated. In the same way, Earth and the sun are attracted to one another because of the way space is distorted by the two bodies.

Einstein's theory, called the general theory of relativity, makes many predictions about how massive objects affect one another. In every test conducted to date, Einstein's theory has been shown to give the correct results.

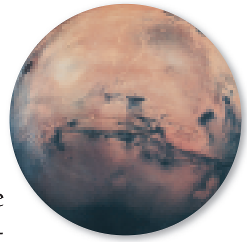
One of the most interesting predictions to come out of Einstein's theory is the deflection of light by massive objects. In 1919, during an eclipse of the sun, astronomers found that light from distant stars that passed near the sun was deflected in agreement with Einstein's predictions. Astronomers have seen light from a distant, bright galaxy bend as it passed by a closer, dark galaxy. The result is two or more images of the bright galaxy. Another result of general relativity is the effect on light of very massive objects. If an object is massive and dense enough, light leaving it will be totally bent back to the object, as **Figure 8–11** shows. No light ever escapes the object. Such an object, called a black hole, is believed to have been identified as a result of its effect on nearby stars.

While Einstein's theory provides very accurate predictions of gravity's effects, it still is not yet complete. It does not explain how masses curve space. Physicists are working to understand the true nature of gravity.

8.2 Section Review

1. What is the strength of the gravitational field on the surface of the moon?
2. Two satellites are in circular orbits about Earth. One is 150 km above the surface, the other 160 km.
   - **a.** Which satellite has the larger orbital period?
   - **b.** Which one has the greater speed?
3. Review Einstein's general theory of relativity. Analyze how mass and gravity are related. Critique both Einstein's theory and Newton's theory. How did Einstein's theory impact how scientists viewed gravity?
4. What is g? Explain in your own words.
5. **Critical Thinking** It is easier to launch a satellite from Earth into an orbit that circles eastward than it is to launch one that circles westward. Explain.

CHAPTER 8 REVIEW



Key Terms

8.1

- Kepler's laws of planetary motion
- gravitational force
- law of universal gravitation

8.2

- inertial mass
- gravitational mass

Summary

8.1 Motion in the Heavens and on Earth

- Kepler's three laws of planetary motion state that planets move in elliptical orbits, that they sweep out equal areas in equal times, and that the square of the ratio of the periods of any two planets is equal to the cube of the ratio of their distances from the sun.
- Newton's law of universal gravitation states that the gravitational force between any two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers. The force is attractive and along a line connecting their centers.
- The mass of the sun can be found from the period and radius of a planet's orbit. The mass of the planet can be found only if it has a satellite orbiting it.
- Cavendish was the first to measure the gravitational attraction between two bodies on Earth.

8.2 Using the Law of Universal Gravitation

- A satellite in a circular orbit accelerates toward Earth at a rate equal to the acceleration of gravity at its orbital radius.
- All bodies have gravitational fields surrounding them that can be represented by a collection of vectors representing the force per unit mass at all locations.
- Gravitational mass and inertial mass are two essentially different concepts. The gravitational and inertial masses of a body, however, are numerically equal.
- Einstein's theory of gravity describes gravitational attraction as a property of space itself.

Key Equations

8.1

$$\left(\frac{T_A}{T_B}\right)^2 = \left(\frac{r_A}{r_B}\right)^3$$

$$F = G\frac{m_A m_B}{d^2}$$

$$T^2 = \left(\frac{4\pi^2}{Gm_s}\right)r^3$$

8.2

$$v = \sqrt{\frac{Gm_E}{r}}$$

$$\boldsymbol{g} = \frac{\boldsymbol{F}}{m}$$

$$T = 2\pi\sqrt{\frac{r^3}{Gm_E}}$$

Reviewing Concepts

Section 8.1

1. In 1609, Galileo looked through his telescope at Jupiter and saw four moons. The name of one of the moons is Io. Restate Kepler's first law for Io and Jupiter.
2. Earth moves more slowly in its orbit during summer in the northern hemisphere than during winter. Is it closer to the sun in summer or in winter?
3. Is the area swept out per unit time by Earth moving around the sun equal to the area swept out per unit time by Mars moving around the sun?
4. Why did Newton think that a force must act on the moon?

5. The force of gravity acting on an object near Earth's surface is proportional to the mass of the object. Why does a heavy object not fall faster than a light object?
6. What information do you need to find the mass of Jupiter using Newton's version of Kepler's third law?
7. The mass of Pluto was not known until a satellite of the planet was discovered. Why?
8. How did Cavendish demonstrate that a gravitational force of attraction exists between two small bodies?

Section 8.2

9. What provides the force that causes the centripetal acceleration of a satellite in orbit?
10. How do you answer the question, "What keeps a satellite up?"
11. A satellite is going around Earth. On which of the following does the speed depend?
    a. mass of the satellite
    b. distance from Earth
    c. mass of Earth
12. Chairs in an orbiting spacecraft are weightless. If you were on board and you were barefoot, would you stub your toe if you kicked a chair? Explain.
13. During space flight, astronauts often refer to forces as multiples of the force of gravity on Earth's surface. What does a force of 5 g mean to an astronaut?
14. Show that the dimensions of g in the equation $g = F/m$ are m/s^2.
15. Newton assumed that the gravitational force acts directly between Earth and the moon. How does Einstein's view of the attractive force between the two bodies differ from the view of Newton?

Applying Concepts

16. Tell whether each of the orbits shown in **Figure 8–12** is a possible orbit for a planet.

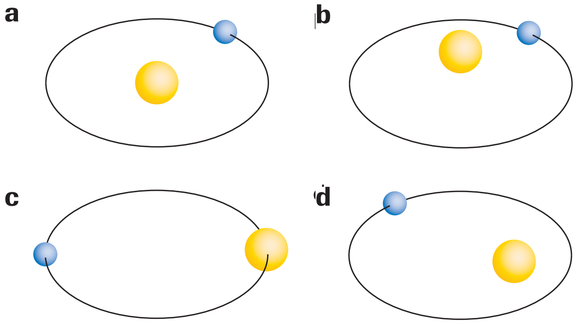


FIGURE 8–12

17. What happens to the gravitational force between two masses when the distance between the masses is doubled?
18. The moon and Earth are attracted to each other by gravitational force. Does the more massive Earth attract the moon with a greater force than the moon attracts Earth? Explain.
19. According to Newton's version of Kepler's third law, how does the ratio $\left(\frac{T^2}{r^3}\right)$ change if the mass of the sun is doubled?
20. If Earth were twice as massive but remained the same size, what would happen to the value of G?
21. Examine the equation relating the speed of an orbiting satellite and the distance from the center of Earth.
    a. Does a satellite with a large or small orbital radius have the greater velocity?
    b. When a satellite is too close to Earth, it can move into the atmosphere where there is air drag. As a result, its orbit gets smaller. Does its speed increase or decrease?
22. If a space shuttle goes into a higher orbit, what happens to the shuttle's period?
23. Mars has about one-ninth the mass of Earth. Satellite M orbits Mars with the same orbital radius as satellite E, which orbits Earth. Which satellite has a smaller period?
24. A satellite is one Earth radius above the surface of Earth. How does the acceleration due to gravity at that location compare to acceleration at the surface of Earth?
25. If Earth were twice as massive but remained the same size, what would happen to the value of g?
26. Jupiter has about 300 times the mass of Earth and about ten times Earth's radius. Estimate the size of g on the surface of Jupiter.
27. If a mass in Earth's gravitational field is doubled, what will happen to the force exerted by the field upon the mass?

28. Suppose that yesterday you had a mass of 50.0 kg. This morning you stepped on a scale and found that you had gained weight.
a. What happened, if anything, to your mass?
b. What happened, if anything, to the ratio of your weight to your mass?

29. As an astronaut in an orbiting space shuttle, how would you go about "dropping" an object down to Earth?

30. The weather pictures you see every day on TV come from a spacecraft in a stationary position relative to the surface of Earth, 35 700 km above Earth's equator. Explain how it can stay exactly in position day after day. What would happen if it were closer? Farther out? **Hint:** Draw a pictorial model.

Problems

Section 8.1

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

31. Jupiter is 5.2 times farther from the sun than Earth is. Find Jupiter's orbital period in Earth years.

32. An apparatus like the one Cavendish used to find G has a large lead ball that is 5.9 kg in mass and a small one that is 0.047 kg. Their centers are separated by 0.055 m. Find the force of attraction between them.

33. Use the data in **Table 8–1** to compute the gravitational force that the sun exerts on Jupiter.

34. Tom has a mass of 70.0 kg and Sally has a mass of 50.0 kg. Tom and Sally are standing 20.0 m apart on the dance floor. Sally looks up and sees Tom. She feels an attraction. If the attraction is gravitational, find its size. Assume that both Tom and Sally can be replaced by spherical masses.

35. Two balls have their centers 2.0 m apart. One ball has a mass of 8.0 kg. The other has a mass of 6.0 kg. What is the gravitational force between them?

36. Two bowling balls each have a mass of 6.8 kg. They are located next to each other with their centers 21.8 cm apart. What gravitational force do they exert on each other?

37. Assume that you have a mass of 50.0 kg and Earth has a mass of 5.97×10^{24} kg. The radius of Earth is 6.38×10^{6} m.
a. What is the force of gravitational attraction between you and Earth?
b. What is your weight?

38. The gravitational force between two electrons 1.00 m apart is 5.42×10^{-71} N. Find the mass of an electron.

39. A 1.0-kg mass weighs 9.8 N on Earth's surface, and the radius of Earth is roughly 6.4×10^{6} m.
a. Calculate the mass of Earth.
b. Calculate the average density of Earth.

40. Use the information for Earth in **Table 8–1** to calculate the mass of the sun, using Newton's version of Kepler's third law.

41. Uranus requires 84 years to circle the sun. Find Uranus's orbital radius as a multiple of Earth's orbital radius.

42. Venus has a period of revolution of 225 Earth days. Find the distance between the sun and Venus as a multiple of Earth's orbital radius.

43. If a small planet were located 8.0 times as far from the sun as Earth is, how many years would it take the planet to orbit the sun?

44. A satellite is placed in an orbit with a radius that is half the radius of the moon's orbit. Find its period in units of the period of the moon.

45. Two spherical balls are placed so that their centers are 2.6 m apart. The force between the two balls is 2.75×10^{-12} N. What is the mass of each ball if one ball is twice the mass of the other ball?

46. The moon is 3.9×10^{5} km from Earth's center and 1.5×10^{8} km from the sun's center. If the masses of the moon, Earth, and the sun are 7.3×10^{22} kg, 6.0×10^{24} kg, and 2.0×10^{30} kg, respectively, find the ratio of the gravitational forces exerted by Earth and the sun on the moon.

47. A force of 40.0 N is required to pull a 10.0-kg wooden block at a constant velocity across a smooth glass surface on Earth. What force would be required to pull the same wooden block across the same glass surface on the planet Jupiter?

48. Mimas, one of Saturn's moons, has an orbital radius of 1.87×10^{8} m and an orbital period of about 23 h. Use Newton's version of Kepler's third law and these data to find Saturn's mass.

49. Use Newton's version of Kepler's third law to find the mass of Earth. The moon is 3.9×10^8 m away from Earth, and the moon has a period of 27.33 days. Compare this mass to the mass found in problem 39.

Section 8.2

50. A geosynchronous satellite is one that appears to remain over one spot on Earth. Assume that a geosynchronous satellite has an orbital radius of 4.23×10^7 m.
    a. Calculate its speed in orbit.
    b. Calculate its period.
51. The asteroid Ceres has a mass of 7×10^{20} kg and a radius of 500 km.
    a. What is g on the surface?
    b. How much would an 85-kg astronaut weigh on Ceres?
52. A 1.25-kg book in space has a weight of 8.35 N. What is the value of the gravitational field at that location?
53. The moon's mass is 7.34×10^{22} kg, and it is 3.8×10^8 m away from Earth. Earth's mass can be found in **Table 8–1.**
    a. Calculate the gravitational force of attraction between Earth and the moon.
    b. Find Earth's gravitational field at the moon.
54. Earth's gravitational field is 7.83 N/kg at the altitude of the space shuttle. What is the size of the force of attraction between a student with a mass of 45.0 kg and Earth?
55. On July 19, 1969, *Apollo 11's* orbit around the moon was adjusted to an average orbit of 111 km. The radius of the moon is 1785 km, and the mass of the moon is 7.3×10^{22} kg.
    a. How many minutes did *Apollo 11* take to orbit the moon once?
    b. At what velocity did it orbit the moon?
56. The radius of Earth is about 6.38×10^3 km. A 7.20×10^3-N spacecraft travels away from Earth. What is the weight of the spacecraft at the following distances from Earth's surface?
    a. 6.38×10^3 km
    b. 1.28×10^4 km
57. How high does a rocket have to go above Earth's surface before its weight is half what it would be on Earth?
58. The following formula represents the period of a pendulum, T.

$$T = 2\pi\sqrt{\frac{l}{g}}$$

    a. What would be the period of a 2.0-m-long pendulum on the moon's surface? The moon's mass is 7.34×10^{22} kg, and its radius is 1.74×10^6 m.
    b. What is the period of this pendulum on Earth?

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

59. Some people say that the tides on Earth are caused by the pull of the moon. Is this statement true?
    a. Determine the forces that the moon and the sun exert on a mass, m, of water on Earth. Your answer will be in terms of m with units of N.
    b. Which celestial body, the sun or the moon, has a greater pull on the waters of Earth?
    c. Determine the difference in force exerted by the moon on the water at the near surface and the water at the far surface (on the opposite side of Earth), as illustrated in **Figure 8–13.** Again, your answer will be in terms of m with units of N.

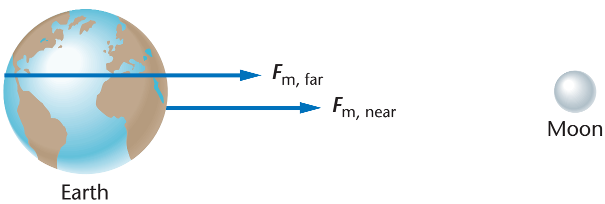


FIGURE 8–13

    d. Determine the difference in force exerted by the sun on water at the near surface and water at the far surface (on the opposite side of Earth).

e. Which celestial body has a greater difference in pull from one side of Earth to the other?

f. Why is the statement that the tides are due to the pull of the moon misleading? Make a correct statement to explain how the moon causes tides on Earth.

60. Graphing Calculator Use Newton's law of universal gravitation to find an equation where x is equal to an object's distance from Earth's center, and y is its acceleration due to gravity. Use a graphing calculator to graph this equation, using 6400-6600 km as the range for x and 9-10 m/s^2 as the range for y. The equation should be of the form $y = c(1/x^2)$. Trace along this graph and find y

a. at sea level, 6400 km.

b. on top of Mt. Everest, 6410 km.

c. in a typical satellite orbit, 6500 km.

d. in a much higher orbit, 6600 km.

Mt. Everest

Going Further

Team Project Design a set of sports competitions to be held in the human base camp on Mars. Assume that Martian explorers would live in a dome filled with an atmosphere at normal Earth pressure and temperature, and that they would wear suits to keep them warm and provide air to breathe when they were outside the dome.

You will need to determine how each sports event would be affected by the Martian gravity and, if the event were to be held outside, how it would be affected by the extremely thin, dry, oxygen-free atmosphere. Consider, for example, how high a bar the high jumpers could clear. How would a discus, shot put, or javelin event have to be adjusted? If there were a pool under the dome, would the swimming and diving events have to be designed in a different way from those on Earth? Could you invent an event that would work only on Mars and not on Earth?

Each team should decide on the new rules for a set of events in one area and create a poster presentation of its designs. The links to physics should be highlighted.

Essay Research and describe the historical development of the concept of gravitational force. Be sure to include Kepler's and Newton's contributions to gravitational physics.

Team Project Review Kepler's third law of planetary motion. Using data for each planet in our solar system, analyze the law. Using your results, critique Kepler's law. Did you find any discrepancies? If so, explain possible reasons. Do you think the law holds up for planets in our solar system? Explain.

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