

# 4

## Making Sense of the Universe

### Understanding Motion, Energy, and Gravity

#### LEARNING GOALS

##### 4.1 Describing Motion: Examples from Daily Life

- How do we describe motion?
- How is mass different from weight?

##### 4.2 Newton's Laws of Motion

- How did Newton change our view of the universe?
- What are Newton's three laws of motion?

##### 4.3 Conservation Laws in Astronomy

- What keeps a planet rotating and orbiting the Sun?
- Where do objects get their energy?

##### 4.4 The Force of Gravity

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?
- How do gravity and energy allow us to understand orbits?
- How does gravity cause tides?



The same laws that govern motion on Earth also govern gargantuan collisions between galaxies.

The history of the universe is essentially a story about the interplay between matter and energy. This interplay began in the Big Bang and continues today in everything from the microscopic jiggling of atoms to gargantuan collisions of galaxies. Understanding the universe therefore depends on becoming familiar with how matter responds to the ebb and flow of energy.

You might guess that it would be difficult to understand the many interactions that shape the universe, but we now know that just a few physical laws govern the movements of everything from atoms to galaxies. The Copernican revolution spurred the discovery of these laws, and Galileo deduced some of them from his experiments. But it was Sir Isaac Newton who put all the pieces together into a simple system of laws describing both motion and gravity.

In this chapter, we'll discuss Newton's laws of motion, the laws of conservation of angular momentum and of energy, and the universal law of gravitation. Understanding these laws will enable you to make sense of many of the wide-ranging phenomena you will encounter as you study astronomy.

## 4.1 Describing Motion: Examples from Daily Life

We all have experience with motion and a natural intuition as to what motion is, but in science we need to define our ideas and terms precisely. In this section, we'll use examples from everyday life to explore some of the fundamental ideas of motion.

### • How do we describe motion?

You are probably familiar with common terms used to describe motion in science, such as *velocity*, *acceleration*, and *momentum*. However, their scientific definitions may differ subtly from those you use in casual conversation. Let's investigate the precise meanings of these terms.

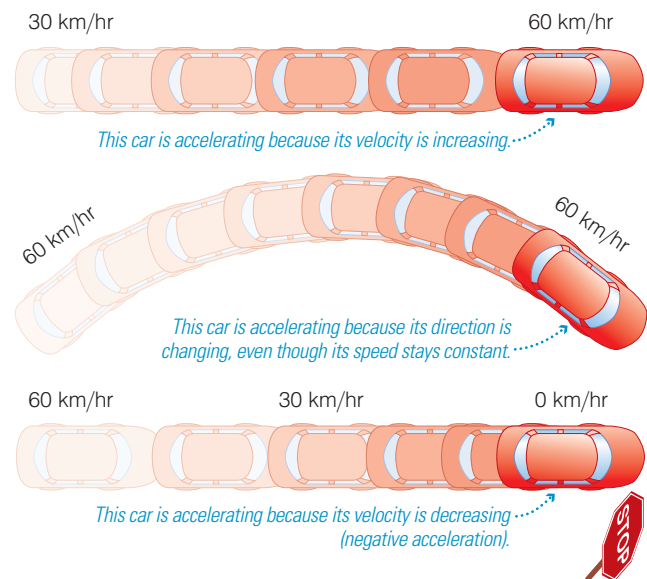
**Speed, Velocity, and Acceleration** A car provides a good illustration of the three basic terms that we use to describe motion:

- The **speed** of the car tells us how far it will go in a certain amount of time. For example, "100 kilometers per hour" (about 60 miles per hour) is a speed, and it tells us that the car will cover a distance of 100 kilometers if it is driven at this speed for an hour.
- The **velocity** of the car tells us both its speed and its direction. For example, "100 kilometers per hour going due north" describes a velocity.
- The car has an **acceleration** if its velocity is changing in any way, whether in speed or direction or both.

Note that while we normally think of *acceleration* as an increase in speed, in science we also say that you are accelerating when you slow down or turn (Figure 4.1). Slowing represents a negative acceleration, causing your

### Essential Preparation

1. How is Earth moving through space? [Section 1.3]
2. How did Copernicus, Tycho, and Kepler challenge the Earth-centered model? [Section 3.3]
3. What are Kepler's three laws of planetary motion? [Section 3.3]



**FIGURE 4.1** Speeding up, turning, and slowing down are all examples of acceleration.

An object is accelerating if either its speed or its direction is changing.

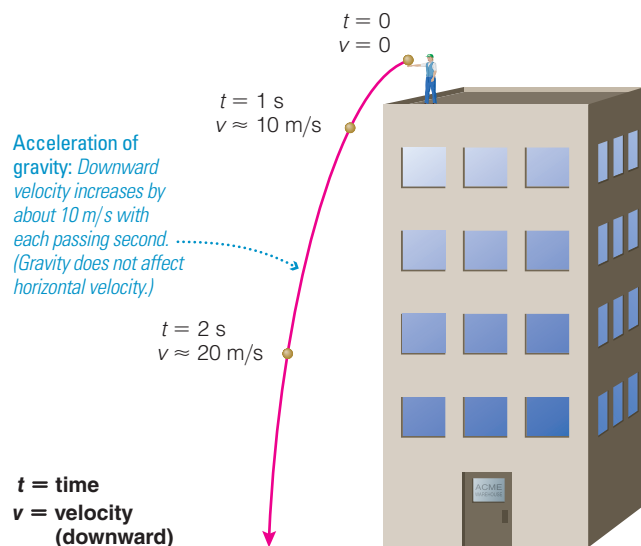
velocity to decrease. Turning means a change in direction—which therefore means a change in velocity—so turning is a form of acceleration even if your speed remains constant.

You can often feel the effects of acceleration. For example, as you speed up in a car, you feel yourself being pushed back into your seat. As you slow down, you feel yourself being pulled forward. As you drive around a curve, you feel yourself being pushed away from the direction of your turn. In contrast, you don't feel such effects when moving at *constant velocity*. That is why you don't feel any sensation of motion when you're traveling in an airplane on a smooth flight.

**The Acceleration of Gravity** One of the most important types of acceleration is the acceleration caused by gravity. In a legendary experiment in which he supposedly dropped weights from the Leaning Tower of Pisa, Galileo demonstrated that gravity accelerates all objects by the same amount, regardless of their mass. This fact may be surprising because it seems to contradict everyday experience: A feather floats gently to the ground, while a rock plummets. However, air resistance causes this difference in acceleration. If you dropped a feather and a rock on the Moon, where there is no air, both would fall at exactly the same rate.

**see it for yourself** ► Find a piece of paper and a small rock. Hold both at the same height and let them go at the same instant. The rock, of course, hits the ground first. Next, crumple the paper into a small ball and repeat the experiment. What happens? Explain how this experiment suggests that gravity accelerates all objects by the same amount.

The acceleration of a falling object is called the **acceleration of gravity**, abbreviated  $g$ . On Earth, the acceleration of gravity causes falling objects to fall faster by 9.8 meters per second (m/s), or about 10 m/s, with each passing second. For example, suppose you drop a rock from a tall building. At the moment you let it go, its speed is 0 m/s. After 1 second, the rock will be falling downward at about 10 m/s. After 2 seconds, it will be falling at about 20 m/s. In the absence of air resistance, its speed will continue to increase by about 10 m/s each second until it hits the ground (Figure 4.2). We therefore say that the acceleration of gravity is about 10 *meters per second per second*, or 10 *meters per second squared*, which we write as  $10 \text{ m/s}^2$  (more precisely,  $g = 9.8 \text{ m/s}^2$ ).



**FIGURE 4.2**

On Earth, gravity causes an unsupported object to accelerate downward at about  $10 \text{ m/s}^2$ , which means its downward velocity increases by about 10 m/s with each passing second. (Gravity does not affect horizontal velocity.)

**Momentum and Force** The concepts of speed, velocity, and acceleration describe how an individual object moves, but most of the interesting phenomena we see in the universe result from *interactions* between objects. We need two additional concepts to describe these interactions:

- An object's **momentum** is the product of its mass and its velocity; that is, momentum = mass  $\times$  velocity.
- The only way to change an object's momentum is to apply a **force** to it.

We can understand these concepts by considering the effects of collisions. Imagine that you're stopped in your car at a red light when a bug flying at a velocity of 30 km/hr due south slams into your windshield. What will happen to your car? Not much, except perhaps a bit of a mess on your windshield. Next, imagine that a 2-ton truck runs the red light and hits you head-on with the same velocity as the bug. Clearly, the truck will cause far more damage. We can understand why by considering the momentum and force in each collision.



Before the collisions, the truck's much greater mass means it has far more momentum than the bug, even though both the truck and the bug are moving with the same velocity. During the collisions, the bug and the truck each transfer some of their momentum to your car. The bug has very little momentum to give to your car, so it does not exert much of a force. In contrast, the truck imparts enough of its momentum to cause a dramatic and sudden change in your car's momentum. You feel this sudden change in momentum as a force, and it can do great damage to you and your car.

The mere presence of a force does not always cause a change in momentum. For example, a moving car is always affected by forces of air resistance and friction with the road—forces that will slow your car if you take your foot off the gas pedal. However, you can maintain a constant velocity, and hence constant momentum, if you step on the gas pedal hard enough to overcome the slowing effects of these forces.

In fact, forces of some kind are always present, such as the force of gravity or the electromagnetic forces acting between atoms. The **net force** (or *overall force*) acting on an object represents the combined effect of all the individual forces put together. There is no net force on your car when you are driving at constant velocity, because the force generated by the engine to turn the wheels precisely offsets the forces of air resistance and road friction. A change in momentum occurs only when the net force is not zero.

**An object must accelerate whenever a net force acts on it.**

Changing an object's momentum means changing its velocity, as long as its mass remains constant. A

net force that is not zero therefore causes an object to accelerate. Conversely, whenever an object accelerates, a net force must be causing the acceleration. That is why you feel forces (pushing you forward, backward, or to the side) when you accelerate in your car. We can use the same ideas to understand many astronomical processes. For example, planets are always accelerating as they orbit the Sun, because their direction of travel constantly changes as they go around their orbits. We can therefore conclude that some force must be causing this acceleration. As we'll discuss shortly, Isaac Newton identified this force as gravity.

## • How is mass different from weight?

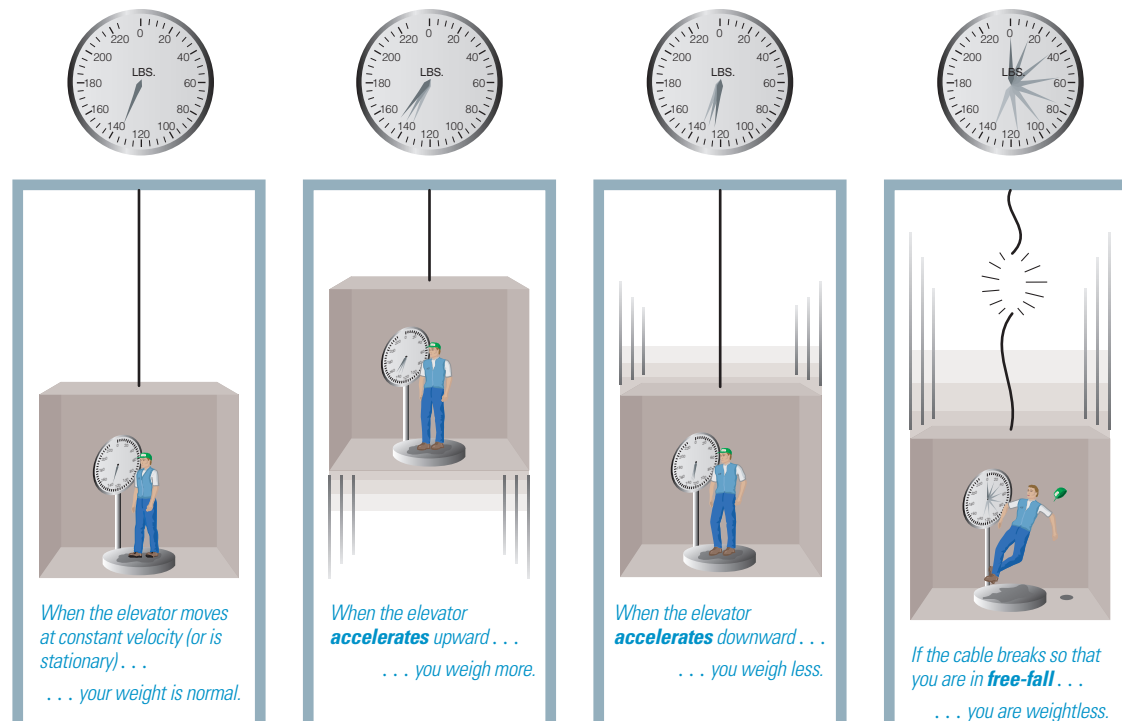
In daily life, we usually think of *mass* as something you can measure with a bathroom scale, but technically the scale measures your *weight*, not your mass. The distinction between mass and weight rarely matters when we are talking about objects on Earth, but it is very important in astronomy:

- Your **mass** is the amount of matter in your body.
- Your **weight** (or **apparent weight**<sup>\*</sup>) is the *force* that a scale measures when you stand on it; that is, weight depends both on your mass and on the forces (including gravity) acting on your mass.

To understand the difference between mass and weight, imagine standing on a scale in an elevator (Figure 4.3). Your mass will be the same no matter how the elevator moves, but your weight can vary. When the elevator is stationary or moving at constant velocity, the scale

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<sup>\*</sup>Some physics texts distinguish between “true weight” due only to gravity and “apparent weight” that also depends on other forces (as in an elevator). In this book, *weight* means “apparent weight.”



**FIGURE 4.3** MA INTERACTIVE FIGURE

Mass is not the same as weight. In an elevator, your mass never changes, but your weight is different when the elevator accelerates.

## common misconceptions

### No Gravity in Space?

If you ask people why astronauts are weightless in space, one of the most common answers is “There is no gravity in space.” But you can usually convince people that this answer is wrong by following up with another simple question: Why does the Moon orbit Earth? Most people know that the Moon orbits Earth because of gravity, proving that there is gravity in space. In fact, at the altitude of the Space Station’s orbit, the acceleration of gravity is only about 10% less than it is on Earth’s surface.

The real reason astronauts are weightless is that they are in a constant state of free-fall. Imagine being an astronaut. You’d have the sensation of free-fall—just as when you jump from a diving board—the entire time you were in orbit. This constant falling sensation makes many astronauts sick to their stomachs when they first experience weightlessness. Fortunately, they quickly get used to the sensation, which allows them to work hard and enjoy the view.

reads your “normal” weight. When the elevator accelerates upward, the floor exerts a greater force than it does when you are at rest. You feel heavier, and the scale verifies your greater weight. When the elevator accelerates downward, the floor and the scale exert a weaker force on you, so the scale registers less weight. Note that the scale shows a weight different from your “normal” weight only when the elevator is *accelerating*, not when it is going up or down at constant speed.

**see it for yourself** ► Find a small bathroom scale and take it with you on an elevator ride. How does your weight change when the elevator accelerates upward or downward? Does it change when the elevator is moving at constant speed? Explain your observations.

**Your mass is the same no matter where you are, but your weight can vary.**

Your mass therefore depends only on the amount of matter in your body and is the same anywhere, but

your weight can vary because the forces acting on you can vary. For example, your mass would be the same on the Moon as on Earth, but you would weigh less on the Moon because of its weaker gravity.

**Free-Fall and Weightlessness** Now consider what happens if the elevator cable breaks (see the last frame in Figure 4.3). The elevator and you are suddenly in **free-fall**—falling without any resistance to slow you down. The floor drops away at the same rate that you fall, allowing you to “float” freely above it, and the scale reads zero because you are no longer held to it. In other words, your free-fall has made you **weightless**.

In fact, you are in free-fall whenever there’s nothing to *prevent* you from falling. For example, you are in free-fall when you jump off a chair or spring from a diving board or trampoline. Surprising as it may seem, you have therefore experienced weightlessness many times in your life.

You can experience it right now simply by jumping off your chair—though your weightlessness lasts for only a very short time until you hit the ground.

**Weightlessness in Space** You've probably seen videos of astronauts floating weightlessly in the Space Station. But why are they weightless? Many people guess that there's no gravity in space, but that's not true. After all, it is gravity that makes the Space Station orbit Earth. Astronauts are weightless for the same reason that you are weightless when you jump off a chair: They are in free-fall.

**People or objects are weightless whenever they are falling freely, and astronauts in orbit are weightless because they are in a constant state of free-fall.**

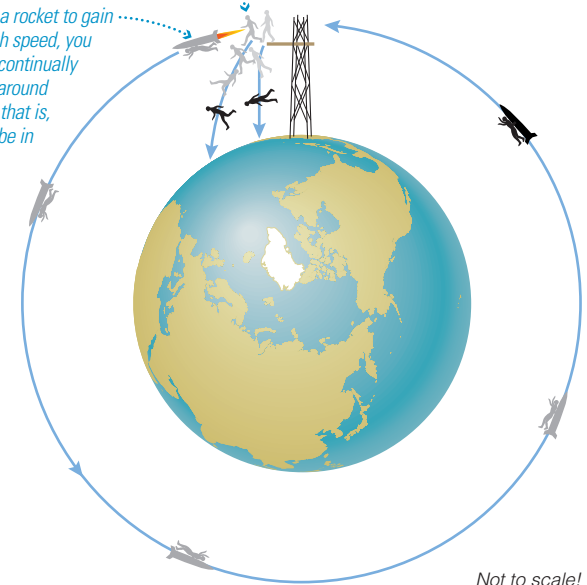
Astronauts are weightless the entire time they orbit Earth because they are in a *constant state of free-fall*. To understand this idea, imagine a tower that reaches all the way to the Space Station's orbit, about 350 kilometers above Earth (Figure 4.4). If you stepped off the tower, you would fall downward, remaining weightless until you hit the ground (or until air resistance had a noticeable effect on you). Now, imagine that instead of stepping off the tower, you ran and jumped out of the tower. You'd still fall to the ground, but because of your forward motion you'd land a short distance away from the base of the tower.

The faster you ran out of the tower, the farther you'd go before landing. If you could somehow run fast enough—about 28,000 km/hr (17,000 mi/hr) at the orbital altitude of the Space Station—a very interesting thing would happen: By the time gravity had pulled you downward as far as the length of the tower, you'd already have moved far enough around Earth that you'd no longer be going down at all. Instead, you'd be just as high above Earth as you'd been all along, but a good portion of the way around the world. In other words, you'd be orbiting Earth.

The Space Station and all other orbiting objects stay in orbit because they are constantly "falling around" Earth. Their constant state of free-fall makes spacecraft and everything in them weightless.

The faster you run from the tower, the farther you go before falling to Earth.

Using a rocket to gain enough speed, you could continually "fall" around Earth; that is, you'd be in orbit.



**FIGURE 4.4** MA INTERACTIVE FIGURE

This figure explains why astronauts are weightless and float freely in space. If you could leap from a tall tower with enough speed, you could travel forward so fast that you'd orbit Earth. You'd then be in a constant state of free-fall, which means you'd be weightless. *Note:* On the scale shown here, the tower extends far higher than the Space Station's orbit; the rocket's orientation shows it rotating once with each orbit. (Adapted from *Space Station Science* by Marianne Dyson.)

MA Motion and Gravity Tutorial, Lesson 1

## 4.2 Newton's Laws of Motion

The complexity of motion in daily life might lead you to guess that the laws governing motion would also be complex. For example, if you watch a falling piece of paper waft lazily to the ground, you'll see it rock back and forth in a seemingly unpredictable pattern. However, the complexity of this motion arises because the paper is affected by a variety of forces, including gravity and the changing forces caused by air currents. If you could analyze the forces individually, you'd find that each force affects the paper's motion in a simple, predictable way. Sir Isaac Newton (1642–1727) discovered the remarkably simple laws that govern motion.

### • How did Newton change our view of the universe?

Newton was born in Lincolnshire, England, on Christmas Day in 1642. He had a difficult childhood and showed few signs of unusual talent. He attended Trinity College at Cambridge, where he earned his keep by



Sir Isaac Newton (1642–1727)

performing menial labor, such as cleaning the boots and bathrooms of wealthier students and waiting on their tables.

The plague hit Cambridge shortly after Newton graduated, and he returned home. By his own account, he experienced a moment of inspiration in 1666 when he saw an apple fall to the ground. He suddenly realized that the gravity making the apple fall was the same force that held the Moon in orbit around Earth. In that moment, Newton shattered the remaining vestiges of the Aristotelian view of the world, which for centuries had been accepted as unquestioned truth.

Aristotle had made many claims about the physics of motion, using his ideas to support his belief in an Earth-centered cosmos. He had also maintained that the heavens were totally distinct from Earth, so physical laws on Earth did not apply to heavenly motion. By the time Newton saw the apple fall, the Copernican revolution had displaced Earth from a central position, and Galileo's experiments had shown that the laws of physics were not what Aristotle had believed.

Newton's sudden insight delivered the final blow to Aristotle's view. By recognizing that gravity operated in the heavens as well as on Earth,

**Newton showed that the same physical laws that operate on Earth also operate in the heavens.**

Newton eliminated Aristotle's distinction between the two realms and brought the heavens and Earth together as one *universe*. This insight

also heralded the birth of the modern science of *astrophysics* (although the term wasn't coined until much later), which applies physical laws discovered on Earth to phenomena throughout the cosmos.

Over the next 20 years, Newton's work completely revolutionized mathematics and science. He quantified the laws of motion and gravity, conducted crucial experiments regarding the nature of light, built the first reflecting telescopes, and invented the mathematics of calculus. We'll discuss his laws of motion in the rest of this section, and later in the chapter we'll turn our attention to Newton's discoveries about gravity.

## • What are Newton's three laws of motion?

Newton published the laws of motion and gravity in 1687, in his book *Philosophiæ Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), usually called *Principia*. He enumerated three laws that apply to all motion, which we now call **Newton's laws of motion**. These laws govern the motion of everything from our daily movements on Earth to the movements of planets, stars, and galaxies throughout the universe. Figure 4.5 summarizes the three laws.

**Newton's First Law** Newton's first law of motion states that in the absence of a net force, an object will move with constant velocity. Objects at rest (velocity = 0) tend to remain at rest, and objects in motion tend to remain in motion with no change in either their speed or their direction.

**Newton's first law: An object moves at constant velocity if there is no net force acting upon it.**

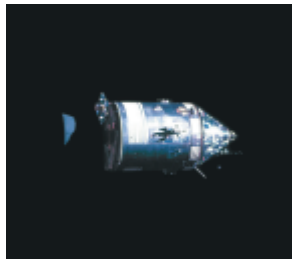
The idea that an object at rest should remain at rest is rather obvious: A car parked on a flat street won't suddenly start moving for no reason.

But what if the car is traveling along a flat, straight road? Newton's first law says that the car should keep going at the same speed forever *unless* a force acts to slow it down. You know that the car eventually will come to a stop if you take your foot off the gas pedal, so one or more forces must be stopping the car—in this case, forces arising from friction and air resistance. If the car were in space, and therefore unaffected by friction



**Newton's first law of motion:**

An object moves at constant velocity unless a net force acts to change its speed or direction.



**Example:** A spaceship needs no fuel to keep moving in space.

**Newton's second law of motion:**

Force = mass  $\times$  acceleration



**Example:** A baseball accelerates as the pitcher applies a force by moving his arm. (Once the ball is released, the force from the pitcher's arm ceases, and the ball's path changes only because of the forces of gravity and air resistance.)

**Newton's third law of motion:**

For any force, there is always an equal and opposite reaction force.



**Example:** A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.

or air, it would keep moving forever (though gravity would gradually alter its speed and direction). That is why interplanetary spacecraft need no fuel to keep going after they are launched into space, and why astronomical objects don't need fuel to travel through the universe.

Newton's first law also explains why you don't feel any sensation of motion when you're traveling in an airplane on a smooth flight. As long as the plane is traveling at constant velocity, no net force is acting on it or on you. Therefore, you feel no different from the way you would feel at rest. You can walk around the cabin, play catch with someone, or relax and go to sleep just as though you were "at rest" on the ground.

**Newton's Second Law** Newton's second law of motion tells us what happens to an object when a net force *is* present. We have already seen that a net force will change an object's momentum, accelerating it in the direction of the force. Newton's second law quantifies this relationship, and is most commonly written as force = mass  $\times$  acceleration, or  $F = ma$  for short.

This law explains why you can throw a baseball farther than you can throw a shot in the shot put. The force your arm delivers to both the baseball and the shot equals the product of mass and acceleration. Because the mass of the shot is greater than that of the baseball, the same force from your arm gives the shot a smaller acceleration. Because of its smaller acceleration, the shot leaves your hand with less speed than the baseball and therefore travels a shorter distance before hitting the ground. Astronomically, Newton's second law explains why large planets such as Jupiter have a greater effect on asteroids and comets than small planets such as Earth [Section 9.4]. Because Jupiter is much more massive than Earth, it exerts a stronger gravitational force on passing asteroids and comets, and therefore sends them scattering with greater acceleration.

**Newton's Third Law** Think for a moment about standing still on the ground. Your weight exerts a downward force; if this force were acting alone, Newton's second law would demand that you accelerate downward. The fact that you are not falling means there must be no *net* force acting on you, which is possible only if the ground is exerting an upward force on you that precisely offsets the downward force you exert on the ground. The fact that the downward force you exert on the ground is offset by an equal and opposite force that pushes upward on you is one

**FIGURE 4.5**

Newton's three laws of motion.



## common misconceptions

### What Makes a Rocket Launch?

If you've ever watched a rocket launch, it's easy to see why many people believe that the rocket "pushes off" the ground. However, the ground has nothing to do with the rocket launch, which is actually explained by Newton's third law of motion. To balance the force driving gas out the back of the rocket, an equal and opposite force must propel the rocket forward. Rockets can be launched horizontally as well as vertically, and a rocket can be "launched" in space (for example, from a space station) with no need for a solid surface to push off from.

example of Newton's third law of motion, which tells us that every force is always paired with an equal and opposite reaction force.

**Newton's third law: For any force, there is always an equal and opposite reaction force.**

This law is very important in astronomy, because it tells us that objects always attract *each other* through gravity. For example, your body always exerts a gravitational force on Earth identical to the force that Earth exerts on you, except that it acts in the opposite direction. Of course, the same force means a much greater acceleration for you than for Earth (because your mass is so much smaller than Earth's), which is why you fall toward Earth when you jump off a chair, rather than Earth falling toward you.

Newton's third law also explains how a rocket works: A rocket engine generates a force that drives hot gas out the back, which creates an equal and opposite force that propels the rocket forward.

## 4.3 Conservation Laws in Astronomy

Newton's laws of motion are easy to state, but they may seem a bit arbitrary. Why, for example, should every force be opposed by an equal and opposite reaction force? In the centuries since Newton first stated his laws, we have learned that they are not arbitrary at all, but instead reflect deeper aspects of nature known as *conservation laws*.

Consider what happens when two objects collide. Newton's second law tells us that object 1 exerts a force that will change the momentum of object 2. At the same time, Newton's third law tells us that object 2 exerts an equal and opposite force on object 1—which means that object 1's momentum changes by precisely the same amount as object 2's momentum, but in the opposite direction. The total combined momentum of objects 1 and 2 remains the same both before and after the collision. We say that the total momentum of the colliding objects is conserved, reflecting a principle that we call *conservation of momentum*. In essence, the law of conservation of momentum tells us that the total momentum of all interacting objects always stays the same. An individual object can gain or lose momentum only when a force causes it to exchange momentum with another object.

Conservation of momentum is one of several important conservation laws that underlie Newton's laws of motion and other physical laws in the universe. Two other conservation laws—one for *angular momentum* and one for *energy*—are especially important in astronomy. Let's see how these important laws work.

### • What keeps a planet rotating and orbiting the Sun?

Perhaps you've wondered how Earth manages to keep rotating and going around the Sun day after day and year after year. The answer relies on a special type of momentum that we use to describe objects turning in circles or going around curves. This special type of "circling momentum" is called **angular momentum**. (The term *angular* arises because an object moving in a circle turns through an *angle* of 360°.)

**Conservation of angular momentum: An object's angular momentum cannot change unless it transfers angular momentum to or from another object.**

The **law of conservation of angular momentum** tells us that total angular momentum can never change. An individual object can change its angular momentum only by transferring some angular momentum to or from another object.

**Orbital Angular Momentum** Consider Earth’s orbit around the Sun. A simple formula tells us Earth’s angular momentum at any point in its orbit:

$$\text{angular momentum} = m \times v \times r$$

where  $m$  is Earth’s mass,  $v$  is its orbital velocity (or more technically, the component of velocity perpendicular to  $r$ ), and  $r$  is the “radius” of the orbit, by which we mean Earth’s distance from the Sun (Figure 4.6). Because there are no objects around to give or take angular momentum from Earth as it orbits the Sun, Earth’s orbital angular momentum must always stay the same. This explains two key facts about Earth’s orbit:

1. Earth needs no fuel or push of any kind to keep orbiting the Sun—it will keep orbiting as long as nothing comes along to take angular momentum away.
2. Because Earth’s angular momentum at any point in its orbit depends on the product of its speed and orbital radius (distance from the Sun), Earth’s orbital speed must be faster when it is nearer to the Sun (and the radius is smaller) and slower when it is farther from the Sun (and the radius is larger).

The second fact is just what Kepler’s second law of planetary motion states [Section 3.3]. That is, the law of conservation of angular momentum tells us *why* Kepler’s law is true.

**Rotational Angular Momentum** The same idea explains why Earth keeps rotating. As long as Earth isn’t transferring any of the angular momentum of its rotation to another object, it keeps rotating at the same rate. (In fact, Earth is very gradually transferring some of its rotational angular momentum to the Moon, and as a result Earth’s rotation is gradually slowing down; see Special Topic, page 99.)

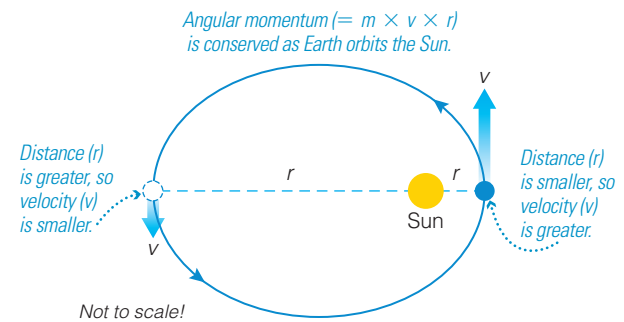
Conservation of angular momentum also explains why we see so many spinning disks in the universe, such as the disks of galaxies like the Milky Way and disks of material orbiting young stars. The idea is easy to illustrate with an ice skater spinning in place (Figure 4.7). Because there is so little friction on ice, the angular momentum of the ice skater remains essentially constant. When she pulls in her extended arms, she decreases her radius—which means her velocity of rotation must increase. Stars and galaxies are both born from clouds of gas that start out much larger in size. These clouds almost inevitably have some small net rotation, though it may be imperceptible. Like the spinning skater as she pulls in her arms, these clouds must spin faster as gravity makes them shrink in size. (We’ll discuss why the clouds also flatten into disks in Chapter 6.)

**think about it** ► How does conservation of angular momentum explain the spiraling of water going down a drain?

 Energy Tutorial, Lesson 1

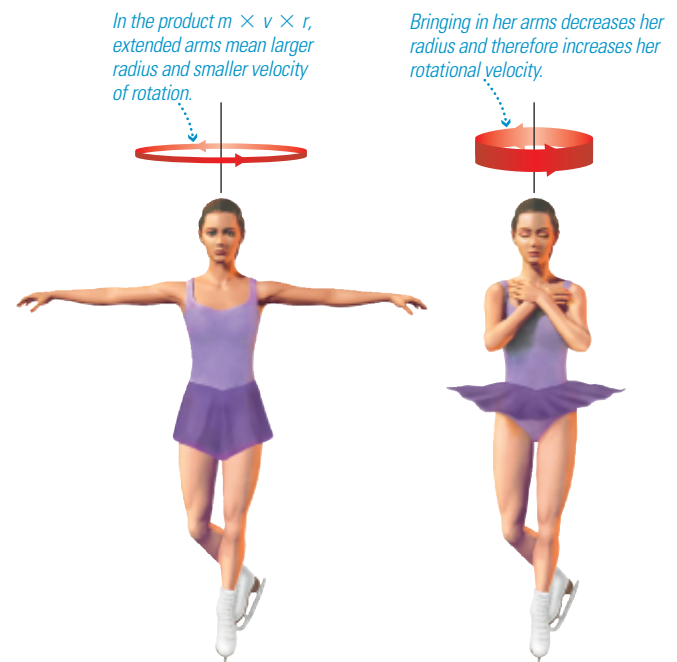
## • Where do objects get their energy?

The **law of conservation of energy** tells us that, like momentum and angular momentum, energy cannot appear out of nowhere or disappear into nothingness. Objects can gain or lose energy only by exchanging energy with other objects. Because of this law, the story of the universe is a



**FIGURE 4.6**

Earth’s angular momentum always stays the same as it orbits the Sun, so it moves faster when it is closer to the Sun and slower when it is farther from the Sun. It needs no fuel to keep orbiting because no forces are acting in a way that could change its angular momentum.



**FIGURE 4.7**

A spinning skater conserves angular momentum.

Energy can be converted from one form to another.



**FIGURE 4.8**

The three basic categories of energy. Energy can be converted from one form to another, but it can never be created or destroyed, an idea embodied in the law of conservation of energy.

**TABLE 4.1** Energy Comparisons

Item	Energy (joules)
Energy of sunlight at Earth (per square meter per second)	$1.3 \times 10^3$
Energy from metabolism of a candy bar	$1 \times 10^6$
Energy needed to walk for 1 hour	$1 \times 10^6$
Kinetic energy of a car going 60 mi/hr	$1 \times 10^6$
Daily food energy need of average adult	$1 \times 10^7$
Energy released by burning 1 liter of oil	$1.2 \times 10^7$
Thermal energy of parked car	$1 \times 10^8$
Energy released by fission of 1 kilogram of uranium-235	$5.6 \times 10^{13}$
Energy released by fusion of hydrogen in 1 liter of water	$7 \times 10^{13}$
Energy released by 1-megaton H-bomb	$4 \times 10^{15}$
Energy released by magnitude 8 earthquake	$2.5 \times 10^{16}$
Annual U.S. energy consumption	$10^{20}$
Annual energy generation of Sun	$10^{34}$
Energy released by a supernova	$10^{44} - 10^{46}$

story of the interplay of energy and matter: All actions involve exchanges of energy or the conversion of energy from one form to another.

Throughout the rest of this book, we'll see numerous cases in which we can understand astronomical processes simply by studying how energy is transformed and exchanged.

**Conservation of energy:** Energy can be transferred from one object to another or transformed from one type to another, but the total amount of energy is always conserved.

For example, we'll see that planetary interiors cool with time because they radiate energy

into space, and that the Sun became hot because of energy released by the gas that formed it. By applying the laws of conservation of angular momentum and conservation of energy, we can understand almost every major process that occurs in the universe.

### Basic Types of Energy

Before we can fully understand the law of conservation of energy, we need to know what energy is. In essence, energy is what makes matter move. Because this statement is so broad, we often distinguish between different types of energy. For example, we talk about the energy we get from the food we eat, the energy that makes our cars go, and the energy a light bulb emits. Fortunately, we can classify nearly all types of energy into just three major categories (Figure 4.8):

- Energy of motion, or **kinetic energy** (*kinetic* comes from a Greek word meaning "motion"). Falling rocks, orbiting planets, and the molecules moving in the air are all examples of objects with kinetic energy.
- Energy carried by light, or **radiative energy** (the word *radiation* is often used as a synonym for *light*). All light carries energy, which is why light can cause changes in matter. For example, light can alter molecules in our eyes—thereby allowing us to see—or warm the surface of a planet.
- Stored energy, or **potential energy**, which might later be converted into kinetic or radiative energy. For example, a rock perched on a ledge has *gravitational* potential energy because it will fall if it slips off the edge, and gasoline contains *chemical* potential energy that can be converted into the kinetic energy of a moving car.

Regardless of which type of energy we are dealing with, we can measure the amount of energy with the same standard units. For Americans, the most familiar units of energy are *Calories*, which are shown on food

**There are three basic categories of energy: energy of motion (kinetic), energy of light (radiative), and stored energy (potential).**

labels to tell us how much energy our bodies can draw from the food. A typical adult needs about 2500 Calories of energy from food

each day. In science, the standard unit of energy is the **joule**. One food Calorie is equivalent to about 4184 joules, so the 2500 Calories used daily by a typical adult is equivalent to about 10 million joules. Table 4.1 compares various energies in joules.

### Thermal Energy—The Kinetic Energy of Many Particles

Although there are only three major categories of energy, we sometimes divide them into various subcategories. In astronomy, the most important subcategory of kinetic energy is **thermal energy**, which represents the collective kinetic energy of the many individual particles (atoms and molecules) moving randomly within a substance like a rock or the air or the gas within a distant star. In such cases, it is much easier to talk about the thermal energy of the object rather than about the kinetic energies of its billions upon billions of individual particles.



Thermal energy gets its name because it is related to temperature, but temperature and thermal energy are not quite the same thing. Thermal energy measures the *total* kinetic energy of all the randomly moving particles in a substance, while **temperature** measures the *average* kinetic energy of the particles. For a particular object, a higher temperature simply means that the particles on average have more kinetic energy and hence are moving faster (Figure 4.9). You're probably familiar with temperatures measured in *Fahrenheit* or *Celsius*, but in science we often use the **Kelvin** temperature scale (Figure 4.10). The Kelvin scale does not have negative temperatures, because it starts from the coldest possible temperature, known as *absolute zero* (0 K).

Thermal energy depends on temperature, because a higher average kinetic energy for the particles in a substance means a higher total energy. But thermal energy also depends on the number and density of the particles, as you can see by imagining that you quickly thrust your arm in

**Thermal energy is the total kinetic energy of many individual particles.**

and out of a hot oven and a pot of boiling water (don't try this!). The air in a hot oven is much higher in temperature than the water boiling in a pot (Figure 4.11). However, the boiling water would scald your arm almost instantly, while you can safely put your arm into the oven air for a few seconds. The reason for this difference is density. In both cases, because the air or water is hotter than your body, molecules striking your skin transfer thermal energy to molecules in your arm. The higher temperature in the oven means that the air molecules strike your skin harder, on average, than the molecules in the boiling water. However, because the *density* of water is so much higher than the density of air (meaning water has far more molecules in the same amount of space), many more molecules strike your skin each second in the water. While each individual molecule that strikes your skin transfers a little less energy in the boiling water than in the oven, the sheer number of molecules hitting you in the water means that more thermal energy is transferred to your arm. That is why the boiling water causes a burn almost instantly.

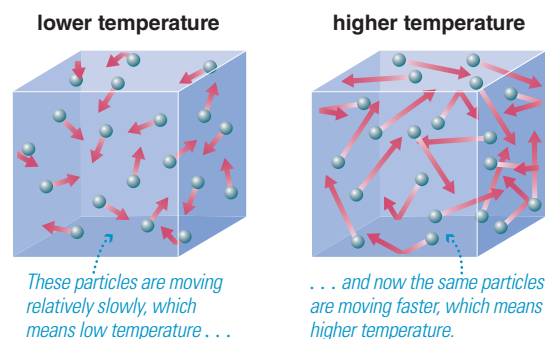
**think about it** ► In air or water that is colder than your body temperature, thermal energy is transferred from you to the surrounding cold air or water. Use this fact to explain why falling into a 32°F (0°C) lake is much more dangerous than standing naked outside on a 32°F day.

**Potential Energy in Astronomy** Many types of potential energy are important in astronomy, but two are particularly important: *gravitational potential energy* and the potential energy of mass itself, or *mass-energy*.

An object's **gravitational potential energy** depends on its mass and how far it can fall as a result of gravity. An object has more gravitational potential energy when it is higher and less when it is lower. For example, if you throw a ball up into the air, it

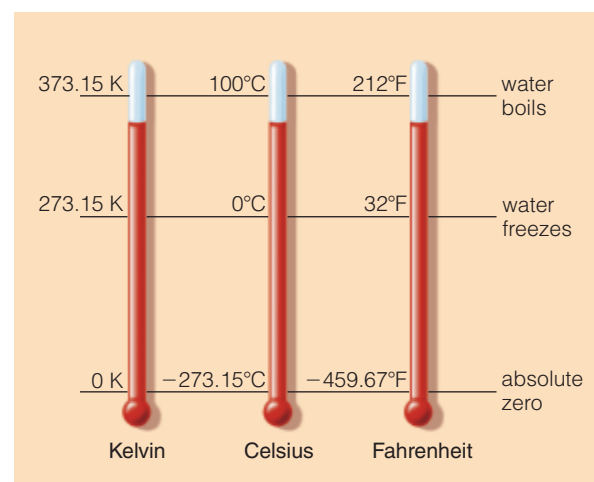
**An object's gravitational potential energy increases when it moves higher and decreases when it moves lower.**

has more potential energy when it is high up than it does near the ground. Because energy must be conserved during the ball's flight, the ball's kinetic energy increases when its gravitational potential energy decreases, and vice versa (Figure 4.12a). That is why the ball travels fastest (has the most kinetic energy) when it is closest to the ground, where it has the least gravitational potential energy. The higher the ball is, the more gravitational potential energy it has and the slower the ball travels (less kinetic energy).



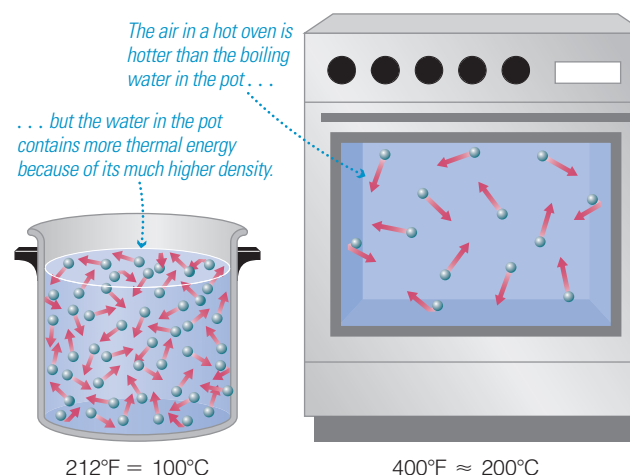
**FIGURE 4.9**

Temperature is a measure of the average kinetic energy of the particles (atoms and molecules) in a substance. Longer arrows represent faster speeds.



**FIGURE 4.10**

Three common temperature scales: Kelvin, Celsius, and Fahrenheit. Scientists generally prefer the Kelvin scale. (The degree symbol ° is not usually used with the Kelvin scale.)

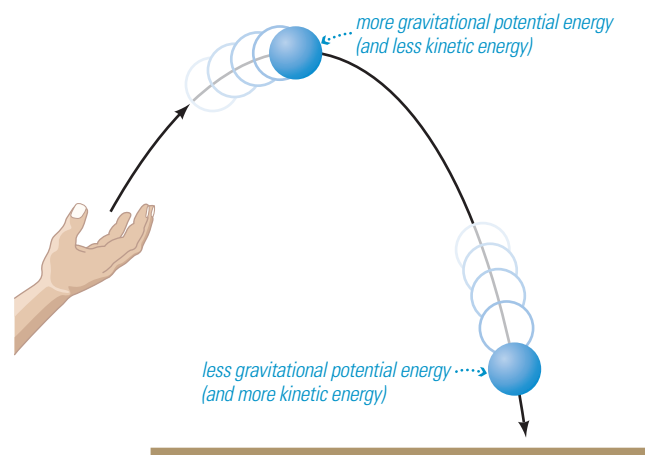


**FIGURE 4.11**

Thermal energy depends on both the temperature and the density of a substance.

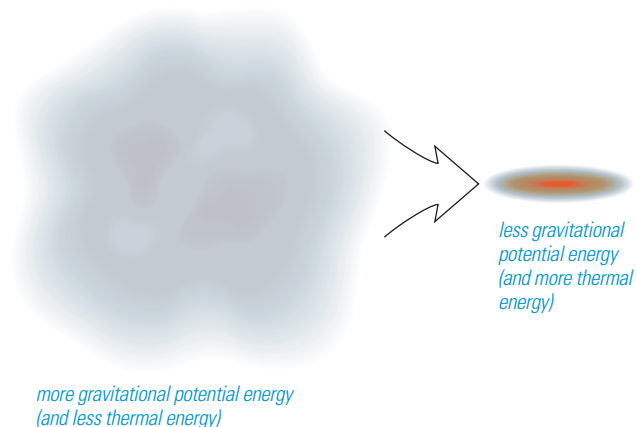


The total energy (kinetic + potential) is the same at all points in the ball's flight.



a The ball has more gravitational potential energy when it is high up than when it is near the ground.

Energy is conserved: As the cloud contracts, gravitational potential energy is converted to thermal energy and radiation.



b A cloud of interstellar gas can contract because of its own gravity. It has more gravitational potential energy when it is spread out than when it shrinks in size.

**FIGURE 4.12**  
Two examples of gravitational potential energy.

The same general idea explains how stars become hot (Figure 4.12b). Before a star forms, its matter is spread out in a large, cold cloud of gas. Most of the individual gas particles are far from the center of this large cloud and therefore have a lot of gravitational potential energy. The particles lose gravitational potential energy as the cloud contracts under its own gravity, and this “lost” potential energy ultimately gets converted into thermal energy, making the center of the cloud hot.

Einstein discovered that mass itself is a form of potential energy, often called **mass-energy**. The amount of potential energy contained in mass is described by Einstein’s famous equation

$$E = mc^2$$

where  $E$  is the amount of potential energy,  $m$  is the mass of the object, and  $c$  is the speed of light. This equation tells us that a small amount of mass contains a huge amount of energy. For example, the energy released by a 1-megaton H-bomb

**Mass itself is a form of potential energy, as described by Einstein’s equation  $E = mc^2$ .**

comes from converting only about 0.1 kilogram of mass

(about 3 ounces—a quarter of a can of soda) into energy (Figure 4.13). The Sun generates energy by converting a tiny fraction of its mass into energy through a similar process of nuclear fusion [Section 11.2].

Just as Einstein’s formula tells us that mass can be converted into other forms of energy, it also tells us that energy can be transformed into mass. This process is especially important in understanding what we think happened during the early moments in the history of the universe, when some of the energy of the Big Bang turned into the mass from which all objects, including us, are made [Section 18.1]. Scientists also use this idea to search for undiscovered particles of matter, using large machines called *particle accelerators* to create subatomic particles from energy.



**FIGURE 4.13**  
The energy released by this H-bomb comes from converting only about 0.1 kilogram of mass into energy in accordance with the formula  $E = mc^2$ .

**Conservation of Energy** We have seen that energy comes in three basic categories—kinetic, radiative, and potential—and explored several subcategories that are especially important in astronomy: thermal energy, gravitational potential energy, and mass-energy. Now we are ready to return to the question of where objects get their energy. Because energy cannot be created or destroyed, objects always get their energy from

other objects. Ultimately, we can always trace an object's energy back to the Big Bang [Section 1.2], the beginning of the universe in which all matter and energy is thought to have come into existence.

For example, imagine that you've thrown a baseball. It is moving, so it has kinetic energy. Where did this kinetic energy come from? The baseball got its kinetic energy from the motion of your arm as you threw it. Your

**The energy of any object can be traced back to the origin of the universe in the Big Bang.**

arm, in turn, got its kinetic energy from the release of chemical potential energy stored in your muscle tissues. Your muscles got this energy from the chemical potential energy stored in the foods you ate. The energy stored in the foods came from sunlight, which plants convert into chemical potential energy through photosynthesis. The radiative energy of the Sun was generated through the process of nuclear fusion, which releases some of the mass-energy stored in the Sun's supply of hydrogen. The mass-energy stored in the hydrogen came from the birth of the universe in the Big Bang. After you throw the ball, its kinetic energy will ultimately be transferred to molecules in the air or ground. It may be difficult to trace after this point, but it will never disappear.

## 4.4 The Force of Gravity

Newton's laws of motion describe how objects in the universe move in response to forces. The laws of conservation of momentum, angular momentum, and energy offer an alternative and often simpler way of thinking about what happens when a force causes some change in the motion of one or more objects. However, we cannot fully understand motion unless we also understand the forces that lead to changes in motion. In astronomy, the most important force is gravity, which governs virtually all large-scale motion in the universe.

MA Motion and Gravity Tutorial, Lesson 2

### • What determines the strength of gravity?

Isaac Newton discovered the basic law that describes how gravity works. Newton expressed the force of gravity mathematically with his **universal law of gravitation**. Three simple statements summarize this law:

- Every mass attracts every other mass through the force called *gravity*.
- The strength of the gravitational force attracting any two objects is *directly proportional* to the product of their masses. For example, doubling the mass of *one* object doubles the force of gravity between the two objects.
- The strength of gravity between two objects decreases with the *square* of the distance between their centers. We therefore say that the gravitational force follows an **inverse square law**. For example, doubling the distance between two objects weakens the force of gravity by a factor of  $2^2$ , or 4.

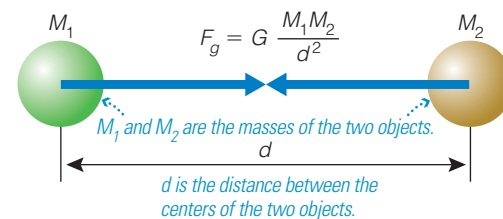
**Doubling the distance between two objects weakens the force of gravity by a factor of  $2^2$ , or 4.**

These three statements tell us everything we need to know about Newton's universal law of gravitation. Mathematically, all three statements can be combined into a single equation, usually written like this:

$$F_g = G \frac{M_1 M_2}{d^2}$$

where  $F_g$  is the force of gravitational attraction,  $M_1$  and  $M_2$  are the masses of the two objects, and  $d$  is the distance between their centers (Figure 4.14).

The **universal law of gravitation** tells us the strength of the gravitational attraction between the two objects.

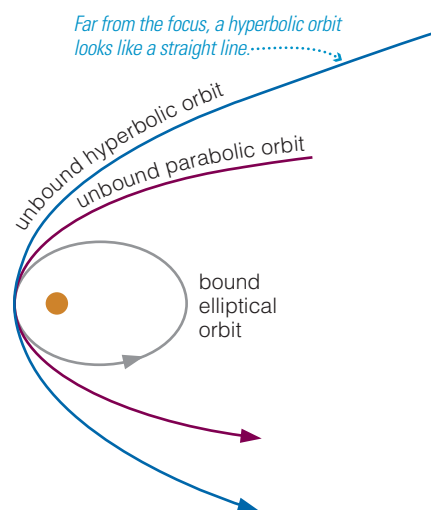


**FIGURE 4.14**

The universal law of gravitation is an *inverse square law*, which means that the force of gravity declines with the *square* of the distance  $d$  between two objects.

**FIGURE 4.15**

Newton showed that ellipses are not the only possible orbital paths. Orbits can also be unbound, taking the mathematical shapes of either parabolas or hyperbolas.



## cosmic calculations 4.1

### Newton's Version of Kepler's Third Law

For an object of mass  $M_1$  orbiting another object of mass  $M_2$ , Newton's version of Kepler's third law states

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

$$(G = 6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2})$$

is the gravitational constant.)

This equation allows us to calculate the sum  $M_1 + M_2$  if we know the orbital period  $p$  and average distance (semimajor axis)  $a$ . The equation is especially useful when one object is much more massive than the other.

**Example:** Use the fact that Earth orbits the Sun in 1 year at an average distance of 1 AU to calculate the Sun's mass.

**Solution:** Newton's version of Kepler's third law becomes

$$p_{\text{Earth}}^2 = \frac{4\pi^2}{G(M_{\text{Sun}} + M_{\text{Earth}})} a_{\text{Earth}}^3$$

Because the Sun is much more massive than Earth, the sum of their masses is nearly the mass of the Sun alone:  $M_{\text{Sun}} + M_{\text{Earth}} \approx M_{\text{Sun}}$ . Using this approximation, we find

$$p_{\text{Earth}}^2 \approx \frac{4\pi^2}{GM_{\text{Sun}}} a_{\text{Earth}}^3$$

We now solve for the mass of the Sun and plug in Earth's orbital period ( $p_{\text{Earth}} = 1 \text{ year} \approx 3.15 \times 10^7 \text{ seconds}$ ) and average orbital distance ( $a_{\text{Earth}} = 1 \text{ AU} \approx 1.5 \times 10^{11} \text{ m}$ ):

$$M_{\text{Sun}} \approx \frac{4\pi^2 a_{\text{Earth}}^3}{G p_{\text{Earth}}^2} \approx \frac{4\pi^2 (1.5 \times 10^{11} \text{ m})^3}{(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}) (3.15 \times 10^7 \text{ s})^2}$$

$$= 2.0 \times 10^{30} \text{ kg}$$

The Sun's mass is about  $2 \times 10^{30}$  kilograms.

The symbol  $G$  is a constant called the **gravitational constant**, and its numerical value has been measured to be  $G = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg} \times \text{s}^2)$ .

**think about it** ► How does the gravitational force between two objects change if the distance between them triples? If the distance between them drops by half?

**MA** Orbits and Kepler's Law Tutorial, Lessons 1–4

## • How does Newton's law of gravity extend Kepler's laws?

By the time Newton published *Principia* in 1687, Kepler's laws of planetary motion [Section 3.3] had already been known for some 70 years and had proven so successful that there was little doubt about their validity. However, there was great debate among scientists about *why* Kepler's laws hold true, a debate resolved only when Newton showed mathematically that Kepler's laws are consequences of the laws of motion and the universal law of gravitation. In doing so, Newton discovered that he could generalize Kepler's laws in several ways, three of which are particularly important for our purposes.

First, Newton discovered that Kepler's first two laws apply to all orbiting objects, not just to planets orbiting the Sun. For example, the orbits of satellites around Earth, of moons around planets, and of asteroids around the Sun are all ellipses in which the orbiting object moves faster at the nearer points in its orbit and slower at the farther points.

Second, Newton found that ellipses are not the only possible orbital paths (Figure 4.15). Ellipses (which include circles) are the only possible shapes for **bound orbits**—orbits in which an object goes around another object over and over again. (The term *bound orbit* comes from the idea that gravity creates a *bond* that holds the objects together.) However, Newton discovered that objects can also follow **unbound orbits**—paths that bring an object close to another object just once. For example, some comets that enter the inner solar system follow unbound orbits. They come in from afar just once, loop around the Sun, and never return.

Third, and perhaps most important, Newton generalized Kepler's third law in a way that allows us to calculate the masses of distant objects. Recall that Kepler's third law states that  $p^2 = a^3$ , where  $p$  is a planet's orbital period in years and  $a$  is its average distance from the

**Newton's version of Kepler's third law allows us to calculate the masses of distant objects.**

Sun in AU. Newton found that this statement is a special case of a more general equation that we call **Newton's version of Kepler's third**

**law** (see Cosmic Calculations 4.1). This equation allows us to calculate the mass of a distant object if we measure the orbital period and distance of another object orbiting around it. For example, we can calculate the mass of the Sun from Earth's orbital period (1 year) and its average distance (1 AU); we can calculate Jupiter's mass from the orbital period and average distance of one of its moons; and we can determine the masses of distant stars if they are members of binary star systems, in which two stars orbit one another. In fact, Newton's version of Kepler's third law is the primary means by which we determine masses throughout the universe.

## • How do gravity and energy allow us to understand orbits?

Newton’s law of universal gravitation explains Kepler’s laws of planetary motion, which describe the stable orbits of the planets, and Newton’s extensions of Kepler’s laws explain other stable orbits, such as the orbit of a satellite around Earth. But orbits do not always stay the same. For example, you’ve probably heard of satellites crashing to Earth from orbit, proving that orbits can sometimes change dramatically. To understand how and why orbits sometimes change, we need to consider the role of energy in orbits.

**Orbital Energy** A planet orbiting the Sun has both kinetic energy (because it is moving around the Sun) and gravitational potential energy (because it would fall toward the Sun if it stopped orbiting). The amount of kinetic energy depends on orbital speed, and the amount of gravitational potential energy depends on orbital distance. Because the planet’s distance and speed both vary as it orbits the Sun, its gravitational potential energy and kinetic energy also vary (Figure 4.16). However, the planet’s total **orbital energy**—the sum of its kinetic and gravitational potential energies—stays the same. This fact is a consequence of the law of conservation of energy. As long as no other object causes the planet to gain or lose orbital energy, its orbital energy cannot change and its orbit must remain the same.

**Orbits cannot change spontaneously—an object’s orbit can change only if it gains or loses orbital energy.**

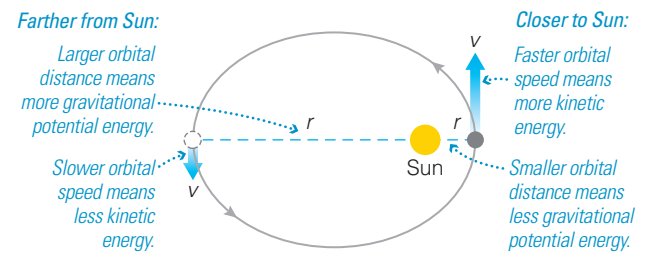
Generalizing from planets to other objects leads to an important idea about motion throughout the cosmos: *Orbits cannot change spontaneously.* Left undisturbed, planets would forever keep the same orbits around the Sun, moons would keep the same orbits around planets, and stars would keep the same orbits in their galaxies.

**Gravitational Encounters** Although orbits cannot change spontaneously, they can change through exchanges of energy. One way that two objects can exchange orbital energy is through a **gravitational encounter**, in which they pass near enough that each can feel the effects of the other’s gravity. For example, in the rare cases in which a comet happens to pass near a planet, the comet’s orbit can change dramatically. Figure 4.17 shows a comet headed toward the Sun on an unbound orbit. The comet’s close passage by Jupiter allows the comet and Jupiter to exchange energy. In this case, the comet loses so much orbital energy that its orbit changes from unbound to bound and elliptical. Jupiter gains exactly as much energy as the comet loses, but the effect on Jupiter is unnoticeable because of its much greater mass.

Spacecraft engineers can use the same basic idea in reverse. For example, on its way to Pluto, the *New Horizons* spacecraft was deliberately sent past Jupiter on a path that allowed it to gain orbital energy at Jupiter’s expense. This extra orbital energy boosted the spacecraft’s speed; without this boost, it would have needed four extra years to reach Pluto.

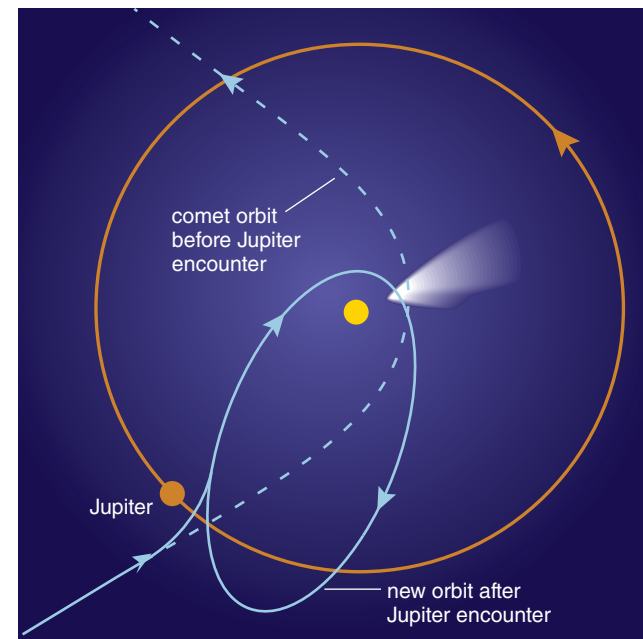
A similar dynamic can occur naturally and may explain why most comets orbit far from the Sun. Comets probably once orbited in the same region of the solar system as the large outer planets [Section 9.2]. Gravitational encounters with the planets then caused some of these comets to be “kicked out” into much more distant orbits around the Sun.

$$\text{Total orbital energy} = \text{gravitational potential energy} + \text{kinetic energy}$$



**FIGURE 4.16**

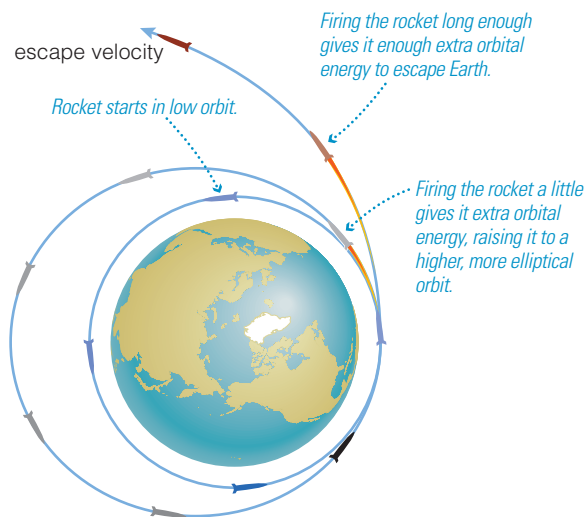
The total orbital energy of a planet stays the same throughout its orbit, because its gravitational potential energy increases when its kinetic energy decreases, and vice versa.



**FIGURE 4.17**

This diagram shows a comet in an unbound orbit of the Sun that happens to pass near Jupiter. The comet loses orbital energy to Jupiter, changing its unbound orbit to a bound orbit around the Sun.





**FIGURE 4.18**  **INTERACTIVE FIGURE**

An object with escape velocity has enough orbital energy to escape Earth completely.

## common misconceptions

### The Origin of Tides

Many people believe that tides arise because the Moon pulls Earth's oceans toward it. But if that were the whole story, there would be a bulge only on the side of Earth facing the Moon, and hence only one high tide each day. The correct explanation for tides must account for why Earth has two tidal bulges.

Only one explanation works: Earth must be stretching from its center in both directions (toward and away from the Moon). This stretching force, or tidal force, arises from the difference between the force of gravity attracting different parts of Earth to the Moon. In fact, stretching due to tides affects many objects, not just Earth. Many moons are stretched into slightly oblong shapes by tidal forces caused by their parent planets, and mutual tidal forces stretch close binary stars into teardrop shapes. In regions where gravity is extremely strong, such as near a black hole, tides can have even more dramatic effects.

**Atmospheric Drag** Friction can cause objects to lose orbital energy. A satellite in low-Earth orbit (a few hundred kilometers above Earth's surface) experiences a bit of drag from Earth's thin upper atmosphere. This drag gradually causes the satellite to lose orbital energy until it finally plummets to Earth. The satellite's lost orbital energy is converted to thermal energy in the atmosphere, which is why a falling satellite usually burns up.

Friction may also help explain why the outer planets have so many small moons. These moons may once have orbited the Sun independently, and their orbits could not have changed spontaneously. However, the outer planets probably once were surrounded by clouds of gas [Section 6.4], and friction would have slowed objects passing through this gas. Some of these small objects may have lost just enough energy to friction to allow them to be "captured" as moons. Mars may have captured its two small moons in a similar way.

**Escape Velocity** An object that gains orbital energy moves into an orbit with a higher average altitude. For example, if we want to boost the orbital altitude of a spacecraft, we can give it more orbital energy by firing a rocket. The chemical potential energy released by the rocket fuel is converted to orbital energy for the spacecraft.

If we give a spacecraft enough orbital energy, it may end up in an unbound orbit that allows it to *escape* Earth completely (Figure 4.18). For example, when we send a space probe to Mars, we must use a large rocket that gives the probe enough energy to leave Earth orbit. Although it would probably make more sense to say that the probe achieves "escape energy," we instead say that it achieves **escape velocity**. The escape velocity from Earth's surface is about 40,000 km/hr, or 11 km/s; this is the minimum velocity required to escape Earth's gravity for a spacecraft that starts near the surface.

Note that the escape velocity does not depend on the mass of the escaping object—*any* object must travel at a velocity of 11 km/s to escape from Earth, whether it is an individual atom or molecule escaping from the atmosphere, a spacecraft being launched into deep space, or a rock blasted into the sky by a large impact. Escape velocity *does* depend on whether you start from the surface or from someplace high above the surface. Because gravity weakens with distance, it takes less energy—and hence a lower velocity—to escape from a point high above Earth than from Earth's surface.

Note that the escape velocity does not depend on the mass of the escaping object—*any* object must travel at a velocity of 11 km/s to escape from Earth, whether it is an individual atom or molecule escaping from the atmosphere, a spacecraft being launched into deep space, or a rock blasted into the sky by a large impact. Escape velocity *does* depend on whether you start from the surface or from someplace high above the surface. Because gravity weakens with distance, it takes less energy—and hence a lower velocity—to escape from a point high above Earth than from Earth's surface.

## • How does gravity cause tides?

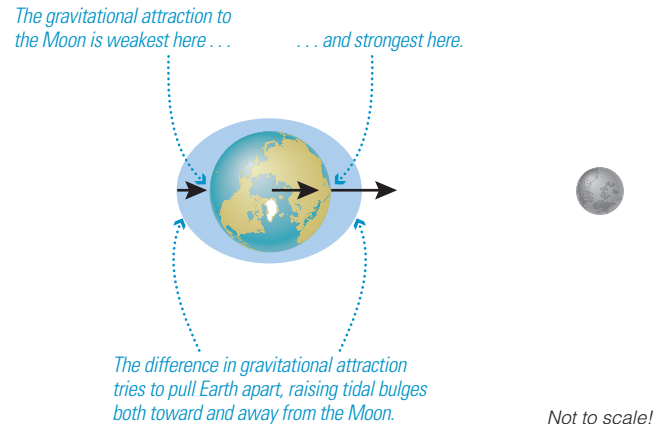
Newton's universal law of gravitation has applications that go far beyond explaining Kepler's laws and orbits. For our purposes, however, there is just one more topic we need to cover: how gravity causes tides.

If you've spent time near an ocean, you've probably observed the rising and falling of the tides. In most places, tides rise and fall twice each day. Tides arise because gravity attracts Earth and the Moon toward each other (with the Moon staying in orbit as it "falls around" Earth), but it affects different parts of Earth slightly differently: Because the strength of gravity declines with distance, the gravitational

attraction of each part of Earth to the Moon becomes weaker as we go from the side of Earth facing the Moon to the side facing away from the Moon. This difference in attraction creates a “stretching force,” or **tidal force**, that stretches the entire Earth to create two tidal bulges, one facing the Moon and one opposite the Moon (Figure 4.19). If you are still unclear about why there are *two* tidal bulges, think about a rubber band: If you pull on a rubber band, it will stretch in both directions relative to its center, even if you pull on only one side (while holding the other side still). In the same way, Earth stretches on both sides even though the Moon is tugging harder on only one side.

Tides affect both land and ocean, but we generally notice only the ocean tides because water flows much more readily than land. Earth’s rotation carries any location through each of the two bulges each day, creating two high tides. Low tides occur when the location is at the points halfway between the two tidal bulges. The height and timing of ocean tides varies considerably from place to place on Earth. For example, while the tide rises gradually in most locations, the incoming tide near

**Tidal forces cause the entire Earth to stretch along the Earth–Moon line, creating two tidal bulges.**



**FIGURE 4.19**

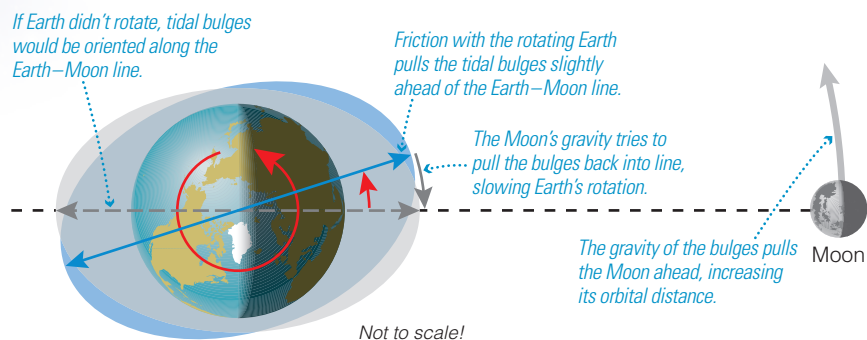
Tides are created by the difference in the force of attraction between different parts of Earth and the Moon. The two daily high tides occur as a location on Earth rotates through the two tidal bulges. (The diagram highly exaggerates the tidal bulges, which raise the oceans only about 2 meters and the land only about a centimeter.)

## special topic Why Does the Moon Always Show the Same Face to Earth?

**TIDAL EFFECTS EXPLAIN** the Moon’s *synchronous rotation*, in which the Moon keeps the same face toward Earth because its orbital period is the same as its rotation period. To understand why, let’s start by considering the Moon’s tidal effect on Earth.

By itself, the Moon’s gravity would keep Earth’s two tidal bulges on the Earth–Moon line. However, because the tidal bulges stretch Earth itself, Earth’s rotation generates friction with the bulges that tries to pull them around with it. The resulting “compromise” keeps the bulges just ahead of the Earth–Moon line at all times (see the figure), which causes two important effects. First, the Moon’s gravity always pulls back on the bulges, slowing Earth’s rotation. Second, the gravity of the bulges pulls the Moon slightly ahead in its orbit, adding orbital energy that causes the Moon to move farther from Earth. These effects are barely noticeable on human time scales, but they add up over billions of years. Early in Earth’s history, a day may have been only 5 or 6 hours long and the Moon may have been one-tenth or less of its current distance from Earth. These changes also provide a great example of conservation of angular momentum: The Moon’s growing orbit gains the angular momentum that Earth loses as its rotation slows.

Now consider Earth’s tidal force on the Moon, which must be greater than the Moon’s tidal force on Earth because of Earth’s greater mass. This tidal force gives the Moon two tidal bulges along the Earth–Moon line, much like the two tidal bulges that the Moon creates on Earth. (The Moon’s tidal bulges are not visible but can be measured in terms of excess mass along the Earth–Moon line.) If the Moon rotated through its tidal bulges in the same way that Earth rotates through its tidal bulges, the resulting friction would cause the Moon’s rotation to slow down. This is exactly what we think happened long ago.



Earth’s rotation pulls its tidal bulges slightly ahead of the Earth–Moon line, leading to gravitational effects that gradually slow Earth’s rotation and increase the Moon’s orbital distance.

The Moon probably once rotated much faster than it does today. As a result, it *did* rotate through its tidal bulges, and its rotation gradually slowed. Once the Moon’s rotation slowed to the point at which the Moon and its bulges rotated at the same rate—that is, synchronously with the orbital period—there was no further source for tidal friction. The Moon’s synchronous rotation was therefore a natural outcome of Earth’s tidal effects on the Moon.

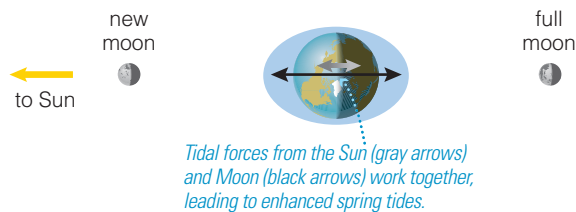
Similar tidal friction has led to synchronous rotation in many other cases. For example, Jupiter’s four large moons (Io, Europa, Ganymede, and Callisto) keep nearly the same face toward Jupiter at all times, as do many other moons. Pluto and its moon Charon *both* rotate synchronously: Like two dancers, they always keep the same face toward each other. Many binary star systems also rotate in this way. Tidal forces may be most familiar because of their effects on our oceans, but they are important throughout the universe.



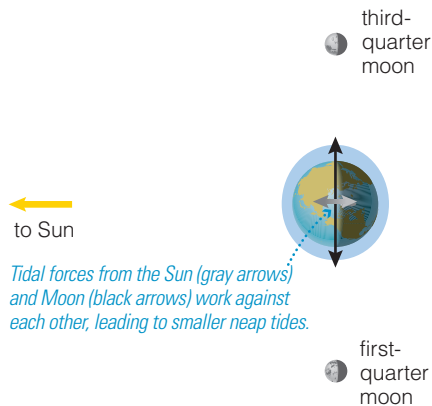
**FIGURE 4.20**

Photographs of high and low tide at the abbey of Mont-Saint-Michel, France. Here the tide rushes in much faster than a person can swim. Before a causeway was built (visible at the far left), the Mont was accessible by land only at low tide. At high tide, it became an island.

**Spring tides** occur at new moon and full moon:



**Neap tides** occur at first- and third-quarter moon:



**FIGURE 4.21** **MA** INTERACTIVE FIGURE

The Sun exerts a tidal force on Earth less than half as strong as that from the Moon. When the tidal forces from the Sun and Moon work together at new moon and full moon, we get enhanced *spring tides*. When they work against each other, at first- and third-quarter moons, we get smaller *neap tides*.

the famous abbey on Mont-Saint-Michel, France, moves much faster than a person can swim (Figure 4.20). In centuries past, the Mont was an island twice a day at high tide but was connected to the mainland at low tide. Many pilgrims drowned when they were caught unprepared by the tide rushing in. Another unusual tidal pattern occurs in coastal states along the northern shore of the Gulf of Mexico, where topography and other factors combine to make only one noticeable high tide and low tide each day.

The Sun also affects the tides. Although the Sun is much more massive than the Moon, its tidal effect on Earth is smaller because its much greater distance means that the *difference* in the Sun's pull on the near and far sides of Earth is relatively small. The overall tidal force caused by the Sun is a little less than half that caused by the Moon (Figure 4.21). When the tidal forces of the Sun and the Moon work together, as is the case at both new moon and full moon, we get the especially pronounced *spring tides* (so named because the water tends to “spring up” from Earth). When the tidal forces of the Sun and the Moon counteract each other, as is the case at first- and third-quarter moon, we get the relatively small tides known as *neap tides*.

**think about it** ► Explain why any tidal effects on Earth caused by the other planets would be unnoticeably small.

Tidal forces affect many objects in the solar system and universe. For example, Earth exerts tidal forces on the Moon that explain why the Moon always shows the same face to Earth (see Special Topic on page 99), and in Chapter 8 we'll see how tidal forces have led to the astonishing volcanic activity of Jupiter's moon Io and the possibility of a subsurface ocean on its moon Europa.



## the big picture

## PUTTING CHAPTER 4 INTO PERSPECTIVE

We've covered a lot of ground in this chapter, from the scientific terminology of motion to the overarching principles that govern motion throughout the universe. Be sure you understand the following “big picture” ideas:

- Understanding the universe requires understanding motion. Motion may seem complex, but it can be described simply using Newton's three laws of motion.
- Today, we know that Newton's laws of motion stem from deeper physical principles, including the laws of conservation of angular momentum and of energy. These principles enable us to understand a wide range of astronomical phenomena.

- Newton also discovered the universal law of gravitation, which explains how gravity holds planets in their orbits and much more—including how satellites can reach and stay in orbit, the nature of tides, and why the Moon rotates synchronously around Earth.
- Newton's discoveries showed that the same physical laws we observe on Earth apply throughout the universe. The universality of physics opens up the entire cosmos as a possible realm of human study.

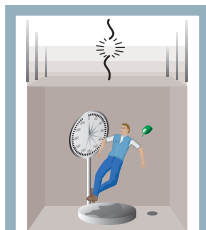
## summary of key concepts

### 4.1 Describing Motion: Examples from Daily Life

#### • How do we describe motion?

**Speed** is the rate at which an object is moving. **Velocity** is speed in a certain direction. **Acceleration** is a change in velocity, meaning a change in either speed or direction. **Momentum** is mass  $\times$  velocity. A **force** can change an object's momentum, causing it to accelerate.

#### • How is mass different from weight?



An object's **mass** is the same no matter where it is located, but its **weight** varies with the strength of gravity or other forces acting on the object. An object becomes **weightless** when it is in **free-fall**, even though its mass is unchanged.

### 4.2 Newton's Laws of Motion

#### • How did Newton change our view of the universe?

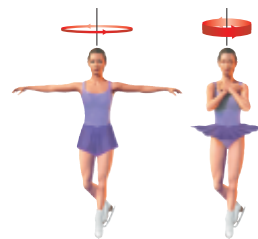
Newton showed that the same physical laws that operate on Earth also operate in the heavens, making it possible to learn about the universe by studying physical laws on Earth.

#### • What are Newton's three laws of motion?

(1) An object moves at constant velocity if there is no net force acting upon it. (2) Force = mass  $\times$  acceleration ( $F = ma$ ). (3) For any force, there is always an equal and opposite reaction force.

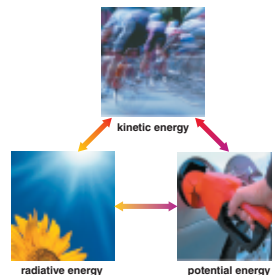
### 4.3 Conservation Laws in Astronomy

#### • What keeps a planet rotating and orbiting the Sun?



**Conservation of angular momentum** means that a planet's rotation and orbit cannot change unless it transfers angular momentum to another object. The planets in our solar system do not exchange substantial angular momentum with each other or anything else, so their orbits and rotation rates remain fairly steady.

#### • Where do objects get their energy?



Energy is always conserved—it can be neither created nor destroyed. Objects received whatever energy they now have from exchanges of energy with other objects. Energy comes in three basic categories—**kinetic**, **radiative**, and **potential**.

### 4.4 The Force of Gravity

#### • What determines the strength of gravity?

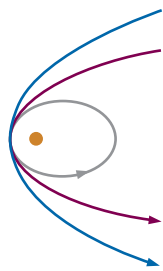


According to the **universal law of gravitation**, every object attracts every other object with a gravitational force that is directly proportional to the product of the objects' masses and declines with the square of the distance between their centers:

$$F_g = G \frac{M_1 M_2}{d^2}$$



• **How does Newton's law of gravity extend Kepler's laws?**



(1) Newton showed that Kepler's first two laws apply to all orbiting objects, not just planets. (2) He showed that elliptical **bound orbits** are not the only possible orbital shape—orbital shapes can also be **unbound** (taking the shape of a parabola or a hyperbola). (3) **Newton's version of Kepler's third law** allows us to calculate the masses of orbiting objects from their orbital periods and distances.

• **How do gravity and energy allow us to understand orbits?**

Gravity determines orbits, and an object cannot change its orbit unless it gains or loses **orbital energy**—the sum of its kinetic and gravitational potential energy—through energy exchange with other objects. If an object gains enough orbital energy, it may achieve **escape velocity** and leave the gravitational influence of the object it was orbiting.

• **How does gravity cause tides?**

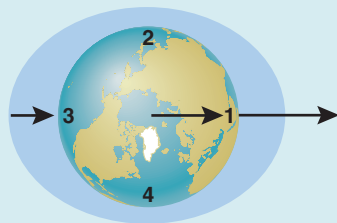


The Moon's gravity creates a **tidal force** that stretches Earth along the Earth–Moon line, causing Earth to bulge both toward and away from the

Moon. Earth's rotation carries us through the two bulges each day, giving us two daily high tides and two daily low tides.

## visual skills check

Check your understanding of some of the many types of visual information used in astronomy. For additional practice, try the Chapter 4 Visual Quiz at MasteringAstronomy®.



The figure represents how the Moon causes tides on Earth; the diagram looks down from above the North Pole, so the numbers 1 through 4 label points along Earth's equator.

- What do the three black arrows represent?
  - the tidal force Earth exerts on the Moon
  - the Moon's gravitational force at different points on Earth
  - the direction in which Earth's water is flowing
  - Earth's orbital motion
- Where is it high tide?
  - point 1 only
  - point 2 only
  - points 1 and 3
  - points 2 and 4
- Where is it low tide?
  - point 1 only
  - point 2 only
  - points 1 and 3
  - points 2 and 4
- What time is it at point 1?
  - noon
  - midnight
  - 6 a.m.
  - cannot be determined from the information in the figure
- The light blue region represents tidal bulges. In what way are these bulges drawn inaccurately?
  - There should be only one bulge rather than two.
  - They should be aligned with the Sun rather than the Moon.
  - They should be much smaller compared to Earth.
  - They should be more pointy in shape.

## exercises and problems

MasteringAstronomy® For instructor-assigned homework and other learning materials, go to MasteringAstronomy®.

### Review Questions

- Define *speed*, *velocity*, and *acceleration*. What are the units of acceleration? What is the *acceleration of gravity*?
- Define *momentum* and *force*. What do we mean when we say that momentum can be changed only by a *net force*?
- What is *free-fall*, and why does it make you *weightless*? Briefly describe why astronauts are weightless in the Space Station.
- State *Newton's three laws of motion*. For each law, give an example of its application.
- Describe the laws of *conservation of angular momentum* and *conservation of energy*. Give an example of how each is important in astronomy.
- Define *kinetic energy*, *radiative energy*, and *potential energy*, with at least two examples for each.
- Define and distinguish *temperature* and *thermal energy*.
- What is *mass-energy*? Explain the formula  $E = mc^2$ .
- Summarize the *universal law of gravitation* both in words and with an equation.

10. What is the difference between a *bound* and an *unbound orbit*?
11. What do we need to know if we want to measure an object's mass with *Newton's version of Kepler's third law*? Explain.
12. Explain why orbits cannot change spontaneously, and how a *gravitational encounter* can cause a change. How can an object achieve *escape velocity*?
13. Explain how the Moon creates tides on Earth. Why do we have two high and low tides each day?
14. How do the tides vary with the phase of the Moon? Why?
29. To make a rocket turn left, you need to (a) fire an engine that shoots out gas to the left. (b) fire an engine that shoots out gas to the right. (c) spin the rocket clockwise.
30. Compared to its angular momentum when it is farthest from the Sun, Earth's angular momentum when it is nearest to the Sun is (a) greater. (b) less. (c) the same.
31. The gravitational potential energy of a contracting interstellar cloud (a) stays the same at all times. (b) gradually transforms into other forms of energy. (c) gradually grows larger.
32. If Earth were twice as far from the Sun, the force of gravity attracting Earth to the Sun would be (a) twice as strong. (b) half as strong. (c) one-quarter as strong.
33. According to the law of universal gravitation, what would happen to Earth if the Sun were somehow replaced by a black hole of the same mass? (a) Earth would be quickly sucked into the black hole. (b) Earth would slowly spiral into the black hole. (c) Earth's orbit would not change.
34. If the Moon were closer to Earth, high tides would (a) be higher than they are now. (b) be lower than they are now. (c) occur three or more times a day rather than twice a day.

## Test Your Understanding

### Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

15. I make it a habit to be weightless for at least a fraction of a second every day.
16. Suppose you could enter a vacuum chamber (a chamber with no air in it) on Earth. Inside this chamber, a feather would fall at the same rate as a rock.
17. When an astronaut goes on a space walk outside the Space Station, she will quickly float away from the station unless she has a tether holding her to the station.
18. I used Newton's version of Kepler's third law to calculate Saturn's mass from orbital characteristics of its moon Titan.
19. If the Sun were magically replaced with a giant rock that had precisely the same mass, Earth's orbit would not change.
20. The fact that the Moon rotates once in precisely the time it takes to orbit Earth once is such an astonishing coincidence that scientists probably never will be able to explain it.
21. Venus has no oceans, so it could not have tides even if it had a moon (which it doesn't).
22. If an asteroid passed by Earth at just the right distance, Earth's gravity would capture it and make it our second moon.
23. When I drive my car at 30 miles per hour, it has more kinetic energy than it does at 10 miles per hour.
24. Someday soon, scientists are likely to build an engine that produces more energy than it consumes.

### Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

25. A car is accelerating when it is (a) traveling on a straight, flat road at 50 miles per hour. (b) traveling on a straight uphill road at 30 miles per hour. (c) going around a circular track at a steady 100 miles per hour.
26. Compared to their values on Earth, on another planet your (a) mass and weight would both be the same. (b) mass would be the same but your weight would be different. (c) weight would be the same but your mass would be different.
27. Which person is weightless? (a) a child in the air as she plays on a trampoline (b) a scuba diver exploring a deep-sea wreck (c) an astronaut on the Moon
28. Consider the statement "There's no gravity in space." This statement is (a) completely false. (b) false if you are close to a planet or moon, but true in between the planets. (c) completely true.

## Process of Science

35. *Testing Gravity.* Scientists are constantly trying to learn whether our current understanding of gravity is complete or must be modified. Describe how the observed motion of spacecraft headed out of the solar system (such as the *Voyager* spacecraft) can be used to test the accuracy of our current theory of gravity.
36. *How Does the Table Know?* Thinking deeply about seemingly simple observations sometimes reveals underlying truths that we might otherwise miss. For example, think about holding a golf ball in one hand and a bowling ball in the other. To keep them motionless, you must actively adjust the tension in your arm muscles so that each arm exerts a different upward force that exactly balances the weight of each ball. Now, think about what happens when you set the balls on a table. Somehow, the table exerts exactly the right amount of upward force to keep the balls motionless, even though their weights are very different. How does a table "know" to make the same type of adjustment that you make consciously when you hold the balls motionless in your hands? (*Hint:* Think about the origin of the force pushing upward on the objects.)

## Group Work Exercise

37. *Your Ultimate Energy Source.* **Roles:** *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), *Moderator* (leads group discussion and makes sure the group works as a team). **Activity:** According to the law of conservation of energy, the energy your body is using right now had to come from somewhere else. Make a list going backwards in time describing how the energy you are using right now has proceeded through time. For each item on the list, identify the energy as kinetic energy, gravitational potential energy, chemical potential energy, electrical potential energy, mass-energy, or radiative energy.

## Investigate Further

### Short-Answer/Essay Questions

38. *Weightlessness.* Astronauts are weightless when in orbit in the Space Station. Are they also weightless during launch to the station? How about during their return to Earth? Explain.
39. *Einstein's Famous Formula.*
  - a. What is the meaning of the formula  $E = mc^2$ ? Define each variable.
  - b. How does this formula explain the generation of energy by the Sun?
  - c. How does this formula explain the destructive power of nuclear bombs?
40. *The Gravitational Law.*
  - a. How does quadrupling the distance between two objects affect the gravitational force between them?
  - b. Suppose the Sun were somehow replaced by a star with twice as much mass. What would happen to the gravitational force between Earth and the Sun?
  - c. Suppose Earth were moved to one-third of its current distance from the Sun. What would happen to the gravitational force between Earth and the Sun?
41. *Allowable Orbits?*
  - a. Suppose the Sun were replaced by a star with twice as much mass. Could Earth's orbit stay the same? Why or why not?
  - b. Suppose Earth doubled in mass (but the Sun stayed the same as it is now). Could Earth's orbit stay the same? Why or why not?
42. *Head-to-Foot Tides.* You and Earth attract each other gravitationally, so you should also be subject to a tidal force resulting from the difference between the gravitational attraction felt by your feet and that felt by your head (at least when you are standing). Explain why you can't feel this tidal force.

### Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

43. *Energy Comparisons.* Use the data in Table 4.1 to answer each of the following questions.
  - a. Compare the energy of a 1-megaton H-bomb to the energy released by a major earthquake.
  - b. If the United States obtained all its energy from oil, how much oil would be needed each year?
  - c. Compare the Sun's annual energy output to the energy released by a supernova.
44. *Fusion Power.* No one has yet succeeded in creating a commercially viable way to produce energy through nuclear fusion. However, suppose we could build fusion power plants using the hydrogen in water as a fuel. Based on the data in Table 4.1, how much water would we need each minute to meet U.S. energy needs? Could such a reactor power the entire United States with the water flowing from your kitchen sink? Explain. (*Hint:* Use the annual U.S. energy consumption to find the energy consumption per minute, and then divide by the energy yield from fusing 1 liter of water to figure out how many liters would be needed each minute.)
45. *Understanding Newton's Version of Kepler's Third Law.* Find the orbital period for the planet in each case. (*Hint:* The calculations for this problem are so simple that you will not need a calculator.)
  - a. A planet with twice Earth's mass orbiting at a distance of 1 AU from a star with the same mass as the Sun.
  - b. A planet with the same mass as Earth orbiting at a distance of 1 AU from a star with four times the Sun's mass.
46. *Using Newton's Version of Kepler's Third Law.*
  - a. Find Earth's approximate mass from the fact that the Moon orbits Earth in an average time of 27.3 days at an average distance of 384,000 kilometers. (*Hint:* The Moon's mass is only about  $\frac{1}{80}$  of Earth's.)
  - b. Find Jupiter's mass from the fact that its moon Io orbits every 42.5 hours at an average distance of 422,000 kilometers.
  - c. You discover a planet orbiting a distant star that has about the same mass as the Sun, with an orbital period of 63 days. What is the planet's orbital distance?
  - d. Pluto's moon Charon orbits Pluto every 6.4 days with a semimajor axis of 19,700 kilometers. Calculate the *combined* mass of Pluto and Charon.
  - e. Calculate the orbital period of a spacecraft in an orbit 300 kilometers above Earth's surface.
  - f. Estimate the mass of the Milky Way Galaxy from the fact that the Sun orbits the galactic center every 230 million years at a distance of 27,000 light-years. (As we'll discuss in Chapter 15, this calculation actually tells us only the mass of the galaxy *within* the Sun's orbit.)

### Discussion Questions

47. *Knowledge of Mass-Energy.* Einstein's discovery that energy and mass are equivalent has led to technological developments that are both beneficial and dangerous. Discuss some of these developments. Overall, do you think the human race would be better or worse off if we had never discovered that mass is a form of energy? Defend your opinion.
48. *Perpetual Motion Machines.* Every so often, someone claims to have built a machine that can generate energy perpetually from nothing. Why isn't this possible according to the known laws of nature? Why do you think claims of perpetual motion machines sometimes receive substantial media attention?

### Web Projects

49. *Space Station.* Visit a NASA site with pictures from the Space Station. Choose two photos that illustrate some facet of Newton's laws. Explain how Newton's laws apply to each photo.
50. *Nuclear Power.* There are two basic ways to generate energy from atomic nuclei: through nuclear fission (splitting nuclei) and through nuclear fusion (combining nuclei). All current nuclear reactors are based on fission, but using fusion would have many advantages if we could develop the technology. Research some of the advantages of fusion and some of the obstacles to developing fusion power. Do you think fusion power will be a reality in your lifetime? Explain.
51. *Space Elevator.* Some people have proposed using a "space elevator" to reach orbit high above Earth. Learn about the concept and write a short report on how it works, what advantages it would have over rockets, and whether it is feasible.